On the other hand, turn-on behaviour of a diode is not important for the power loss balance, since turn-on losses only amount to a small percentage of the losses during turn-off and forward on-state and may therefore be neglected.

1.3.1.3 Reverse recovery behaviour

When passing over from the conductive to the blocking state, the internal diode storage charge has to be discharged. This results in a current flowing in reverse direction in the diode. The waveform of this current is characterized as the reverse-recovery behaviour.
Figure 1.19 shows the simplest circuit for the characterisation.

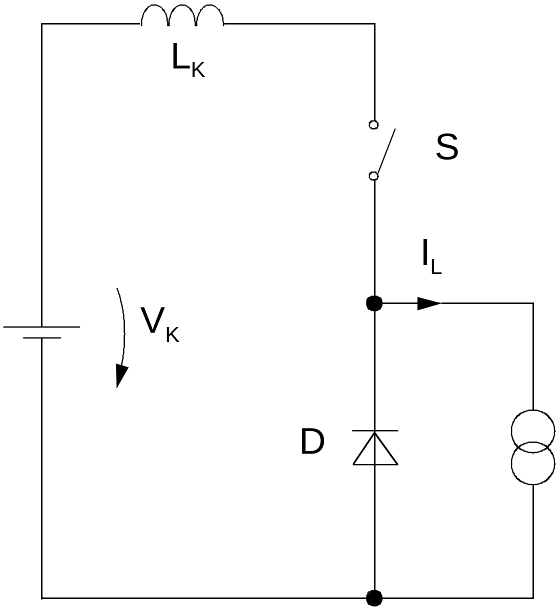


Figure 1.19 Reverse-recovery test circuit

S depicts an ideal switch, I_L is the current source, V_K a voltage source and L_K stands for the commutation circuit inductance.

After closing switch S, a soft-recovery diode will show a current and voltage characteristic as shown in Figure 1.20. Figure 1.20 is an example for a soft-recovery behaviour of a diode.

Figure 1.21 shows two examples for diode current characteristics with snappy switching behaviour. Firstly, the definitions are explained by referring to Figure 1.20.

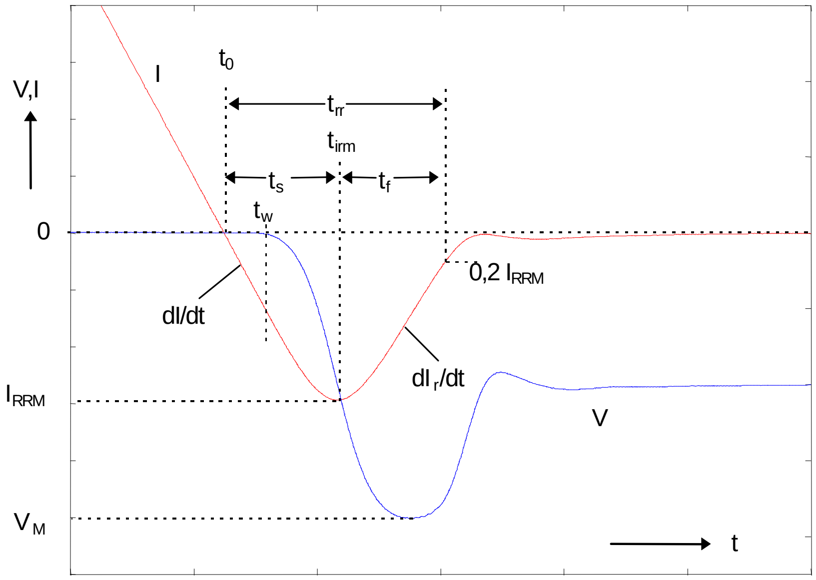


Figure 1.20 Current and voltage characteristic of the reverse recovery process of a soft-recovery diode in a circuit as shown in Figure 1.19 and definition of the characteristics of the recovery behaviour

The commutation velocity dI/dt is determined by voltage and inductance:

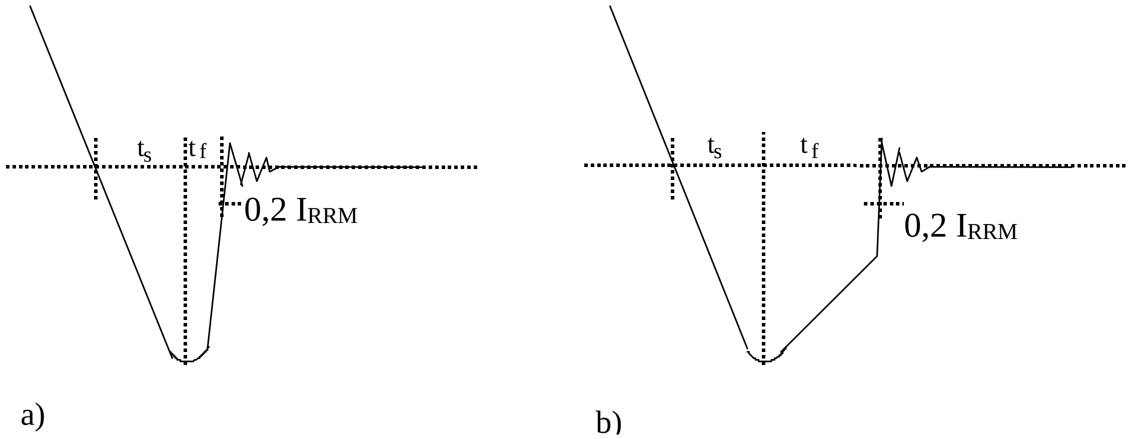
$$-\frac{dI}{dt} = \frac{V_K}{L_K} \tag{1.1}$$

At t_0 current is at zero passage. At t_w the diode starts to block. At this instant, the pn-junction in the diode gets free of charge carriers. At t_{irm} the reverse current is at its maximum I_{RRM}.
After t_{irm} the current will fall to leakage current level, the current characteristic depends solely on the diode. If the current drops very steeply, this is called snappy recovery behaviour. If the current drops very softly, this is called soft recovery behaviour.

The reverse recovery time t_{rr} is defined as the time between t_0 and the time, where the current has dropped to 20 % of I_{RRM}. The subdivision of t_{rr} into t_f and t_s shown in Figure 1.20 defines as quantitative value for the recovery behaviour:

$$\text{Soft factor} \quad s = \frac{t_f}{t_s} \tag{1.2}$$

This definition is insufficient, because, as a consequence, the current characteristic as in Figure 1.21a would be snappy. The characteristic in Figure 1.21b, however, would be classified as soft even though $t_f > t_s$ holds, there is a hard snapp-off.



a) b)

Figure 1.21 Current characteristic for two different possibilities of snappy reverse recovery behaviour

Better is the definition:

Soft-factor

$$S = \left| \frac{-\frac{dI}{dt}\Big|_{I=0}}{\left(\frac{dI_r}{dt}\right)_{max}} \right| \tag{1.3}$$

Measurements have to be taken at a current flow of less than 10 % and of 200 % of the specified current. By this also the charactertistic in Figure 1.21b will be defined as snappy.
Moreover, this considers that small currents are extremely critical for the reverse-recovery behaviour.
The occurring overvoltage is determined by dI_r/dt according to the inductance law

$$V_{ind} = -L_K \cdot \left(\frac{dI_r}{dt}\right)_{max} \tag{1.4}$$

Therefore, overvoltage occurring under certain measuring conditions or the peak voltage $V_M = V_K + V_{ind}$ may also be seen as characteristics for the recovery behaviour. V_K and dI/dt have to be figured in this context.
But also this definition is not sufficient, because it still neglects the following parameters:

1. Temperature. Mostly, high temperatures have a negative influence on the recovery behaviour. But for certain fast diodes, the recovery behaviour will get worse at ambient temperature or at lower temperatures.
2. Applied voltage. Higher voltages will lead to impaired reverse recovery
3. Rate of rise of commutation current dI/dt. The dependency on dI/dt is very different for diodes of various manufacturers. Some types of diodes react more softly with increase of dI/dt, other types behave more snappy.

All these different influences may not be summarized in one simple definition of quantity. Therefore, the circuit in Figure 1.19 and the definitions according to (1.2) or (1.3.) are only usefull to explain the effects of the single production parameters of diode behaviour. An overall estimation of reverse recovery behaviour can only be made under application-related conditions.
An application-related measuring circuit is shown in Figure 1.22.

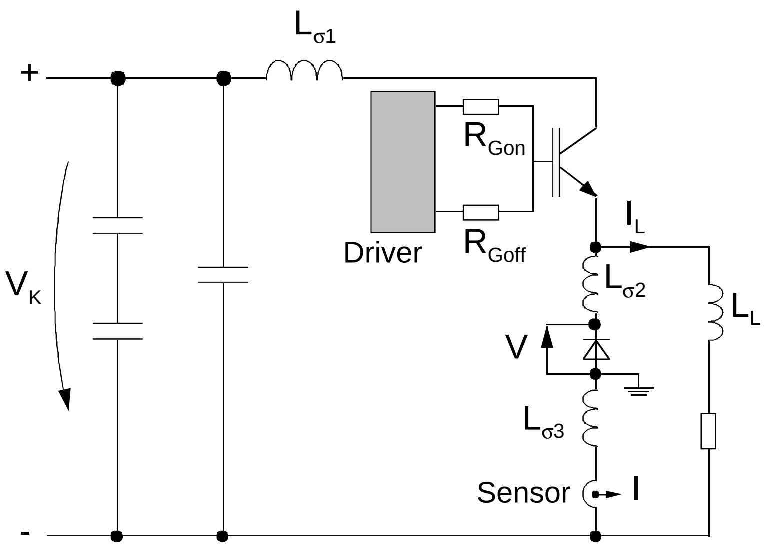


Figure 1.22 Application-related chopper circuit of a step-down converter (double-pulse operation) for reverse recovery measurements

The commutation velocity dI/dt is adjusted by the gate resistor R_{Gon} of the switching device. V_K is the DC-link voltage. A parasitic inductance $L_{\sigma1}$ is generated in the connections between capacitors, IGBT and diode. Figure 1.23 shows the IGBT control signals and the current flow within IGBT and diode under double-pulse operation. By turn-off of the IGBT, the load current will be taken over by the free-wheeling diode. As soon as the IGBT is turned on next time, the diode will be commutated, characterizing its recovery behaviour at that moment. During turn-on, the IGBT also takes over the reverse current of the free-wheeling diode. This procedure is depicted for a soft-recovery diode in Figure 1.24 at a higher resolution of the time axis. Figure 1.24a shows an IGBT current and voltage characteristic and also the turn-on power losses. Figure 1.24b shows the FWD-current and voltage characteristic as well as power losses.

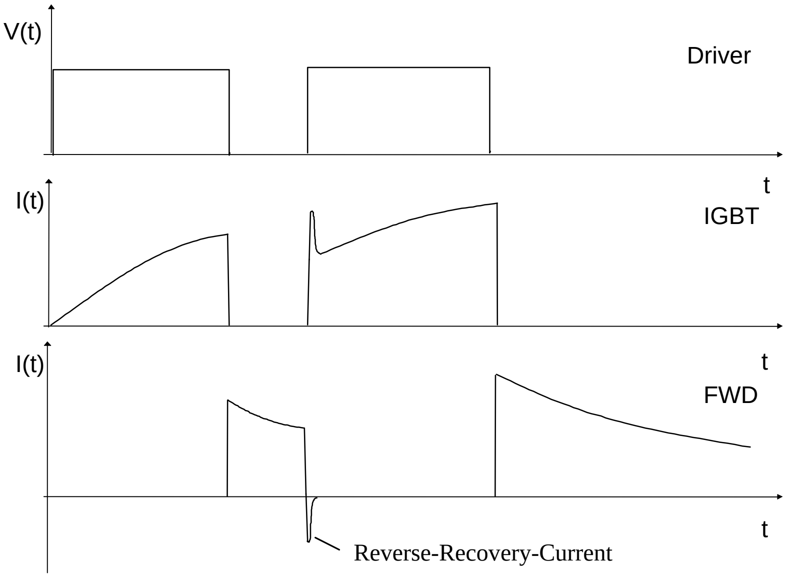


Figure 1.23 Driver control signal, IGBT- and FWD-current waveforms in a circuit according to Fig. 1.22 (double-pulse operation)

While the IGBT conducts the peak reverse current I_{RRM}, the IGBT-voltage is still on DC-link voltage level (1200V in Figure 1.24a). This is the moment of maximum turn-on losses in the IGBT.

The diode reverse recovery characteristic may be divided up into two phases:

1. The phase of increase up to the reverse peak current and the consequent reverse drop current with dI_r/dt. dI_r/dt is within the range of dI/dt as far as a soft-recovery diode is concerned. The peak reverse recovery current I_{RRM} exerts most stress on the switching device.

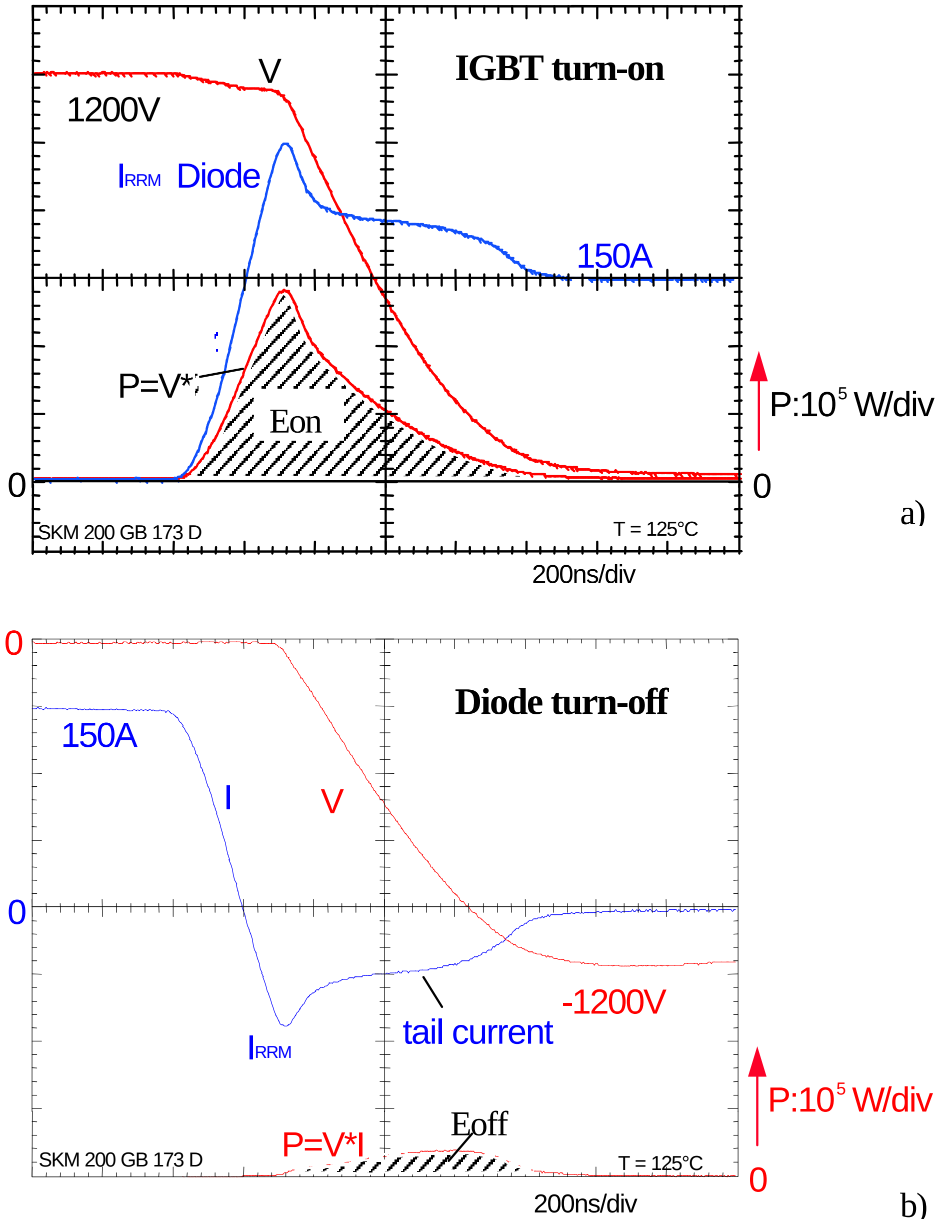


Figure 1.24 Current, voltage and power losses during IGBT turn-on (a) and diode turn-off (b) for a measurement in a test circuit according to Figure 1.22

2. The tail phase, where the reverse current slowly declines to zero. There is no point in defining a t_{rr}. The main power losses in the diode are due to the tail phase, where voltage has already been applied to the diode. A snappy diode without tail current would cause less

switching losses, but would be unsuitable for the application. In the IGBT, the switching losses during the tail phase are not that extreme, because the applied voltage has already decreased at that time.

Compared to IGBT switching losses, the losses the diode are low in the application (diode switching losses in Fig. 1.24b are drawn to the same scale as the IGBT switching losses in Fig. 1.24b). In order to keep power losses of both, IGBT and diode, as low as possible, it is important to care for a small peak reverse current and to have the main part of the storage charge discharged during the tail phase. A limit to this is set by the maximum switching losses that can be dissipated in the diode.

The peak reverse recovery current I_{RRM} is the most important parameter for the diode taking influence on the total losses. Therefor it should be minimized.

In a typical application, where the chopper is in a semiconductor module, the parasitic inductance $L_{\sigma ges}$ is in the range of 40nH, reducing the generated overvoltage. Due to lack of ideal switches, the voltage applied to the IGBT will drop to a certain degree during the recovery phase. The voltage taken becomes

$$-V(t) = -V_K - L_{\sigma ges} \cdot \frac{dI_R}{dt} + V_{CE}(t) \qquad (1.5)$$

with $V_{CE}(t)$ being the voltage still applied to the IGBT at the respective time. It is typical of soft-recovery diodes that, for moderate rates of rise up to 1500A/µs and minimized parasitic inductances, V(t) is smaller than V_K at any time and that there will be no voltage peaks.

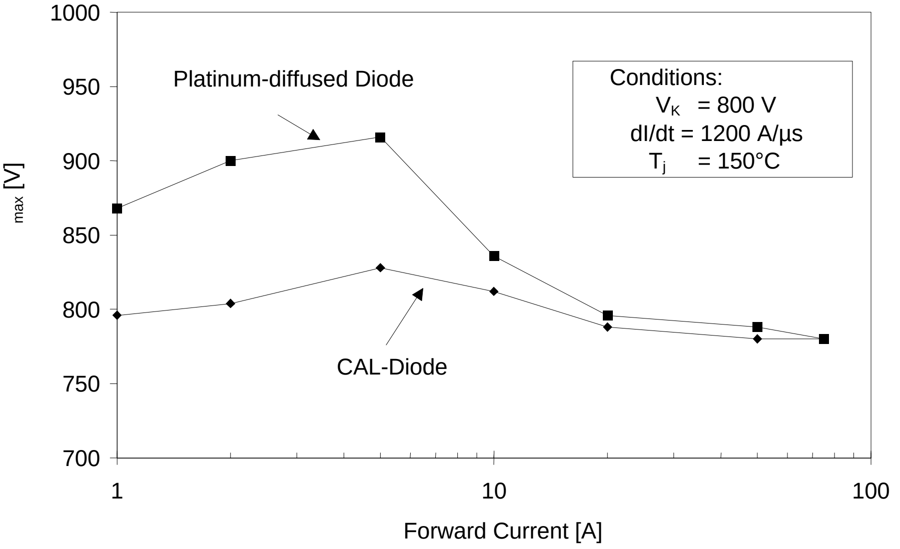


Figure 1.25 Peak voltage during commutation in dependence of forward on-state current as a parameter for the switching behaviour of diodes

Figure 1.25 gives an example for characterization of the recovery behaviour by this method. In these conditions, the overvoltage occurring in a CAL-diode has been compared to that occurring in a diode, the charge carrier life of which had been adjusted by platinum-diffusion, showing soft-recovery behaviour by reduced p-emitter efficiency. A platinum-diffused diode behaves as soft as a CAL-diode at rated current (75A). Smaller currents, however, will cause overvoltages up to a maximum of more than 100 V at 10 % of rated current due to snappy switching behaviour. Even smaller currents are switched more slowly by the applied IGBT, affecting a