Total power dissipation P_{tot}
Maximum power dissipation per transistor/ diode or within the whole power module $P_{tot} = (T_{jmax}-T_{case})/R_{thjc}$,
Parameter: case temperature T_{case} = 25°C

Operating temperature range T_{vj} or T_j ; $T_{j(min)}$....$T_{j(max)}$
Permissible chip temperature range within which the module may be permanently operated.

Storage temperature range T_{stg}; $T_{stg(min)}$....$T_{stg(max)}$)
Temperature range within which the module may be stored or transported without being subject to electrical load.

Isolation test voltage V_{isol} or V_{is}
Effective value of the permissible test voltage between input terminals/ control terminals (short-circuited, all terminals connected to each other) and module base plate.
Parameters: test duration (1 min, 1 s), rate of rise of test voltage, if required;
according to IEC 146-1-1 (1991), EN 60146-1-1 (1993), section 4.2.1 (corresponds to VDE 0558, volume 1-1: 1993-04) and DIN VDE 0160 (1988-05), section 7.6 (corresponds to EN 50178 (1994)/ E VDE 0160 (1994-11) the test voltage shall only rise gradually up to its maximum rating.

Grade of humidity
describes the permissible ambient conditions (atmospheric humidity) according to DIN 40 040

Grade of climate
describes the permissible ambient test conditions (climate) according to DIN IEC 68-1

Inverse diodes/ free-wheeling diodes

Forward current I_F
Maximum forward current value of the inverse or free-wheeling diodes,
Parameter: case temperature, e.g. T_{case} = 25°C, 80°C

Peak periodic forward current I_{FM} or pulsed forward current I_{Fpuls}
Peak value of the diode current during pulse operation
Parameters: pulse duration t_p, case temperature, e.g. T_{case} = 25°C, 80°C

2.3.2 Characteristics

IGBTs/ module structure

Collector-emitter breakdown voltage $V_{(BR)CES}$
Breakdown voltage between collector and emitter, gate-emitter short-circuited (V_{GE} = 0),
Parameters: collector blocking current I_C, case temperature T_{case} = 25°C

Gate-emitter threshold voltage $V_{GE(th)}$
Gate-emitter voltage above which considerable collector current will flow
Parameters: collector-emitter voltage $V_{CE} = V_{GE}$, collector current I_C, case temperature T_{case} = 25°C

Collector-emitter cut-off current I_{CES}
Collector-emitter blocking current with gate-emitter short-circuited (V_{GE} = 0) and collector-emitter voltage $V_{CE} = V_{CES}$
Parameter: chip temperature, e.g. T_j = 25°C and 125°C

Gate-emitter leakage current I_{GES}
Leakage current between gate and emitter with collector-emitter short-circuited (V_{CE} = 0) and at maximum gate-emitter voltage V_{GE}
Parameter: gate-emitter voltage V_{GE}, case temperature T_{case} = 25°C

Collector-emitter saturation voltage V_{CEsat}
Saturation value of collector-emitter voltage (on-state voltage drop of the active IGBT) at a specified collector current I_C (at "rated current", see chapter 2.3.3, or at maximum collector current). For PT-IGBTs V_{CEsat} will drop proportionally to the temperature within rated current range, for NPT-IGBTs, however, it will rise proportionally to the temperature.
Parameters: collector current I_C, gate-emitter voltage V_{GE}, chip temperature, e.g. T_j = 25°C and 125°C.
For calculation of forward on-state losses the following parameters are often indicated additionally in the datasheets: $V_{CE(TO)}$ (static collector-emitter threshold voltage) and r_{CE} (on-state slope resistance) of a substitutional straight line.

$$V_{CEsat} = f(I_C) = V_{CE(TO)} + r_{CE} * I_C$$

This means that, for calculation, the saturation voltage characteristic is approximated by means of a diode characteristic.

Forward transconductance g_{fs}
Quotient of changing collector current and gate-emitter voltage at a specified collector current I_C,
Parameters: collector-emitter voltage V_{CE}, collector current I_C ("rated current", resp.),
case temperature T_{case} = 25°C

Capacitance chip-case C_{CHC}
Capacitance between a sub-component and case base plate or heatsink potential
Parameter: case temperature T_{case} = 25°C

Input capacitance C_{iss}
Capacitance between gate and emitter with collector-emitter short-circuited for AC and gate-emitter voltage V_{GE} = 0.
Parameters: collector-emitter voltage $V_{CE,}$ measuring frequency f, case temperature T_{case} = 25°C

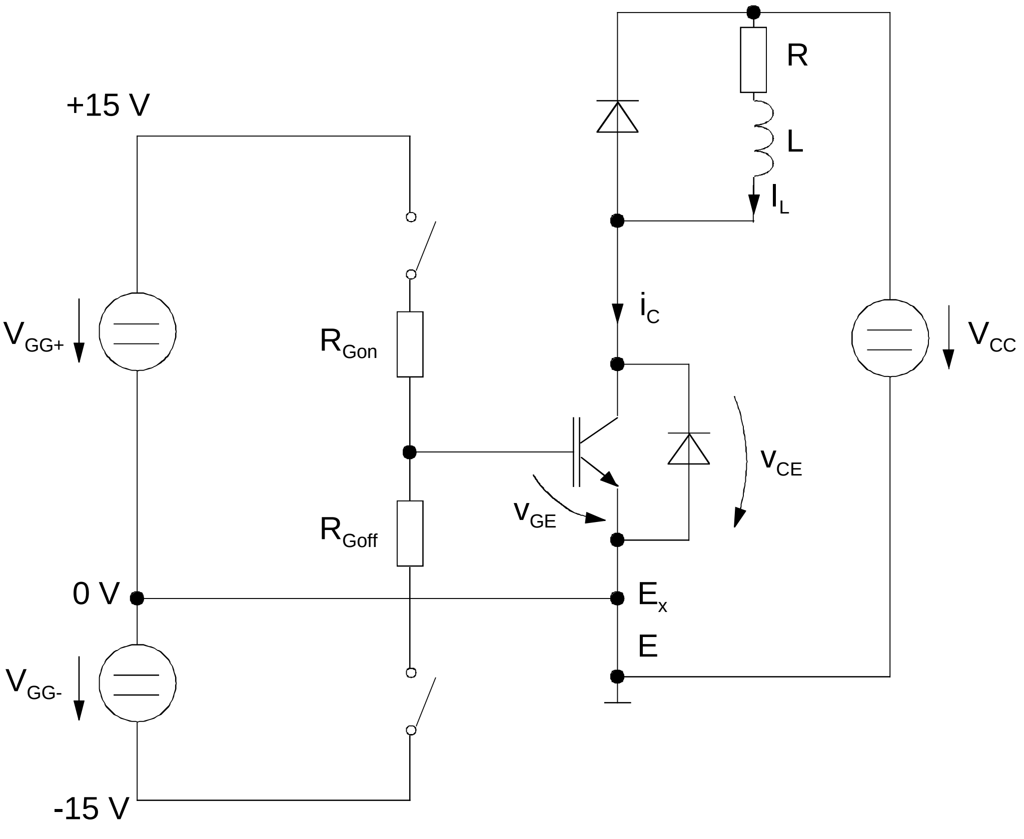
Output capacitance C_{oss}
Capacitance between collector and emitter with gate-emitter short-circuited (V_{GE} = 0).
Parameters: collector-emitter voltage V_{CE}, measuring frequency f, case temperature T_{case} = 25°C

Reverse transfer capacitance (Miller capacitance) C_{rss}, C_{mi}
Capacitance between collector and gate with collector-emitter short-circuited for AC and gate-emitter voltage V_{GE} = 0. For measuring the emitter has to be connected with the protective shield of the measuring bridge.
Parameters: collector-emitter voltage V_{CE}, measuring frequency f, case temperature T_{case} = 25°C

Parasitic collector-emitter inductance L_{CE}
Inductance between collector and emitter

Switching times
More related to practice than switching times of MOSFETs, switching times of IGBTs indicated in the datasheets are determined from a measuring circuit under ohmic-inductive load according to Figure 2.9a. The load time constant L/R is high compared to the switching frequency cycle duration T = 1/f, so that an continuous load current is generated by the load inductance.
Just as with MOSFETs, switching times of IGBTs refer to the gate-emitter characteristics during turn-on and turn-off, see Figure 2.9b.

Switching times as well as real current and voltage characteristics are determined by internal and external capacitances, inductances and resistances of the gate and drain circuit; for this reason, all indications in the datasheets and the characteristics depicted therein may only serve as a guide.



a)

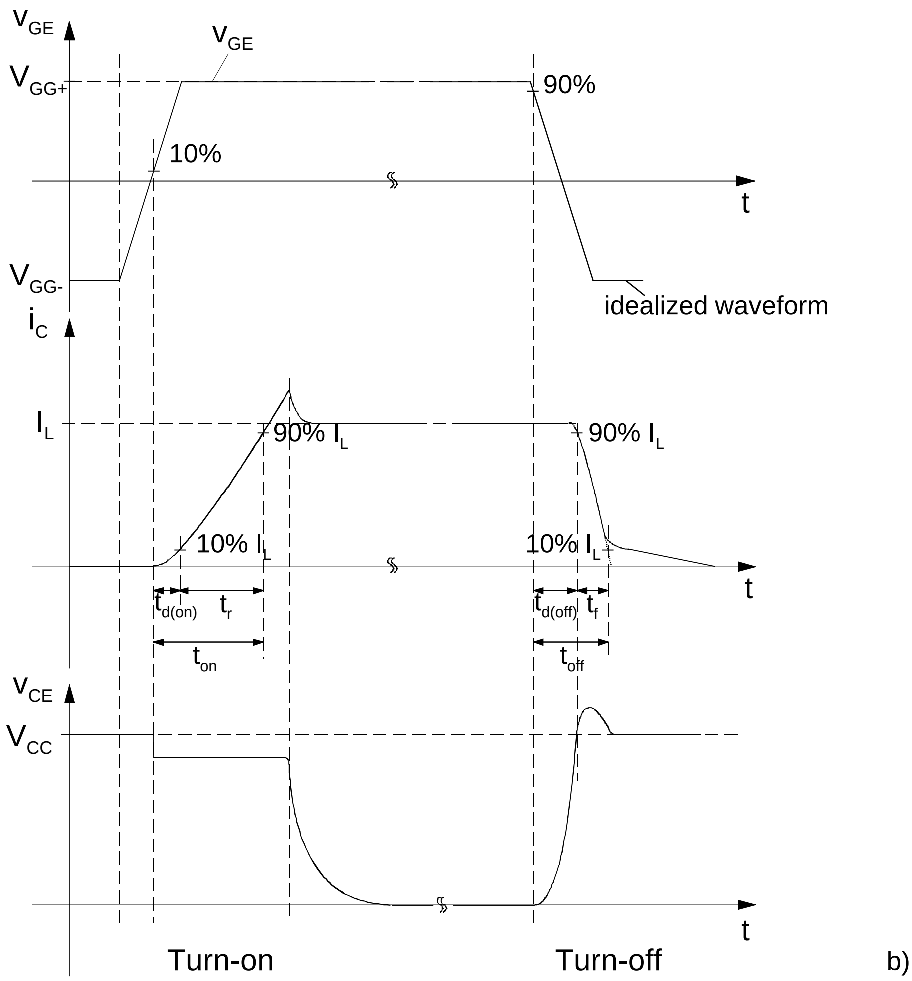


Figure 2.9 a) Measuring circuit
b) Definition of IGBT switching times under ohmic-inductive load [264],[265]

The following parameters are indicated in the datasheets relevant to switching times: measuring circuit, collector-emitter supply voltage V_{CC}, gate-emitter control voltages V_{GG+}, V_{GG-} or V_{GE}, collector current I_C, external gate series resistors R_{Gon} ,R_{Goff} (resistance of control circuit at turn-on and turn-off), chip temperature T_j = 125°C

Turn-on delay time $t_{d(on)}$

As already mentioned, the total forward on-state current of the IGBT is to be conducted by the load inductance before turn-on.

After sudden turn-on of a positive gate-emitter control voltage, the gate-emitter voltage V_{GE} starts to rise with a time constant determined by IGBT input capacitance and gate resistance. As soon as the threshold voltage $V_{GE(th)}$ has been reached, the collector current I_C will start to rise.

The **turn-on delay time $t_{d(on)}$** is defined as the time interval between the moment when the gate-emitter voltage v_{GE} has reached 10 % of its end value, and the collector current i_C has increased to 10 % of the load current.

Rise time t_r

The **rise time t_r** is defined as the time interval following the turn-on delay time, where the collector current i_C increases from 10 % to 90 % of the load current. During this time interval most of the turn-on losses are generated in the IGBT, since a certain share of I_L is continuously conducted through the free-wheeling diode as long as the i_C-value is below load current I_L.

Therefore, the collector-emitter voltage v_{CE} will not drop significantly below the collector-emitter supply voltage V_{CC}.
The difference between V_{CC} and v_{CE} depicted in Figure 2.9b during t_r is basically determined by the transient voltage drop over the internal parasitic inductances of the commutation circuit.

The sum of **turn-on delay time $t_{d(on)}$** and **rise time t_r** is called **turn-on time t_{on}**.

As the collector-emitter voltage v_{CE} will not yet have reached its forward on-state value V_{CEsat} at the (defined) end of t_{on}, the major share of the switching losses will be generated after t_{on}.
Turn-on peak current: after the total load current I_L has been commutated to the IGBT, the free-wheeling diode will block, releasing its recovered charge Q_{rr} at the same time. Therefore, the IGBT collector current i_C will rise during reverse recovery of the free-wheeling diode (t_{rr}) by the value of the peak reverse recovery current I_{RRM} over I_L (turn-on peak current see Figure 2.10).

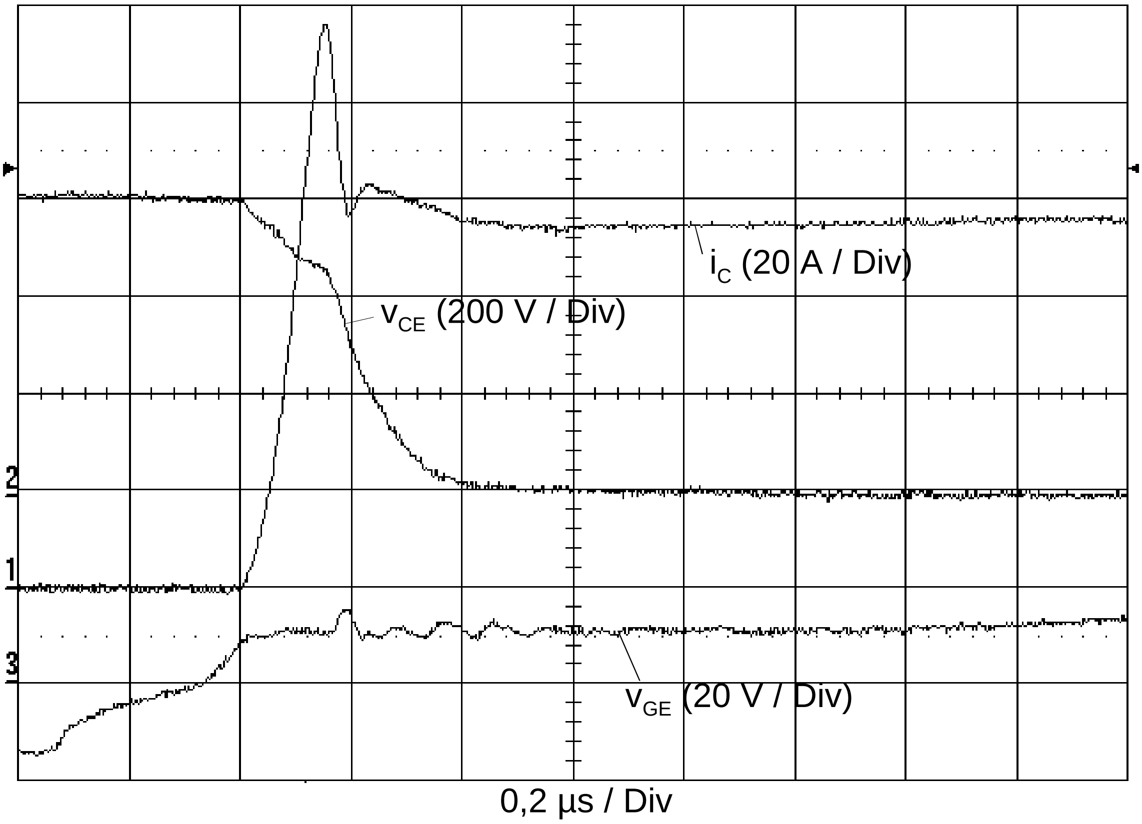


Figure 2.10 Commutation from the conducting free-wheeling diode to the IGBT (turn-on peak current) during turn-on of an IGBT

Dynamic saturation voltage: after having dropped very steeply during turn-on time, the collector-emitter voltage v_{CE} will decline relatively slowly (within µs-range) to its static value V_{CEsat}. This “dynamic saturation phase” is necessary for flooding the wide n^--zone of the IGBT with (bipolar) minority carriers (conductivity modulation).

Turn-off delay time $t_{d(off)}$
After sudden turn-off of the positive control voltage and turn-on of a negative gate-source control voltage, the gate-source voltage V_{GS} starts to decline with the time constant determined by the input capacitance of the IGBT and the gate resistance. The collector-emitter voltage v_{CE} of the IGBT begins to rise. The IGBT's collector current i_C cannot drop considerably at that time, since the free-wheeling diode is poled in reverse direction as long as V_{CC} is higher than v_{CE} and, therefore, is not able to take over load current I_L.

Due to this, the **turn-off delay time $t_{d(off)}$** for IGBTs is defined as the time interval between the moment when the gate-emitter voltage v_{GE} has dropped to 90 % of its turn-on value and the collector current has declined to 90 % of the load current value.

Fall time t_f
As soon as the collector-emitter voltage v_{CE} has exceeded the supply voltage V_{CC} during turn-off of the IGBT, the load current may commutate to the free-wheeling diode, which is poled in forward direction at that time and the collector current i_C will drop.
The **fall time t_f** is defined as the time interval, where the collector current i_C drops from 90 % to 10 % of the load current I_L.

The overshoot of v_{CE} over V_{CC} indicated in Figure 2.11 mainly results from the parasitic inductances of the commutation circuit and increases proportionally to the turn-off speed - di_C/dt of the IGBT.

The **turn-off time t_{off}** is defined as the sum of **turn-off delay time $t_{d(off)}$** and **fall time t_f**.
Since i_C will not have dropped to cut-off current level at the defined end of t_{off}, but still amounts to 10 % of the load current, the losses arising after t_{off} will still exceed the blocking losses.

Tail time t_t, tail current I_t
Other than with MOSFETs, the drastic decrease of power losses in IGBTs achieved by the injection of minority carriers in the n^--zone is realized by generation of a **tail current I_t**, shown in Figure 2.11.

The tail time t_t is not included in the turn-off time t_{off} per definition, however it contributes to a significant share of switching losses due to the collector-emitter supply voltage V_{CC} which has already been applied during that time interval.

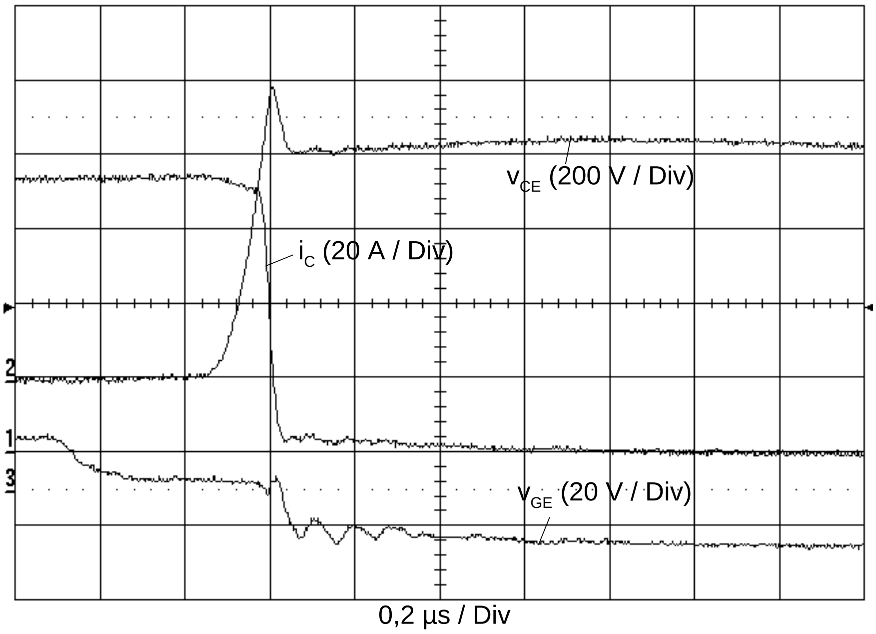


Figure 2.11 Turn-off characteristics of an NPT-IGBT

Energy dissipation during turn-on E_{on}; energy dissipation during turn-off E_{off} per cycle

The typical values of E_{on} and E_{off} of an IGBT are indicated in the diagram "turn-on/ turn-off energy E_{on}, E_{off} as a function of the collector current I_C included in the datasheet.

Power dissipation during switching may be calculated by multiplication of the switching frequency f with E_{on} or E_{off}, respectively: $P_{on} = f * E_{on}$ or $P_{off} = f * E_{off}$.

The turn-on energy dissipation E_{on} comprises the effects of the reverse peak current of the free-wheeling diode, which corresponds to the diode integrated in the power module. Energy dissipation during turn-on may be determined by integration of the power dissipation during turn-on P_{on} up to the moment when V_{CE} amounts to approximately 3 % of the collector-emitter supply voltage V_{CC}.

Apart from the power losses generated during the actually defined turn-off time $t_{off} = t_{d(off)} + t_f$, energy dissipation during turn-off also comprises the tail current losses generated during the tail time t_t up to the moment when the collector current has fallen below load current by 1 %.

Parameters: operating voltage, chip temperature T_j = 125°C, control voltages, gate series resistance.

Thermal resistance junction to case R_{thjc} per IGBT

The thermal resistance R_{thjc} describes the passage of heat between the IGBT chips (index j) and the module case (index c). It characterizes the static heat dissipation of an IGBT system within a module (mostly consisting of paralleled chips) and depends on chip size and module assembly.

The temperature difference ΔT_{jc} between chip temperature T_j and case temperature T_{case} at a constant power dissipation P is defined as follows: $\Delta T_{jc} = T_j - T_{case} = P * R_{thjc}$.

Contact thermal resistance case to heatsink R_{thch} per IGBT module

The thermal resistance R_{thch} describes the passage of heat between module case (index c) and heatsink (index h). It characterizes the static heat dissipation of an IGBT module (possibly with several IGBT switches) and depends on module size, heatsink and case surfaces, thickness and parameters of thermal layers (pastes, foils, print covers) between module and heatsink as well as on the mounting torque of the fixing screws.

The temperature difference ΔT_{ch} between case temperature T_c and heatsink temperature T_h at a constant total amount of single power dissipations P_n within the module is defined as follows: $\Delta T_{ch} = T_{case} - T_h = P_n * R_{thch}$.

Separate determination of R_{thjc} and R_{thch} is not possible for modules without base plate (e.g. SEMITOP, SKiiPPACK, MiniSKiiP). For these module, R_{thjh} is indicated per IGBT and per module. The temperature differences may be calculated in analogy.

Mechanical data

Apart from the **case construction type** mainly the following mechanical data are indicated in the datasheets:
Mounting torque M_1 of the fixing screws (minimum and maximum value) in Nm or lb.in.;
Mounting torque M_2 of the output terminals (minimum and maximum value) in Nm or lb. in.;
Weight w of the module in g;
Permissible **acceleration under vibration a** in $m*s^{-2}$.

Free-wheeling diodes

Inverse diode forward voltage (negative emitter-collector voltage) V_{EC}, V_F
Negative emitter-collector voltage drop with gate-emitter short-circuited ($V_{GE} = 0$). V_{EC} describes the forward characteristics of free-wheeling diodes, which are connected antiparallel to the IGBTs.
Parameters: forward current I_F; case temperature T_{case} = 25°C

Threshold voltage of the inverse diode $V_{(T0)}$
Forward slope resistance of the inverse diode r_T
With the help of threshold voltage and forward slope resistance a simplified approximation of the forward characteristic may be produced. The threshold voltage indicates the point of crossover with the voltage axis, the forward slope resistance determines the rate of rise of the characteristic.

Reverse recovery time of the inverse diode t_{rr}
Reverse recovery time of the IGBT inverse diode during free-wheeling operation, i.e. when a high collector current $-I_C = I_F$ is commutated with a high di_F/dt and a high reverse voltage $V_R = V_{CC}$.
Note: t_{rr} is very strongly dependent on the temperature (almost doubled value between 25°C and 150°C).
Parameters: forward current I_F; reverse voltage V_R, rate of fall of forward current $-di_F/dt$, chip temperature T_j = 25°C and 150°C.

Recovered charge of inverse diode Q_{rr}
Recovered charge of IGBT inverse diode during free-wheeling operation, i.e. when a high collector current $-I_C = I_F$ is commutated with a high di_F/dt and a high reverse voltage $V_R = V_{CC}$.
Note: Q_{rr} is very strongly dependent on the temperature (initial value may be doubled or even increased eight-fold between 25°C and 150°C).
Parameters: forward current I_F; reverse voltage V_R, rate of fall of forward current $-di_F/dt$, chip temperature T_j = 25°C and 150°C.