Application Note
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Determining switching losses of SEMIKRON IGBT modules

To select an IGBT module suitable in switching frequency and dynamic performance it is essential to know its switching behaviour with regard to the specific application.
IGBT module datasheets characterize the switching behaviour under specific conditions that have been selected by the manufacturer. Different manufacturers may use some different conditions. Some conditions might not be stated clearly in the datasheet. Therefore, in order to select a module, it is essential to compare datasheet specifications and conditions with each other and evaluate the effects with regard to the switching properties in the actual application.
With respect to the above, it is the purpose of this application note to offer guidance.
Furthermore, it will detail which information SEMIKRON will add to datasheets of new IGBT modules, to facilitate comparability and module selection for customers.

1. Datasheet information

IGBT module datasheets describe the switching behaviour of IGBTs and freewheeling diodes showing data and graphs, [1], [2].
Typical values of switching times and switching energy dissipations at a common operating point are specified in the table "characteristics". Refer to the example of a SEMIKRON datasheet in Table 1.

For the IGBT part, the turn-on delay time $t_{d(on)}$, the rise time t_r, the turn-off delay time $t_{d(off)}$ and the fall time t_f are listed as well as the turn-on/turn-off energy dissipations E_{on} and E_{off}. For the diode part, the Peak reverse current I_{RRM} and the reverse recovery charge Q_{rr} are listed as well as the energy dissipation E_{rr} during reverse recovery at turn-off.
Furthermore, it will detail which information SEMIKRON will add to datasheets of new IGBT modules, to facilitate comparability and module selection for customers.

Table 1: Dynamic characteristics for a current SEMIKRON IGBT module datasheet

Characteristics						
Symbol	**Conditions**		**min.**	**typ.**	**max.**	**Unit**
IGBT						
$t_{d(on)}$	V_{CC} = 600 V	T_j = 150 °C		220		ns
t_r	I_C = 300 A	T_j = 150 °C		44		ns
E_{on}	V_{GE} = ±15 V $R_{G\,on}$ = 1.5 Ω	T_j = 150 °C		27		mJ
$t_{d(off)}$	$R_{G\,off}$ = 1.5 Ω	T_j = 150 °C		520		ns
t_f	di/dt_{on} = 6100 A/µs	T_j = 150 °C		117		ns
E_{off}	di/dt_{off} = 3000 A/µs	T_j = 150 °C		39		mJ
Diode						
I_{RRM}	I_F = 300 A	T_j = 150 °C		345		A
Q_{rr}	di/dt_{off} = 7300 A/µs	T_j = 150 °C		54		µC
E_{rr}	V_{GE} = ±15 V V_{CC} = 600 V	T_j = 150 °C		23		mJ

The parameters specifying the dynamic characteristics are listed in the column "conditions" of Table 1. These are the supply voltage V_{CC}, the collector current I_C, V_{GE} for the turn-on/turn-off gate voltage levels $V_{G(on)}$ and $V_{G(off)}$, as well as the external gate resistors R_{Gon} for turn-on and R_{Goff} for turn-off.
Some manufacturers also specify the stray inductance L_σ of the DC-link, the rise and fall times of the collector current di/dt_{on} at turn on and di/dt_{off} at turn-off, as well as the rise time of the collector-emitter voltage dv_{CE}/dt at IGBT turn-off.
The parameters to specify the diode switching behaviour are the slope of the diode current di/dt_{off} at turn-off and the gate voltage levels V_{GE} ($V_{G(on)}$ and $V_{G(off)}$).

In this example, E_{on}, E_{off} and also E_{rr} are specified with the same external gate resistors, but E_{on} and E_{rr} measured for the commutation between different switches (BOT/TOP). Therefore, the di/dt does not match exactly.

Furthermore, the datasheets include graphs - for example the dependencies of E_{on}, E_{off} and E_{rr} on I_C and R_G.

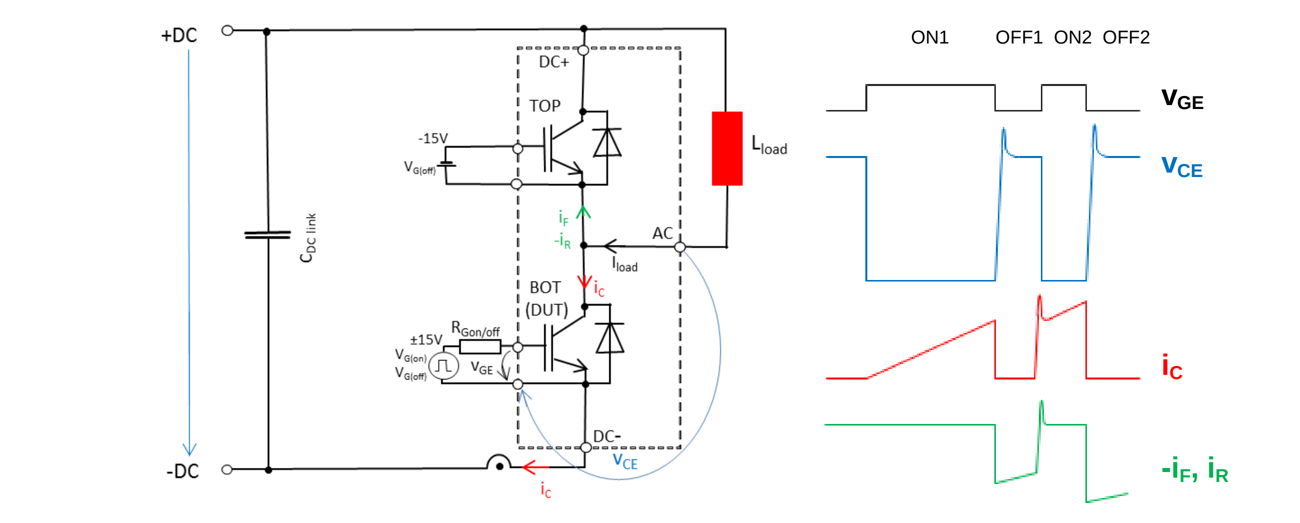
2. General methods to specify switching energy dissipations

2.1 Test setup

The measurements of switching times and energy dissipations of IGBT modules are carried out with a double pulse test connected to an inductive load in a test circuit according to Figure 1 [3], [4].

The IGBT (device under test - DUT) is turned on and off twice and only the first turn-off OFF1 and the second turn-on ON2 are used to measure the dynamic parameters. During the first pulse ON1 the current is increased to the specified level I_C. The load inductance L_{load} has to be large enough to keep the load current constant during the freewheeling interval OFF1.
Figure 1 describes the measurement of the lower (BOT) IGBT and the upper (TOP) freewheeling diode. To measure the upper IGBT and the lower diode, the load inductance must be connected between AC and -DC. Now the TOP IGBT must be switched and the BOT IGBT is blocked with a negative voltage V_G.

Figure 1: Test circuit and graphs of v_{CE} and i_C to specify switching losses



2.2 Specification hints on IEC 60747

The measurement method above is described in the standard IEC 60747-9, chapters 6.3.11 and 6.3.17 "Measuring methods for switching energy dissipations" [3].

According to the Standard the turn-on energy dissipation E_{on} should be calculated using equation (1) as:

$$E_{on} = \int_{t1}^{t2} p_v(t)\,dt = \int_{t1}^{t2} v_{CE}(t) * i_C(t)\,dt \qquad (1)$$

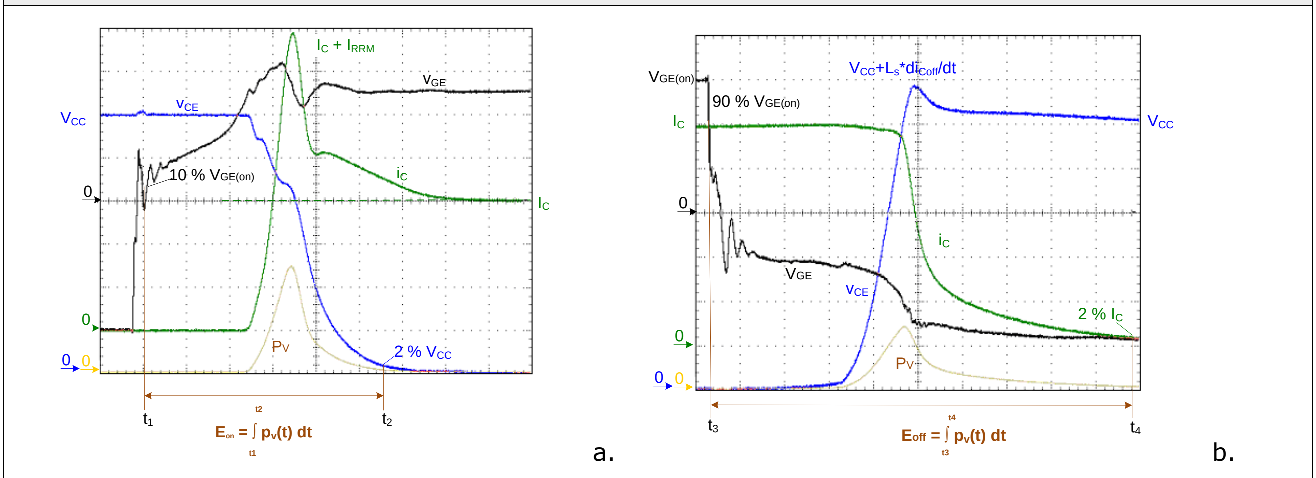
between the integration limits t_1 (10% of $V_{G(on)}$) and t_2 (2% of V_{CC}), see Figure 2a.

The turn-off energy dissipation E_{off} should be calculated using equation (2) as:

$$E_{off} = \int_{t3}^{t4} p_v(t)\,dt = \int_{t3}^{t4} v_{CE}(t) * i_C(t)\,dt \qquad (2)$$

between the integration limits t_3 (90% of $+V_{G(on)}$) and t_4 (2% of I_C), see Figure 2b.

Figure 2: Specification of switching energy dissipations E_{on} and E_{off} according to IEC 60747-9



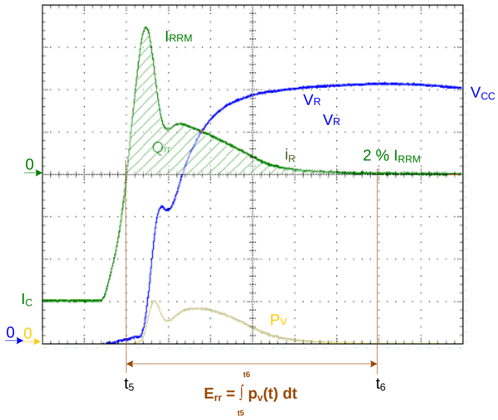
Also stated in the datasheets is the turn-off energy dissipation E_{rr} of the freewheeling diode.

According to IEC 60747-2 [5], chapter 5.7 and Figure 3 below, E_{rr} should be calculated using equation (3) as:

$$E_{rr} = \int_{t5}^{t6} p_v(t)\,dt = \int_{t5}^{t6} v_r(t) * i_r(t)\,dt \qquad (3)$$

between the integration limits t_5 and t_6, which starts at the zero crossing of the diode reverse current and ends when the decreasing current in the diode has reached 2% of I_{RRM}.

Figure 3: Specification of turn-off energy dissipation E_{rr} of the freewheeling diode according to IEC 60747-2



2.3 Main parameters – current I_C, supply Voltage V_{CC} and chip temperature T_j

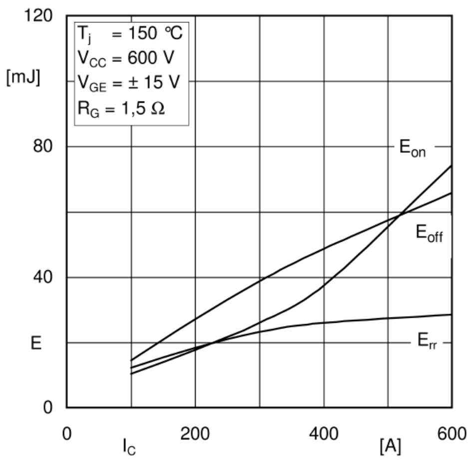
The main test parameters collector current I_C, supply voltage V_{CC} and chip temperature T_j have significant impact on the switching energy dissipation E_{sw}.
Equation (4) allows a rough calculation of the dependency of the switching energy dissipation E_{sw} = E_{on} + E_{off} for the IGBT and E_{sw}= E_{rr} for the freewheeling diode (FWD) on the current I, chip temperatures T_j and supply voltage V_{CC}. These differ from the nominal test conditions I_{ref}, V_{CCref}, T_{jref} and E_{swref}. Figure 4 illustrates the increase of the switching losses with the chip temperature.

$$E_{sw} = E_{swref} \cdot \left(\frac{I}{I_{ref}}\right)^{Ki} \cdot \left(\frac{V_{cc}}{V_{CCref}}\right)^{Kv} \cdot \left(1 + TC_{sw}(T_j - T_{jref})\right) \qquad (4)$$

Ki: Exponent of current dependency (IGBT~1; FWD~0.5…0.6)
Kv: Exponent of voltage dependency (IGBT~1.2…1.4; FWD~0.6)
TC_{sw}: Temperature coefficient of switching losses (IGBT~0.003; FWD ~0.005…0.006)

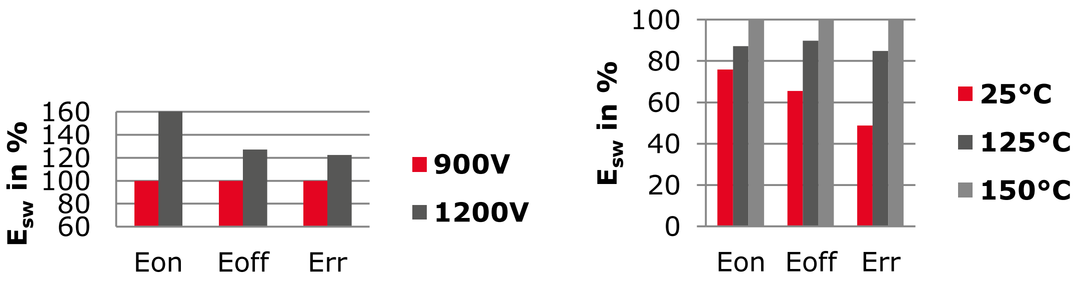
Figure 4 is detailed in the datasheet of a 300A/1200V IGBT4 module. It shows a graph of the typical dependencies of the switching energy dissipations E_{on}, E_{off} and E_{rr} on the value of collector current I_C.

Figure 4: Typical dependencies of the switching energy dissipations of an IGBT4 module on the collector current



In addition Figure 5 shows bar graphs to compare the switching energy dissipations E_{on}, E_{off} and E_{rr} of a 600A/1700V IGBT4 module at different supply voltages V_{CC} and chip temperatures T_j. The values of the switching losses are given in percent. One hundred percent corresponds to the datasheet value V_{CC}@ 900V and T_j@150°C.

Figure 5: Switching energy dissipations E_{on}, E_{off} and E_{rr} in % at different supply voltages V_{CC} and chip temperatures T_j



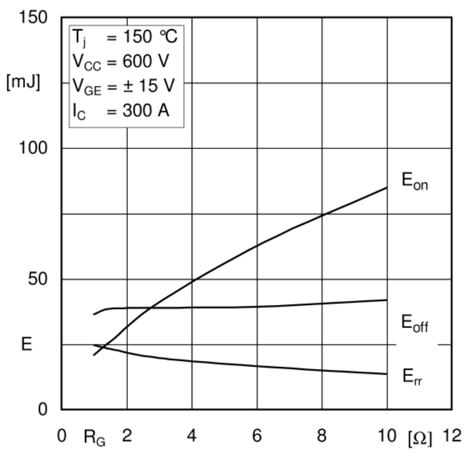
2.4 Driver output stage

The driving parameters too affect the measured switching losses in the test setup. Parameters of the datasets are the gate resistor R_G as well as the gate voltage levels $V_{G(on)}$ for turn-on and $V_{G(off)}$ for turn-off. The parameter R_G may be different for turn-on (R_{Gon}) and for turn-off (R_{Goff}).

Effect of R_G:
Figure 6 is detailed in the datasheet of a 300A/1200V IGBT4 module. It shows a graph of the typical dependencies of the switching energy dissipations E_{on}, E_{off} and E_{rr} on the value of the external gate resistor R_G.
Since the collector current rises slower (longer rise time) with an increasing external gate resistor, the turn-on energy dissipation E_{on} is rapidly increasing with R_G. In contrast – but especially in the IGBT4 – the turn-off energy dissipation E_{off} only slightly depends on R_G.
A faster turn-on of the IGBT causes a faster current commutation into the freewheeling diode circuit. Thus, the reverse recovery losses E_{rr} decrease with increasing R_G.

Lower limits for R_{Gon} are determined (amongst others) by the peak reverse recovery current of the freewheeling diode and the overvoltage v_R at the permitted overcurrent.

Figure 6: Typical dependencies of the switching energy dissipations of an IGBT4 module on the gate resistor R_G



Lower limits for R_{Goff} are determined (amongst others) by the turn-off overvoltage and the limits of the safe operating area. For comparability of data a number of manufacturers specify the di/dt in the datasheets as parameters for E_{on} and dv_{CE}/dt as parameters of E_{off}.

<u>Effect of V_G:</u>
The higher the gate voltage levels V_G (with the same R_G), the faster the gate charge occurs into or out of the gate, whilst the IGBT switching times and switching energy dissipations decrease. Since the permissible gate voltage is limited to V_{GES} = ±20V, there are strict limits. So a majority of manufacturers specify 1200V and 1700V IGBT modules with the gate voltages $V_{G(on)}$ = +15V and $V_{G(off)}$ = -15V and 600/650V modules with +15V/-7.5V.
Information on the specific requirements for the IGBT drivers is, for example, contained in [2] and [6] .

Please note that many of the commercially available driver circuits work with turn-off gate voltages less than -15V, e.g. -8V. Low power drivers often work without negative turn-off voltage, but instead with $V_{G(off)}$ = 0V. More detailed information on this is available in [7].

3. Additional factors influencing the switching loss specification

3.1 Load conditions

According to the test setup the measurements are done with an inductive load. Resistive loads produce lower losses, since the collector current increases only while the collector-emitter voltage falls. In contrast, the switching losses with a capacitive load (e.g. motor cables) are higher, as the IGBT has to conduct the increasing collector current plus the capacitive discharge current.

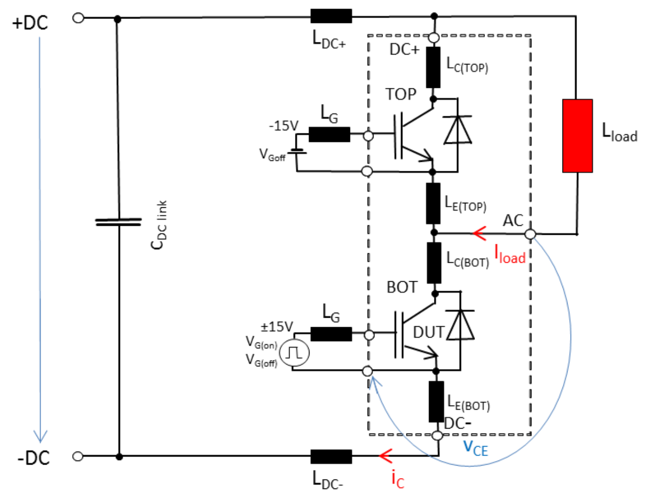
3.2 Parasitic DC link inductance L_σ

The stray inductances in the commutation circuit have an important effect on the switching losses. In a test setup for BOT IGBT and TOP diode, according to Figure 7, with the v_{CE} measurement between AC and the auxiliary emitter terminal (continuous blue line in Figure 7) the total stray inductance L_σ is

$$L_\sigma = L_{DC+} + L_{DC-} + L_{E(BOT)} \qquad (5)$$

where L_{DC+} and L_{DC-} are the stray inductances of the DC bus and $L_{E(BOT)}$ is the parasitic emitter inductance of the BOT IGBT.

Figure 7: Parasitic inductances of a test circuit for BOT IGBT and TOP Diode



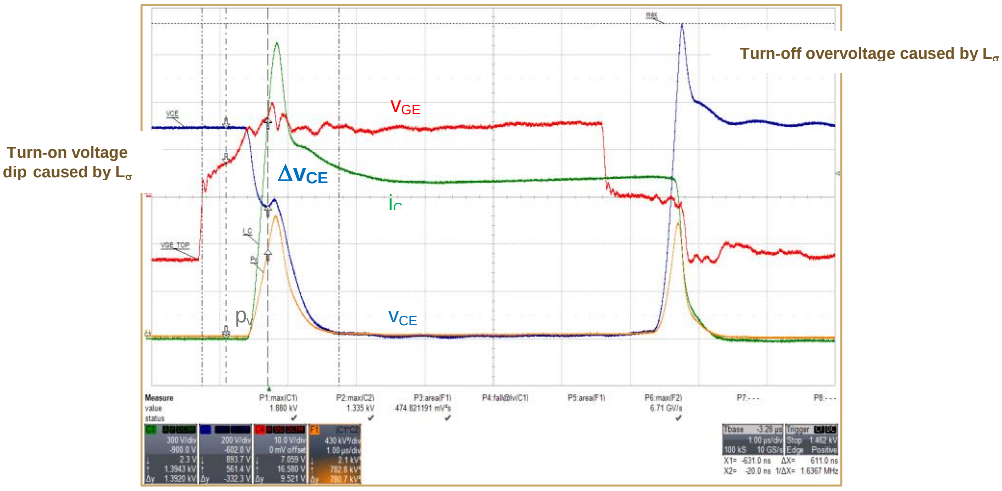
Depending on whether TOP or BOT IGBT is measured, the parasitic inductance L_E of one emitter path is denominated either $L_{E(TOP)}$ for the upper or $L_{E(BOT)}$ for the lower IGBT.
The inductances $L_{E(TOP)}$ or $L_{E(BOT)}$ of the emitter bond wires and terminals are a substantial part of the module stray inductance L_{CE}, quoted in the datasheet.

Figure 8 shows the effects of the parasitic DC link inductances on the commutation process. These are namely the voltage dip Δv_{CE} at turn-on and the turn off overvoltage. L_σ can be calculated using

$$L_\sigma = \Delta v_{CE} \, / \, di_C/dt \qquad (6)$$

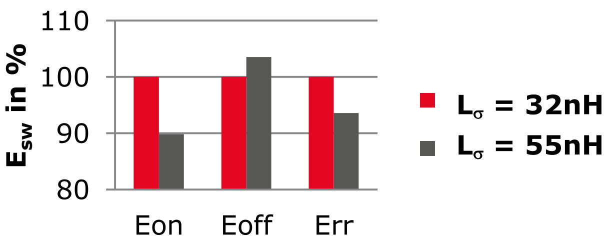
during IGBT turn-on.

Figure 8: Turn-on voltage dip and turn-off overvoltage caused by the parasitic inductances of the DC link



During the turn-on process, the higher L_σ the more distinct the drop of v_{CE} will be during the increase of the collector current. Therefore, the energy dissipation E_{on} decreases with an increasing inductance L_σ.
Conversely are the effects at turn-off. Here the higher L_σ the greater the switching losses. Reasons are the increase of the collector-emitter voltage overshoot and the lower di/dt with increasing L_σ.
Usual L_σ datasheet specifications for standard IGBT modules are in the range of 30nH to 60nH. Figure 9 demonstrates the effect of higher Lσ values on the switching energy dissipation.

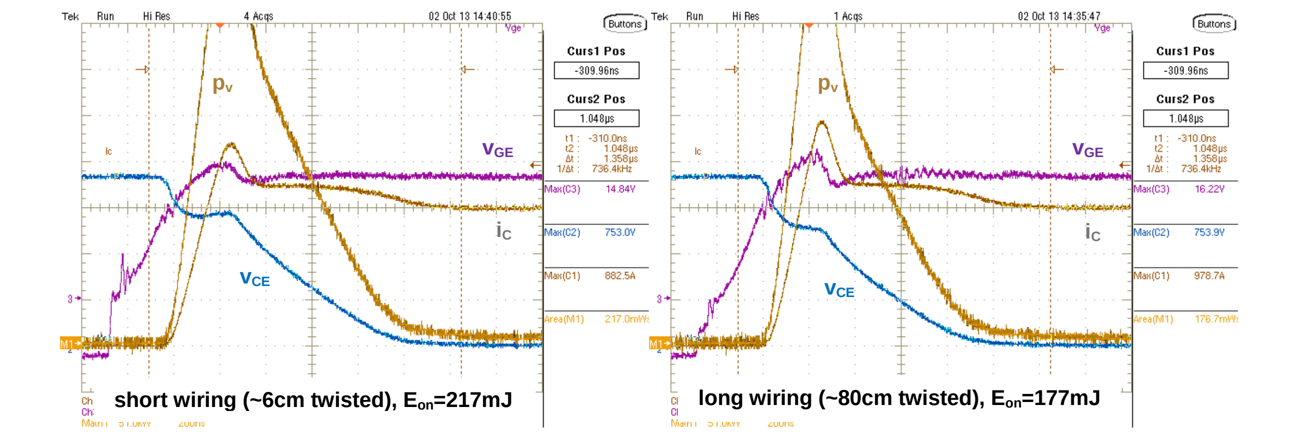
Figure 9: Effects of the DC link inductance L_σ on the switching energy dissipations E_{on}, E_{off} and E_{rr}



3.3 Gate circuit inductance L_G

Even the parasitic inductances L_G of the gate circuits (see Figure 7) affect the switching behaviour of the IGBT module. L_G mainly depends on the length and wiring of the gate cables and the driver PCB layout.
The effect of this inductance can be compared with a current source, which supplies additional gate charge at the beginning of the "v_{GE}-plateau" period. This increases the slope of the di_C/dt which results in a lower E_{on} of the IGBT. The faster turn-on causes a faster current commutation from the freewheeling diode circuit into the collector-emitter path. Thus, the reverse recovery energy dissipation E_{rr} of the diode increases with increasing L_G. Figure 10 shows a comparison of the turn-on behaviour with two different gate cable wirings.
During the IGBT turn-off process the switching speed is not influenced by L_G. But the delay time $t_{d(off)}$ increases with an increased value of L_G. Thus, E_{off} increases when the specification is applied according to IEC 60747-9. When the integration interval for E_{off} starts at v_{CE} = 0.1 * V_{CC}, however, E_{off} remains unaffected by L_G (compare Table 2, e.g. manufacturer IN).

Figure 10: Turn-on energy dissipation E_{on} of a 1200V/450A IGBT4 module with 2 different gate circuit inductances L_G



Furthermore, long gate wiring adds an inductive effect. This leads to overvoltage on v_{GE}, gate voltage oscillations and higher peak currents in case of a short circuit. Gate clamping measures will be less effective.
In conclusion, for each application it is, therefore, advisable to minimize the gate lead inductance L_G, although this may result in slightly higher turn-on energy dissipation.
Please note that usually no information about L_G is given in the datasheet.

3.4 Integration limits to ascertain the switching energy dissipations E_{on} and E_{off}

Chapter 2.2 presented the specifications for the integration limits in IEC 60747-9. However, the majority of IGBT modules manufacturers today use other limits for the specification of E_{on} and E_{off}. Table 2 outlines some examples.

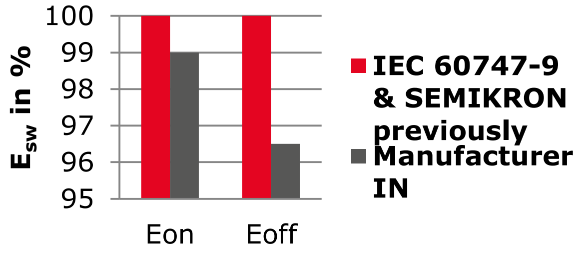
Table 2: Usual integration limits of switching energy dissipations

Switching energy dissipat. acc. to	Turn-on: E_{on}		Turn-off: E_{off}	
	t_1	t_2	t_3	t_4
IEC 60747-9	$v_{GE} = 0.1 * V_{G(on)}$	$v_{CE} = 0.02 * V_{CC}$	$v_{GE} = 0.9 * V_{G(on)}$	$i_C = 0.02 * I_C$
SEMIKRON prev.	$v_{GE} = 0.1 * V_{G(on)}$	$v_{CE} = 0.02 * V_{CC}$	$v_{GE} = 0.9 * V_{G(on)}$	$i_C = 0.02 * I_C$
Manufacturer IN	$i_C = 0.1 * I_C$	$v_{CE} = 0.02 * V_{CC}$	$v_{CE} = 0.1 * V_{CC}$	$i_C = 0.02 * I_C$
Manufacturer MI	$i_C = 0.1 * I_C$	$v_{CE} = 0.1 * V_{CC}$	$v_{CE} = 0.1 * V_{CC}$	$i_C = 0.02 * I_C$
Manufacturer AB	$v_{GE} = 0.1 * V_{G(on)}$	$t_2 = t_1 + (10...20)\mu s$ [1)]	$v_{GE} = 0.9 * V_{G(on)}$	$t_4 = t_3 + (10...20)\mu s$ [1)]
Manufacturer IX	$i_C = 0.1 * I_C$	$v_{CE} = 0.1 * V_{CC}$	$v_{CE} = 0.1 * V_{CC}$	$i_C = 0.1 * I_C$

[1)] depending on IGBT module voltage class

Advantages to reference the integration limits to i_C at turn-on and to v_{CE} at turn-off instead of referencing them to v_{GE} are the independence of the results due to oscillations of the gate-emitter voltage and the tolerances of turn-on and turn-off delay times. The calculated E_{on} and E_{off} values are slightly less than those when determined according to IEC 60747-9. Figure 11 gives an example with the comparison of two datasheet values.

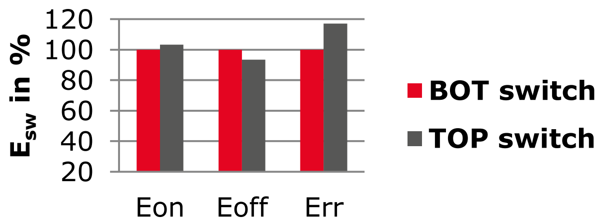
Figure 11: Datasheet values of E_{on} and E_{off} at different integration limits



3.5 Selecting the switches and assessment of the measurement results

All values given for dynamic characteristics in datasheets are typical values. These are determined in accordance with IEC 60747-9 from the measured switching losses of the BOT IGBT / diode and the TOP IGBT / diode using statistical methods.
Because the standard specifies individual semiconductors (not modules) every IGBT/diode switch needs to be measured. If there are six IGBTs in a full bridge module - each with different properties - the property of each one has to be specified. However, it is common, to specify only one value in the datasheet for modules containing more than one switch (except 3-level modules). So, for the user it is often irreproducible, for which of the switches a value is valid.
Slightly different internal module inductances and different commutation paths cause small differences in the switching energy dissipations between the switches. As an example, Figure 12 outlines such differences.
Since the choice of statistical methods is up to the manufacturer, he can decide, for example, which safety margin to apply when comparing measured values and datasheet specifications.

Figure 12: Differences in switching energy dissipations between TOP and BOT switch of an IGBT module



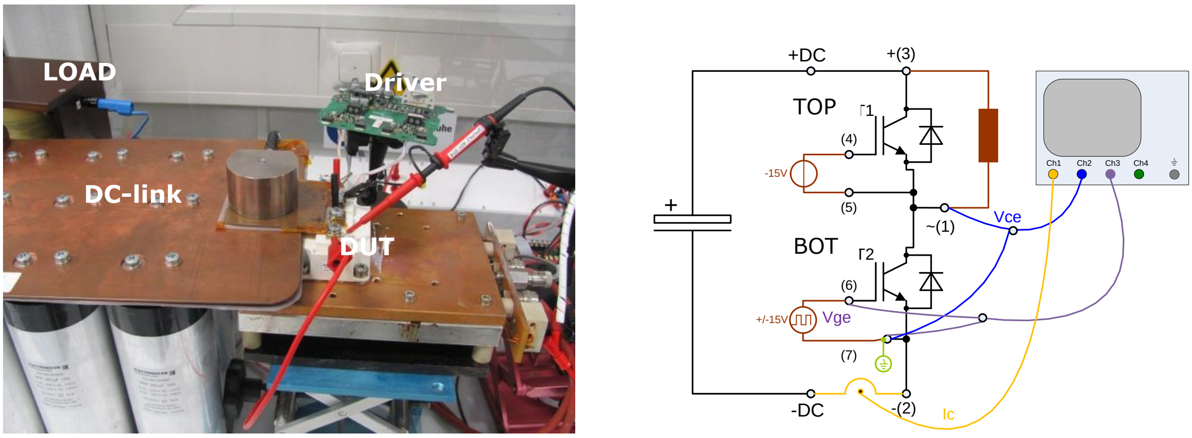
4. Specification of switching losses for SEMIKRON IGBT modules

4.1 SEMIKRON test setup for IGBT halfbridge modules

Figure 13 shows the test setup to specify the switching behavior of 62mm IGBT halfbridge modules SEMITRANS 3.

The IGBT module is mounted on a heating plate, with which its temperature can be controlled. The DC terminals are connected to the DC-bus capacitors via a low-inductance "sandwich" type DC-bus and implemented current sensor (Pearson), in order to provide a constant supply voltage V_{CC}. A large load inductance is connected between +DC and the AC terminal of the tested IGBT module. The example shows the test setup for BOT IGBT and TOP diode, so the TOP IGBT is blocked with $V_{G(off)}$ = -15V between gate and auxiliary emitter. The driver circuit is coupled by a 10cm long twisted, low inductance wire to gate and auxiliary emitter of the BOT IGBT (DUT).

Figure 13: SEMIKRON test setup for dynamic IGBT module tests and test circuit to measure BOT IGBT and TOP diode



4.2 Test conditions

Table 3 compares the main test parameters, collector current I_C, supply voltage V_{CC} and chip temperature T_j, used by SEMIKRON to determine the switching losses.

Table 3: SEMIKRON test conditions for IGBT modules for I_C, V_{CC} and T_j

IGBT module group		I_C	V_{CC}		T_j
Product class	V_{CES}		until now	for new modules	
SEMITRANS, SEMiX, SKiM, MiniSKiiP, SEMITOP	600/650V	I_{Cnom} 1)	300V	300V	25°C and $T_{j(max)}$ - 25K
	1200V		600V	600V	
	1700V		1200V	900V (1200V) 2)	
SKiiP3, SKiiP4 IPM	1200V		600V and 900V	600V and 900V	
SKiiP3 IPM	1700V		900V and 1200V	900V and 1200V	
SKiiP4 IPM			900V und 1300V	900V and 1300V	

1) for SEMITOP and SKiiP3 type specific I_C test conditions   3) V_{CC} = 1200V on request

The SEMIKRON test parameters coincide basically with the specifications of most competitors' IGBT modules. To date, SEMIKRON specifies the switching behaviour of 1700V IGBT modules with a V_{CC} = 1200V, i.e. 300V higher compared to most competitors.
For better comparability with competitive products SEMIKRON will list switching times and switching losses at V_{CC} = 900V in datasheets for new 1700V IGBT modules.

For SKiiP IPMs the switching losses are also measured at higher voltages, as applications with higher voltages are possible, due to very low stray inductances compared to other modules.

4.3 DC link inductance L_σ during measurements

As discussed in chapter 3.2, an increase of stray inductance L_σ in the commutation circuit causes a decrease in turn-on losses and an increase in turn-off losses.
To date, SEMIKRON doesn't specify L_σ in the datasheets but for new IGBT modules this parameter will be listed.

4.4 Selection of the integration limits to measure the switching energy dissipations E_{on} and E_{off}

Like the majority of IGBT module manufacturers, SEMIKRON uses different integration limits to determine E_{on} and E_{off} in datasheets of future IGBT modules compared to IEC 60747-9, see Table 4.

Table 4: Changes in integration limits for switching energy dissipations for new IGBT modules

		previously	new
Turn-on	$E_{on} = \int_{t1}^{t2} v_{CE}(t) * i_C(t)\,dt$	0.1 * $V_{G(on)}$…0.02 * V_{CC}	0.1 * I_C…0.02 * V_{CC}
Turn-off	$E_{off} = \int_{t3}^{t4} v_{CE}(t) * i_C(t)\,dt$	0.9 * $V_{G(on)}$…0.02 * I_C	0.1 * V_{CC}…0.02 * I_C

Using the 10% limits of I_C at turn-on and V_{CC} at turn-off changes the switching losses only a few percent, but allows the usage of measurement equipment with programmable settings and ensures better reproducibility of the measurement results. Furthermore the comparability with competitors' datasheet specifications is improved. Furthermore the comparability with competitor's datasheet specifications is improved, see Table 2.

4.5 Interpreting the measurement results against the datasheet specifications

SEMIKRON generally measures all IGBTs and diodes in IGBT modules to specify switching energy dissipations according to IEC 60747-9.
For datasheet characterization of existing IGBT modules, SEMIKRON uses the dynamic data of the switch which has the highest switching losses. For halfbridge modules this is mostly the BOT switch. A 10% safety margin is added to the result to compensate for batch fluctuations and measurement tolerances.
For newly released IGBT modules SEMIKRON has moved to another procedure: As in the past all switches of a module are measured. But now the switch with the highest switching losses is measured in a greater – more representative – number of modules. The average values of those switching energy dissipations will be the datasheet values of new types of SEMIKRON IGBT modules.

5. Summary

The task is to ease the comparison and selection of IGBT modules on the basis of their datasheet information. In order to achieve this, the specifications in the datasheets with regard to the switching losses are described as well as the influence of the measuring conditions on them.
In future, to allow for better comparison with competitive products, SEMIKRON will add or change some measurement conditions in datasheets of new modules. This Application Note describes these changes and their consequences for the switching loss specifications.

Symbols and Terms

Letter Symbol	Term
AC	AC terminal (E_{TOP}_C_{BOT}) of IGBT module
BOT IGBT, switch	Bottom side IGBT (emitter connected with –DC), BOT side switch (IGBT + diode)
C	Collector
C_{BOT}, C_{TOP}	Collector terminal of bottom side IGBT, Collector terminal of top side IGBT
DC+, DC-	DC+ terminal (C_{TOP}), DC- terminal (E_{BOT}) of IGBT module
+DC, -DC	+ Potential, - Potential of DC link
di/dt	Change of current per unit of time
di/dt_{off}, di/dt_{on}	Change of current per unit of time at turn-off, per unit of time at turn-on
dv_{CE}/dt	Change of collector-emitter voltage per unit of time
DUT	Device under test
E	Emitter, Energy dissipation
E_{BOT}, E_{TOP}	Emitter terminal of bottom side IGBT, emitter terminal of top side IGBT
E_{off}, E_{on}	Energy dissipation during turn-off time, during turn-on time (IGBT)
E_{rr}	Energy dissipation during recovery time (FWD)
E_{sw}	Energy dissipation during switching process (IGBT module)
E_{swref}	Reference value of energy dissipation during switching process
f_{sw}	Switching frequency
FWD	Freewheeling diode
G	Gate
IGBT	Insulated Gate Bipolar Transistor
I_C, i_C, I_{Cnom}	Collector current, Nominal collector current
i_F	Diode forward current
I_{load}	Load current
i_R, I_{RRM}	Reverse current at diode turn-off, Peak reverse recovery current of FWD
I_{ref}	Reference value of IGBT or FWD current
Ki	Exponent of current dependency for switching loss calculation
Kv	Exponent of voltage dependency for switching loss calculation
L	Inductance
$L_{C(BOT)}$, $L_{C(TOP)}$	Collector inductance of BOT IGBT, collector inductance of TOP IGBT,

Letter Symbol	Term
L_{DC+}, L_{DC-}	Stray inductance of +bus bar, stray inductance of -bus bar
$L_{E(BOT)}$, $L_{E(TOP)}$	Emitter inductance of BOT IGBT, emitter inductance of TOP IGBT,
L_G	Gate circuit inductance
L_{load}	Load inductance
L_σ	Parasitic inductance of DC link
P_v, p_v	Power dissipation
R_G	External gate resistor
R_{Goff}, R_{Gon}	External gate resistor at turn-off, External gate resistor at turn-on
t	Time
TC_{sw}	Temperature coefficient of switching losses
$t_{d(off)}$, $t_{d(on)}$	Turn-off delay time, Turn-on delay time
t_f, t_r	Fall time, Rise time
T_j, $T_{j(max)}$, T_{jref}	Chip temperature, Reference value of chip temperature
TOP IGBT, switch	TOP side IGBT (collector connected with +DC), Top side switch (IGBT + diode)
ΔV_{CE}	Change of collector-emitter voltage
V_{CC}, V_{CCref}	Supply voltage, Reference value of supply voltage
V_{CE}, v_{CE}	Collector-Emitter voltage
V_G, $V_{G(off)}$, $V_{G(on)}$	Gate voltage, Gate turn-off voltage, Gate turn-on voltage (driver)
V_{GE}, v_{GE}	Gate-Emitter voltage
V_{GES}	Maximum permissible gate-emitter voltage, (collector-emitter short circuited)
v_R	Reverse voltage at diode turn-off

A detailed explanation of the terms and symbols can be found in the "Application Manual Power Semiconductors" [2]

References

[1] www.SEMIKRON.com
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[5] IEC 60747-2: Semiconductor devices – discrete devices, part 2: Rectifier diodes
[6] M. Hermwille, "IGBT Driver Calculation", Application Note AN-7004, SEMIKRON
[7] N. Hofstoetter, " Limits and hints how to turn off IGBTs with unipolar supply", Application Note AN-1401, SEMIKRON

HISTORY

SEMIKRON reserves the right to make changes without further notice herein

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