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Application Note
AN 15-002

Revision:	00
Issue date:	2015-12-03
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Keyword: MLI, TMLI, NPC, TNPC, power losses, stray inductance

How to Read a SEMIKRON 3-Level Datasheet

1. General

The aim of this Application Note is to point out the most important differences and special features of 3-Level (3L) NPC and TNPC datasheets compared to 2-Level (2L).
A general explanation and derivation of all datasheet values is not intended; this information can be found in SEMIKRON's "Application Manual Power Semiconductors" [2] or in particular Technical Explanations.

2. Theoretical Groundwork

2.1 Definition

The following list shows abbreviations and terms for 3L devices that are used in SEMIKRON datasheets, Technical Explanation, Application Notes and other documents:

NPC	**N**eutral **P**oint **C**lamped; describes the 3L NPC topology
TNPC	**T**-type **N**eutral **P**oint **C**lamped; describes the 3L TNPC topology
MLI	**M**ulti-**L**evel **I**nverter; is used as family name of 3L modules in NPC topology
TMLI	**T**-type **M**ulti-**L**evel **I**nverter; is used as family name of 3L modules in TNPC topology
Tx / Dx	Describes the position of the particular switch within the 3L topology where x is a number between 1 and 4; T refers to a transistor, D refers to a diode;
IGBT1	Represents transistors T1 and T4 in SEMIKRON datasheets
IGBT2	Represents transistors T2 and T3 in SEMIKRON datasheets

Diode1	Represents diodes D1 and D4 in SEMIKRON datasheets
Diode2	Represents diodes D2 and D3 in SEMIKRON datasheets
Diode5	Represents diodes D5 and D6 in SEMIKRON datasheets (only in NPC topology)
Outer switches	Refers to T1, T4, D1 and D4 (in other words: IGBT1 and Diode1)
Inner switches	Refers to T2, T3, D2 and D3 (in other words: IGBT2 and Diode2)
Clamping diodes	Refers to D5 and D6 (in other words: Diode5)

2.2 3L PWM pattern

2.2.1 PWM generation

All SEMIKRON 3L datasheets and calculations are based on a PWM pattern derived by using the sine-triangular comparison.
In short the amplitudes of two triangular waves are compared with the amplitude of one sine wave. The result of the comparison (e.g. *sine > triangular_1 & sine < triangular_2*) defines the switching states of the 3-Level module's IGBTs. Further information is given for example in [3] and [4].

2.2.2 PWM restrictions

This abovementioned comparison results in a set of rules that are to be maintained at any time:

1. A maximum of two switches may be turned on at the same time,
2. Only two adjacent switches may be turned on at the same time,
3. Switches T1 and T3 as well as switches T2 and T4 switch inversely.

Further considerations (explained in AN11001, [4]) lead to additional rules:

4. Start of operation: inner switches (T2 or T3) must be turned on first, outer switches (T1 or T4) afterwards.
5. End of operation: outer switches (T1 or T4) must be turned off first, inner switches (T2 or T3) afterwards.

Although some of the restrictions seem to make no sense at a first glance (e.g. an IGBT is turned on while it is not conducting; an example is given in Figure 10, image on right) it does indeed make a big difference in the resulting datasheet values.

SEMIKRON's datasheet measurements and simulations are based on the rules derived by the sine-triangular comparison. As long as the PWM pattern is identical of course other methods can be used.
Note: If these rules are not met SEMIKRON datasheet values or simulation results are possibly not correct!

2.3 Commutation

When a semiconductor is turned off actively during normal operation (i.e. the PWM pulse ends) a current has been flowing through that device. Because of the turn-off the previous current path is no longer existent and as a current is not intended to be stopped, it needs to be passed on to another semiconductor. This process of passing the current flow from one to another path is called commutation.

2.3.1 NPC commutation

Figure 1 shows the current paths (left and centre image) of operating area 1 (positive output voltage and current) that alternate with the switching frequency. The image on the right shows the resulting commutation loop in blue colour.
Figure 2 shows the current paths and the commutation loop of operating area 3. In this operating area output current and voltage are negative.
The commutation in these two operating areas is geometrically rather short and therefore called "short commutation loop".
Figure 3 shows the current paths (left and centre image) of operating area 2 (negative output voltage and positive output current) that alternate with the switching frequency. The image on the right shows the resulting commutation loop in blue colour.
Figure 4 shows the current paths and the commutation loop of operating area 4. In this operating the output current is negative and the output voltage positive.
The commutation in these two operating areas is geometrically much longer than those of operating areas 1 and 3 and is therefore called "long commutation loop".

Figure 1: NPC current paths (red) and commutation loop (blue) for operating area 1

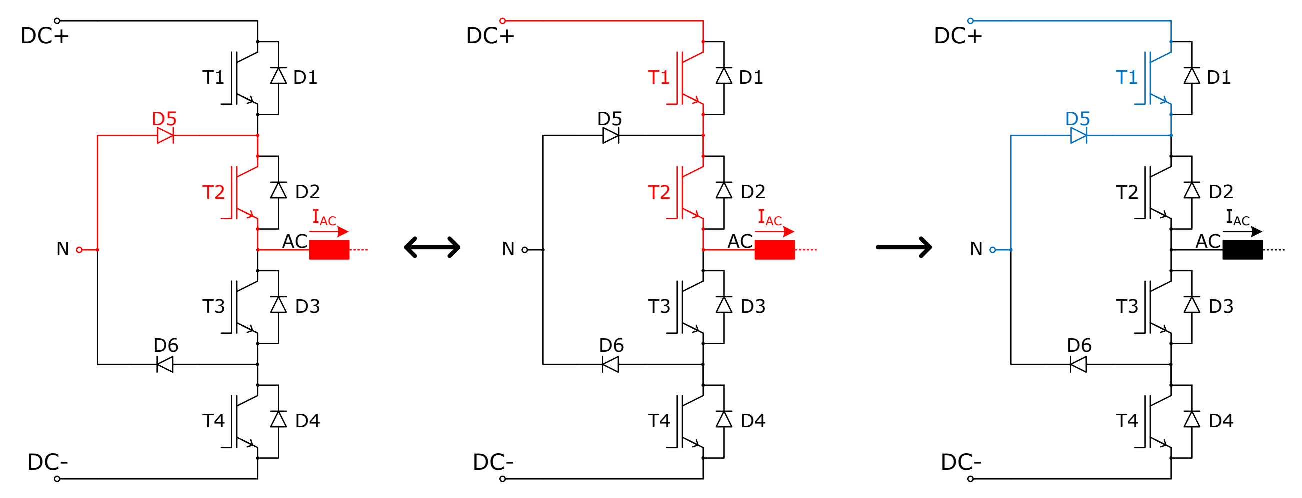


Figure 2: NPC current paths (red) and commutation loop (blue) for operating area 3

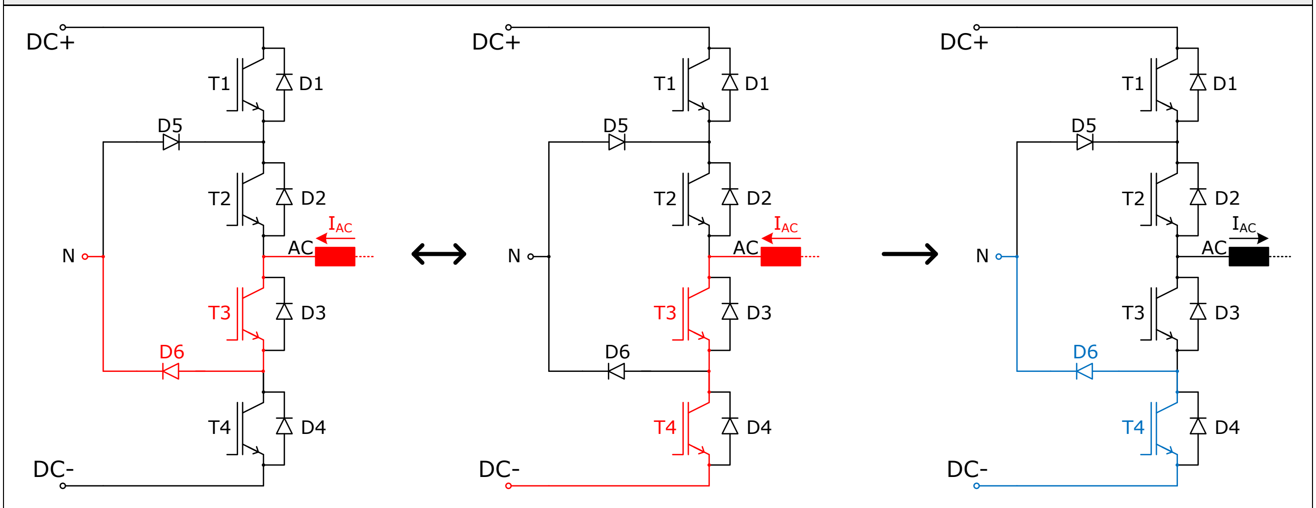


Figure 3: NPC current paths (red) and commutation loop (blue) for operating area 2

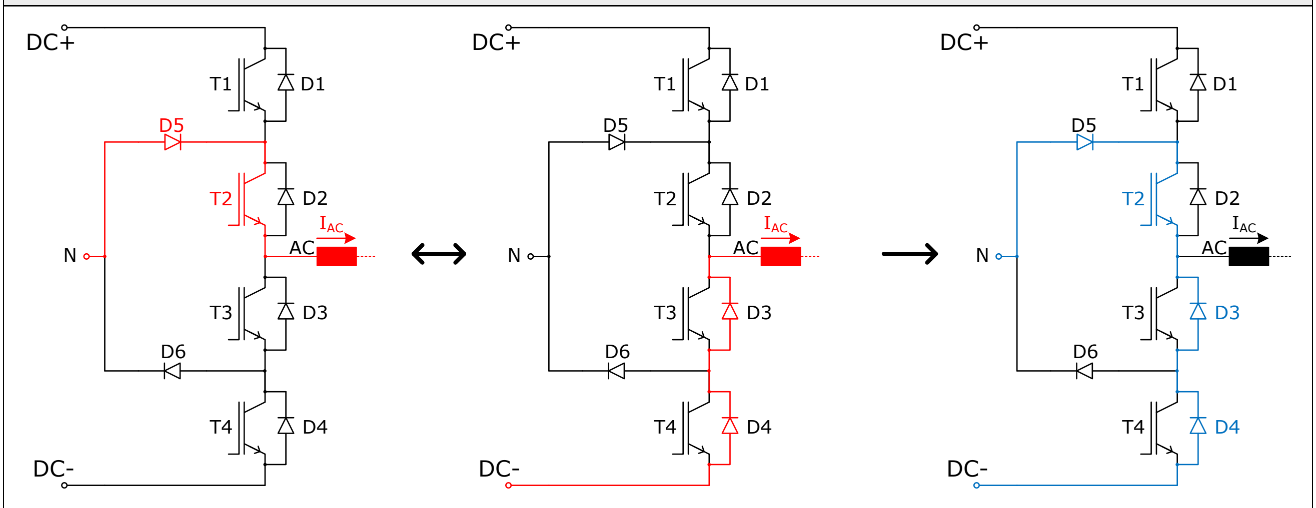
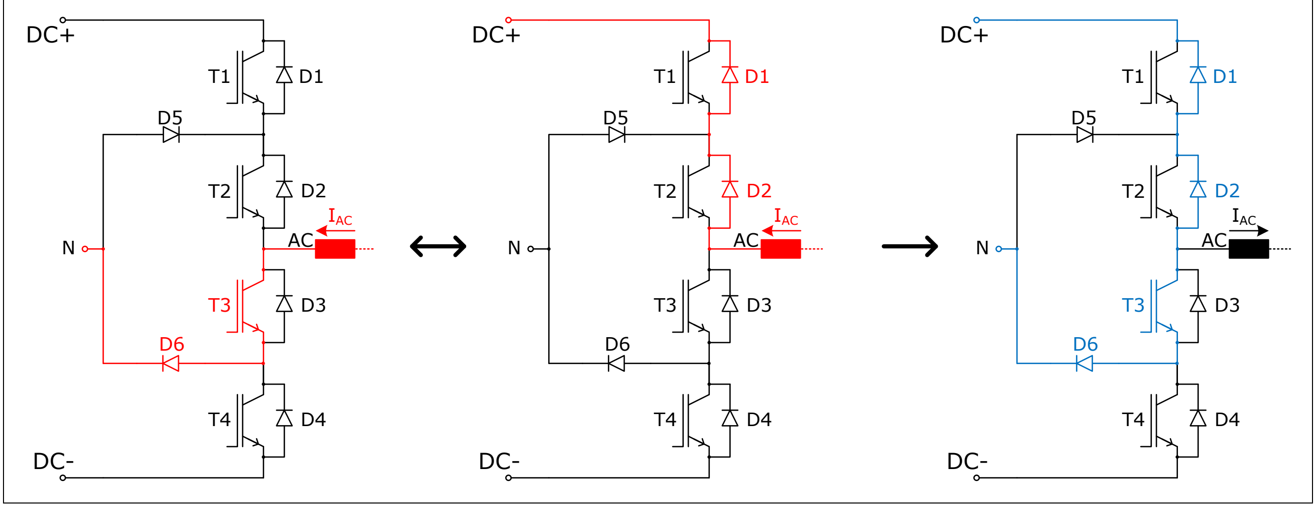


Figure 4: NPC current paths (red) and commutation loop (blue) for operating area 4



2.3.2 TNPC commutation

Figure 5 shows the current paths (left and centre image) of operating area 1 (positive output voltage and current) that alternate with the switching frequency. The image on the right shows the resulting commutation loop in blue colour.
Figure 6 shows the current paths and the commutation loop of operating area 3. In this operating area output current and voltage are negative.
By analogy with NPC the commutation in these two operating areas is called "short commutation loop".

Figure 7 shows the current paths (left and centre image) of operating area 2 (negative output voltage and positive output current) that alternate with the switching frequency. The image on the right shows the resulting commutation loop in blue colour.
Figure 8 shows the current paths and the commutation loop of operating area 4. In this operating area the output current is negative and the output voltage positive.
By analogy with NPC the commutation in these two operating areas is called "long commutation loop".

Figure 5: TNPC current paths (red) and commutation loop (blue) for operating area 1

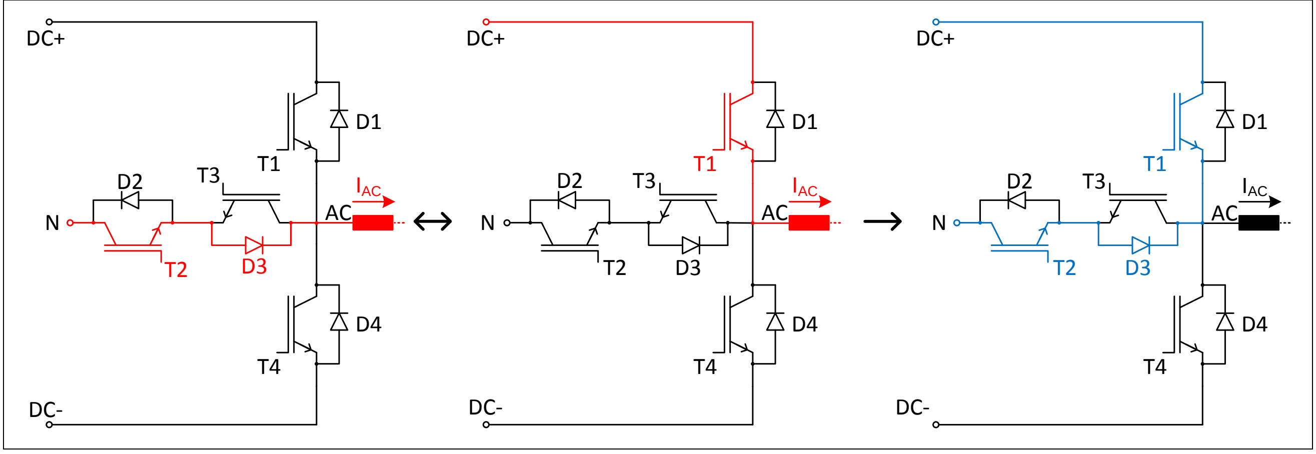


Figure 6: TNPC current paths (red) and commutation loop (blue) for operating area 3

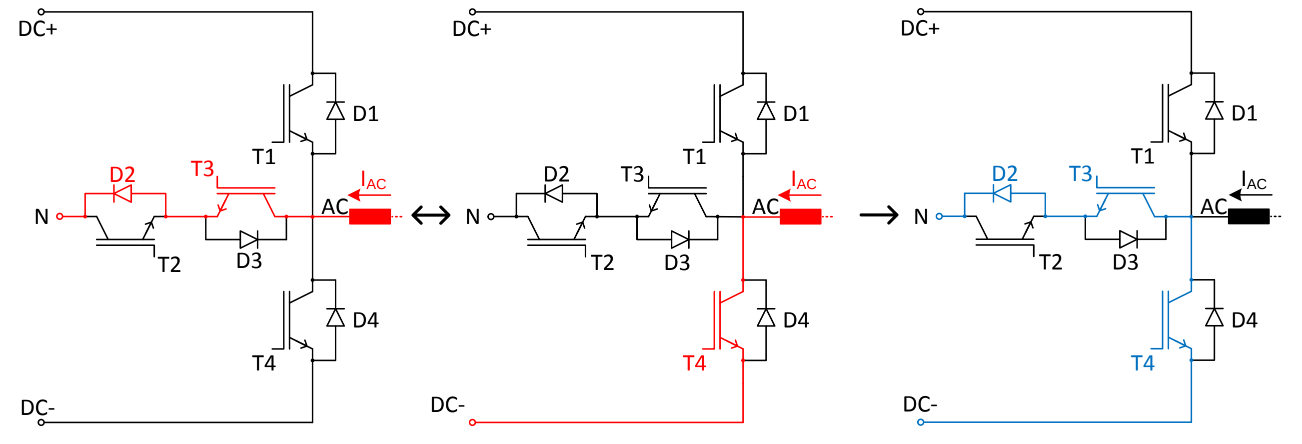


Figure 7: TNPC current paths (red) and commutation loop (blue) for operating area 2

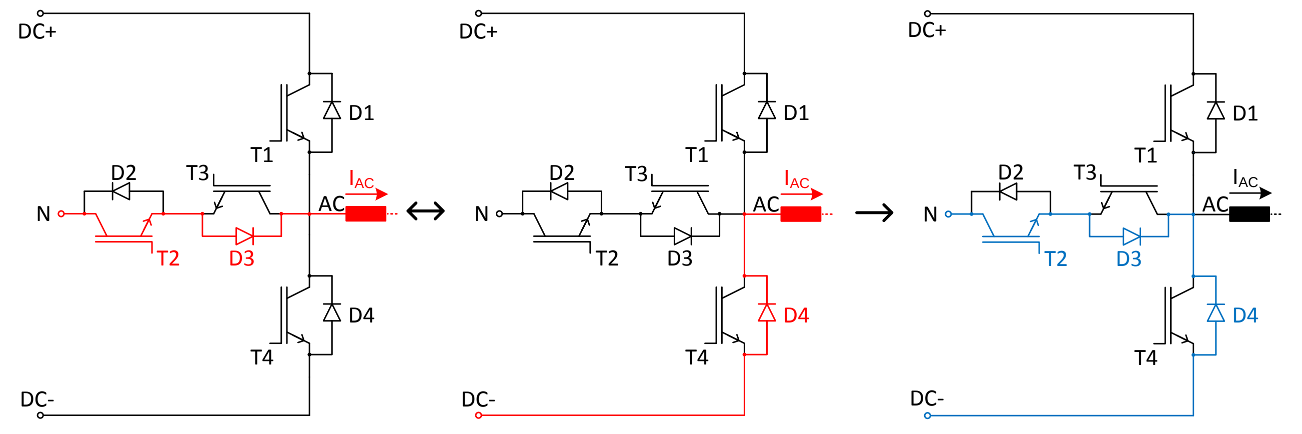
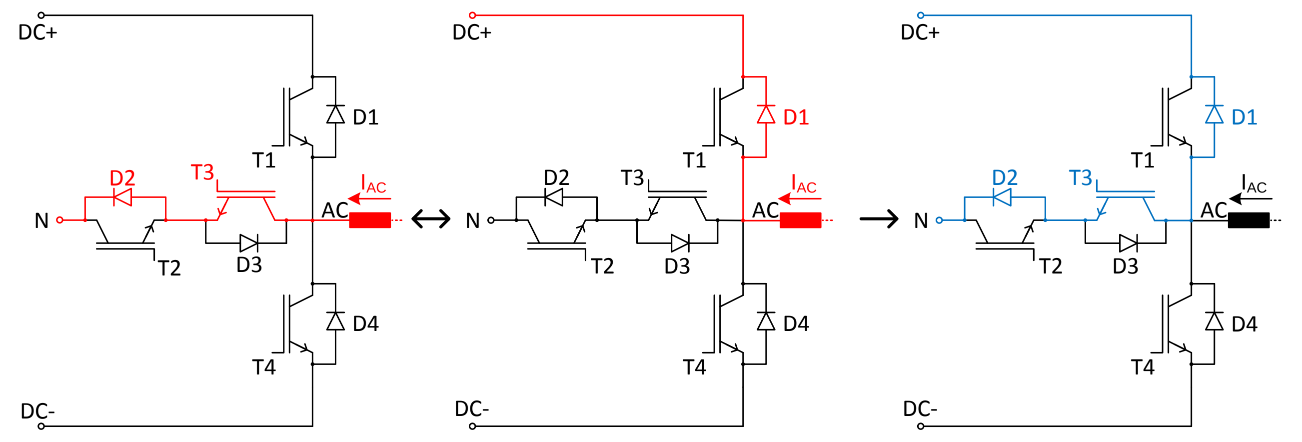


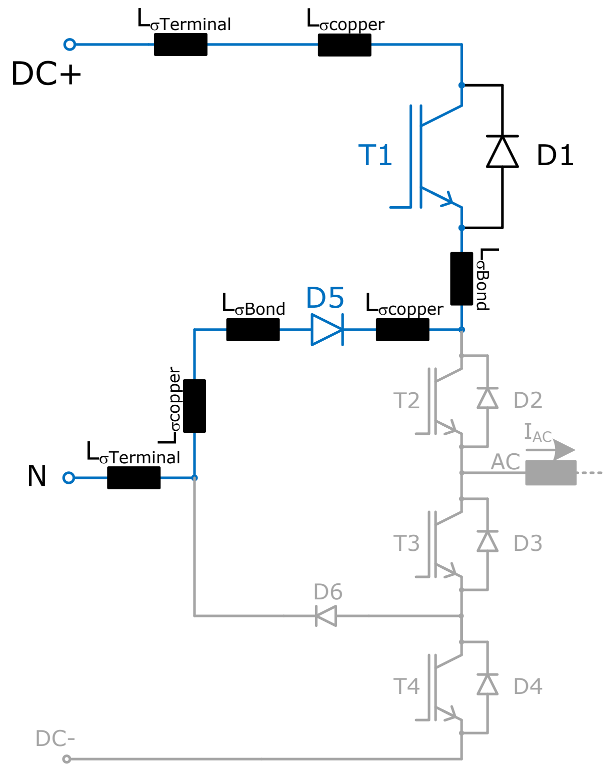
Figure 8: TNPC current paths (red) and commutation loop (blue) for operating area 4



2.4 Commutation inductance

When a conducting switch is turned off it experiences a voltage overshoot. This overshoot is due to the fact that the stray inductance in the current path needs to be overcome.
Figure 9 shows exemplarily (NPC short commutation loop, operating area 1) the stray inductances that form the commutation inductance. Additionally to the shown stray inductances also a coupling of inductances needs to be concerned. The sum of all stray inductances (and their possible coupling) is called commutation inductance.

Figure 9: NPC commutation inductance (exemplarily)



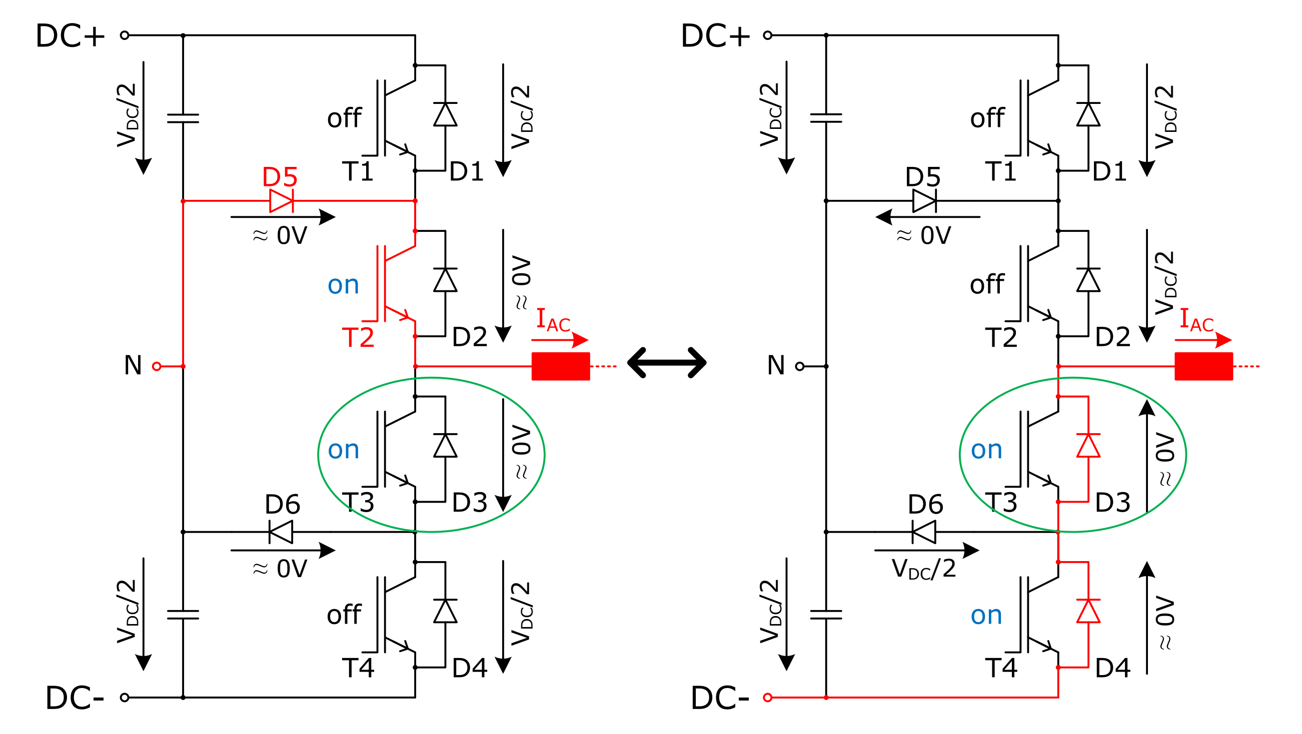
2.5 Semiconductor switching losses

The turn-on or turn-off process of a semiconductor produces losses. Those switching losses are defined by the multiplication of the voltage change across and the current change through the switching device during the switching process.

2.5.1 Switching losses of Diode2 (NPC)

The inner diodes D2 and D3 produce almost no switching losses. Figure 10 shows the two current paths in operating area 2, the voltages across the semiconductors, and the switching states of the IGBTs. In the image on the right the load current flows from DC- across D4 and D3 to the AC terminal. The IGBTs T3 and T4 are turned on. As a current flows the voltages across the diodes correlates to their forward voltage drops. Here it would make no difference whether T3 and T4 were switched on or off.
For changing the current path from what is shown in the right to what is shown in the left image in Figure 10 first IGBT T4 is turned off and then IGBT T2 is turned on. As the driving voltage from N to AC is larger than that from DC- to AC the current commutates to the upper path.
As stated above the switching losses are calculated by multiplying the voltage change across and the current change through the particular device. In operating area 2 IGBT T3 stays switched on all the time no matter whether the antiparallel diode is conducting current or not. During diode D3 conduction the voltage drop is almost zero. When D3 is not conducting the voltage across it is kept almost zero by the always turned-on IGBT T3. Here “close to zero” refers to the forward voltage drop of IGBT T3.
As the voltage change across D3 is close zero (it is the difference between the forward voltage drops of IGBT and diode) the losses are also close zero and hence negligible.

Figure 10: Switching losses of D3 (NPC) in operating area 2



The same methodology as explained for D3 (operating area 2) also applies for the switching losses of diode D2 in operating area 3.

3. SEMIKRON 3L Datasheets

Concerning the content SEMIKRON 2L and 3L datasheets are very much alike. An explanation of the particular values is given in SEMIKRON's "Application Manual Power Semiconductors" [2]. The differences can be found in the stray inductances of the devices and the switching losses of certain semiconductors as described below.

3.1 Measurements

The datasheet values for switching losses and stray inductances are measured in the abovementioned commutations. That guarantees values that meet the real switching behaviour as long as the PWM pattern is generated by using the sine-triangular comparison.
Please note that if different PWM patterns (different from what the sine-triangular comparison delivers) are used the SEMIKRON datasheet values may not thoroughly apply any longer.
Of course other PWM patterns are allowed, but it remains with the user to specify valid datasheet values.

3.2 Measurement of commutation inductances

The commutation inductances are measured by using a setup with an additional external switch and an external diode where required.
The following figures show the measurement setups of NPC (Figure 11 and Figure 12) and TNPC (Figure 13, Figure 14 and Figure 15): the external switch (and diode) as well as a load inductor are drawn in green colour, blue marks the involved semiconductors, the other semiconductors are marked grey.
The external switch pulses twice: during the first pulse the load inductor is charged. When the external switch turns off the load current commutates to the commutation loop which is under investigation (drawn in blue colour). At turn-on of the second pulse the current commutates back to the external switch and hence the commutation path is turned off. This turn-off is the time when the voltage across and the di/dt through the commutation loop is measured. From these values the commutation inductance can be calculated.
This method for measuring the commutation inductances is as close to IEC60747 as possible. The standard states that only external semiconductors may be used for switching and the di/dt is measured when the

Figure 11: Measurement setup of NPC commutation inductances in operating areas 1 (left) and 2 (right)

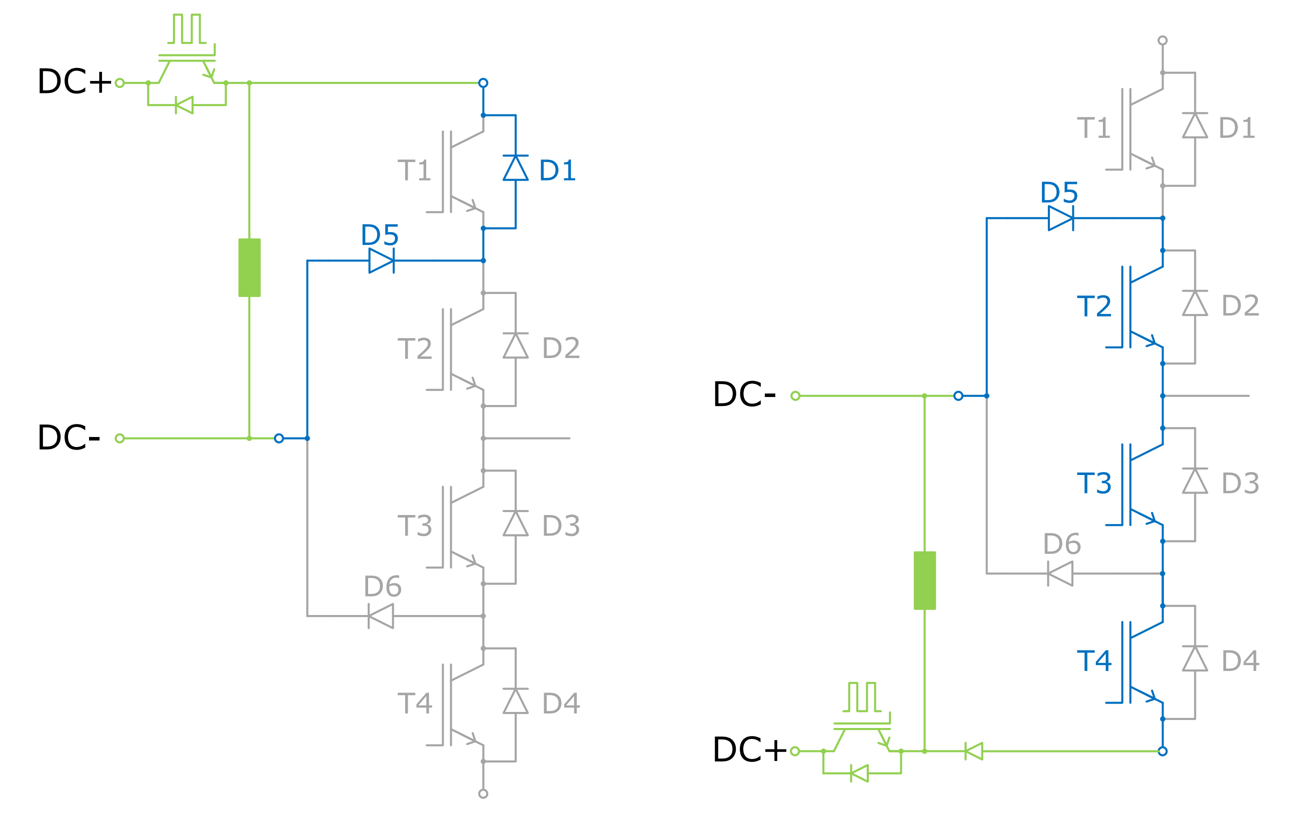
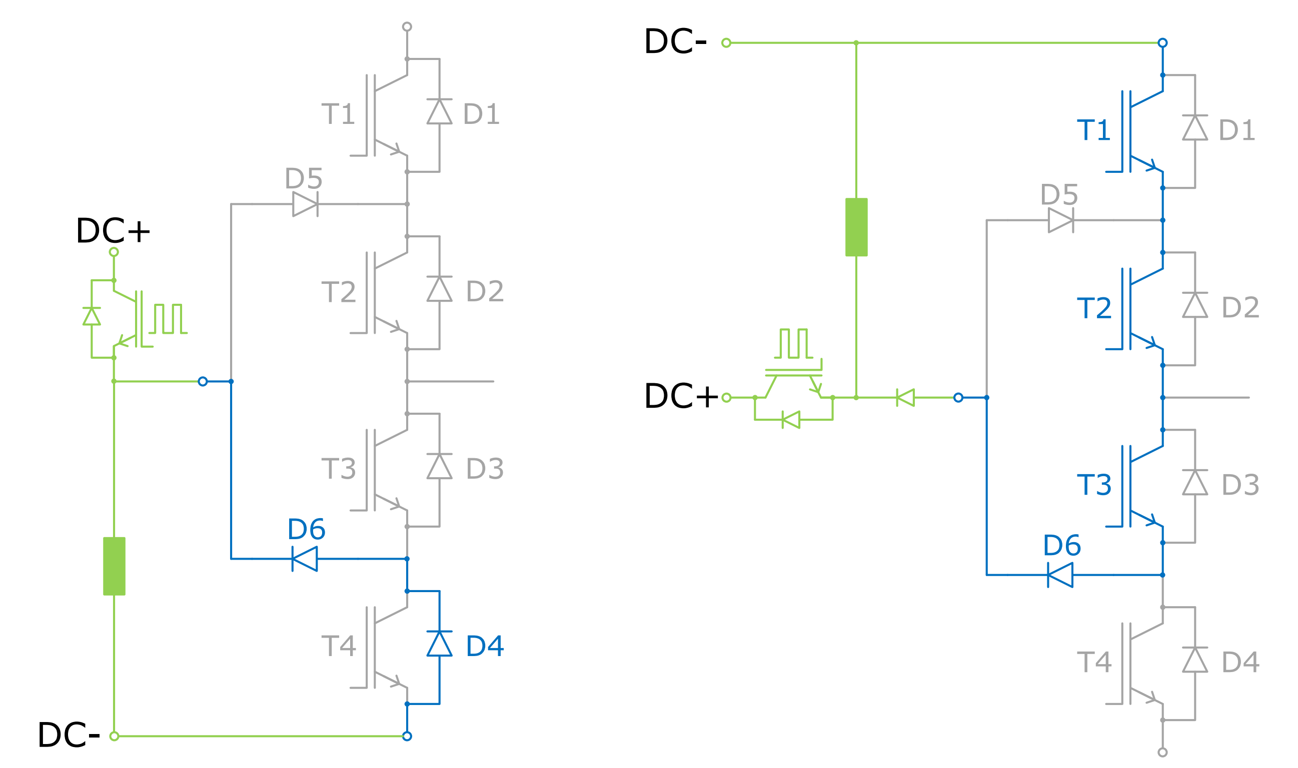


Figure 12: Measurement setup of NPC commutation inductances in operating areas 3 (left) and 4 (right)



module's internal diodes turn-off the load current. The measurement of the 2L commutation inductance in TMLI (Figure 15) follows this standard to the letter.
For the measurements of the 3L commutation inductances some slight modifications need to be made: when the load current is turned off a current path is needed. As the 3L commutation paths do not only include diodes but also one or more IGBTs. Those IGBTs need to be involved in that measurement. During the measurement they are permanently turned on and provide the required current path.

Figure 13: Measurement setup of TNPC commutation inductances in upper module half

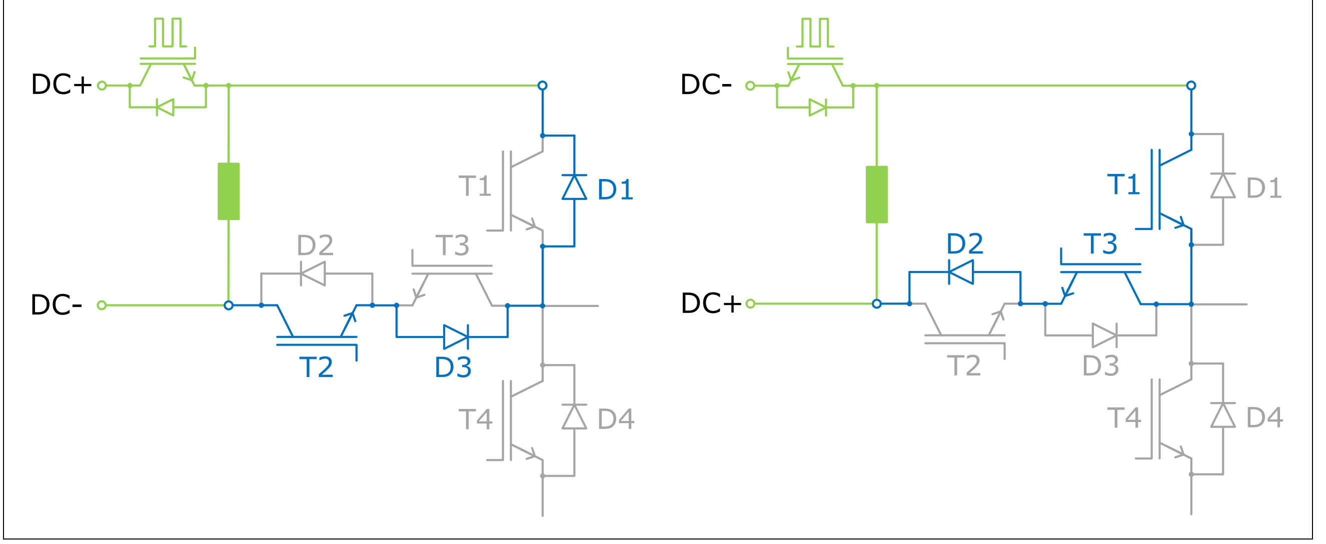


Figure 14: Measurement setup of TNPC commutation inductances in lower module half

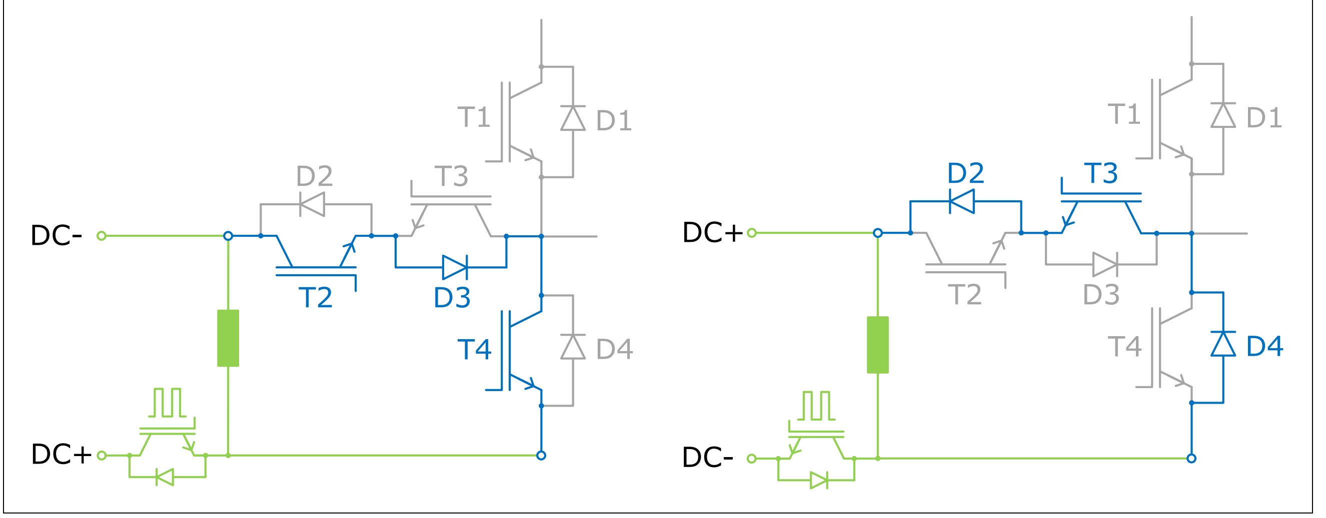
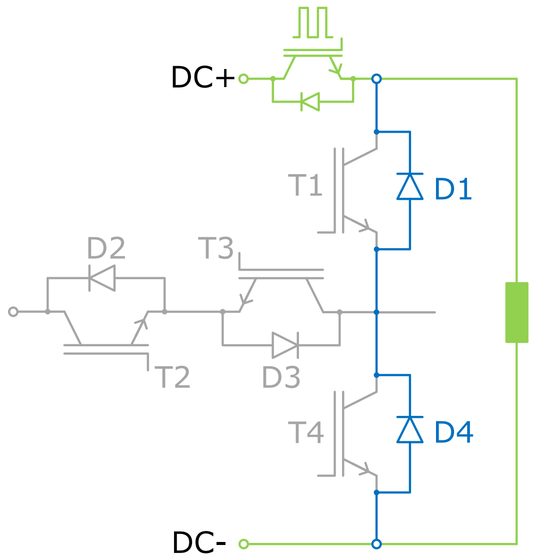


Figure 11 and Figure 12 show how the NPC commutation inductances of the two short and the two long commutation loops are measured. As the module layouts are very symmetrical the two short (as well as the two long) commutation loops are very similar and hence show the same commutation inductance in regard of measurement accuracy. For that reason the datasheets contain one value for the short (L_{sCE1}) and one for the long (L_{sCE2}) commutation loop.
Figure 13 and Figure 14 show the setups for the measurement of the TNPC commutation inductances. These paths differ slightly from the commutation loops shown in Figure 5 to Figure 8 because in order to achieve a current path that can be turned on and off by an external switch it is necessary to use for example D1 instead of T1 (which would be involved in the real commutation loop). This deviation of the current path leads to a deviation of the measured value. As T1 and D1 are located very close to each other this deviation is minimal and may be neglected.

SEMIKRON TNPC modules are designed with a very symmetrical layout; as consequence all four measurement setups lead to the same commutation inductance (within the boundaries of measurement accuracy). This is why the datasheets come with only one value for the 3L commutation inductance (L_{sCE1}).

Figure 15: Measurement setup of 2L commutation in TNPC



Under certain circumstances it is possible to operate a 3L TNPC module in 2L mode which means that IGBTs T2 and T3 are inactive and only T1 and T4 (and their inverse diodes D1 and D4) are operated. For a better estimation of the before mentioned circumstances SEMIKRON decided to measure the 2L commutation inductance and place it in the datasheet as well. This value is called L_{CE} in accordance with the stray inductance given in SEMIKRON 2L module datasheets.

3.3 Diode2 switching losses

As explained in chapter 2.5.1 the switching losses E_{rr} of the inner diodes D2 and D3 (in the datasheets referred to as "Diode2") are almost zero, hence Diode2 will not be a restricting element in a SEMIKRON NPC module concerning junction temperature. For that reason the almost not existing losses are not measured and the column for Diode2 switching losses contains a dash ("-").

3.4 List of datasheet figures

SEMIKRON 3L datasheets offer space for up to 24 diagrams. Depending on the status of the datasheet (e.g. "target" or "final") it is possible that less diagrams are shown. In that case the numbering of the possible diagram subtitles (shown in Table 1 and Table 2) remains the same. Example: when Fig. 11 and Fig. 12 are missing Fig. 10 is directly followed by Fig. 13 and all further figures move up.
The figure numbering of NPC and TNPC is similar where possible. Example: Fig. 3 (NPC) shows the switching losses of IGBT1 and Diode5, Fig. 3 (TNPC) shows this values of IGBT1 and Diode2. In both topologies the load current is commutated between the two particular semiconductors in operating area 1 and 3 respectively. The same methodology applies for all figures.
Fig. 2 and Fig. 14 display a rated current as a function of temperature: for modules with baseplate (e.g. SEMiX) this is the case temperature (T_C). For modules without baseplate (e.g. MiniSKiiP) it is the heatsink temperature (T_S).

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3.4.1 MLI datasheet figures

Table 1: Figure captions in SEMIKRON 3-Level NPC datasheets	
Fig. 1	Typ. IGBT1 output characteristic
Fig. 2	IGBT1 rated current vs. Temperature I_C=f(T_C) [or I_C=f(T_s), depending on module type]
Fig. 3	Typ. IGBT1 & Diode5 turn-on/-off energy =f(I_C)
Fig. 4	Typ. IGBT1 & Diode5 Turn-on/-off energy = f(R_G)
Fig. 5	Typ. IGBT1 transfer characteristic
Fig. 6	Typ. IGBT1 gate charge characteristic
Fig. 7	Typ. IGBT1 switching times vs. I_C
Fig. 8	Typ. IGBT1 switching times vs. gate resistor R_G
Fig. 9	Transient thermal impedance of IGBT1 & Diode5
Fig. 10	Diode5 forward characteristic
Fig. 11	Typ. Diode5 peak reverse recovery current
Fig. 12	Typ. Diode5 recovery charge
Fig. 13	Typ. IGBT2 output characteristic
Fig. 14	IGBT2 rated current vs. Temperature I_C=f(T_C) [or I_C=f(T_s), depending on module type]
Fig. 15	Typ. IGBT2 & Diode1 turn-on/-off energy =f(I_C)
Fig. 16	Typ. IGBT2 & Diode1 Turn-on/-off energy = f(R_G)
Fig. 17	Typ. IGBT2 transfer characteristic
Fig. 18	Typ. IGBT2 gate charge characteristic
Fig. 19	Typ. IGBT2 switching times vs. I_C
Fig. 20	Typ. IGBT2 switching times vs. gate resistor R_G
Fig. 21	Transient thermal impedance of IGBT2, Diode1 & Diode2
Fig. 22	Diode1 & Diode2 forward characteristic
Fig. 23	Typ. Diode1 peak reverse recovery current
Fig. 24	Typ. Diode1 recovery charge

3.4.2 TMLI datasheet figures

Table 2: Figure captions in SEMIKRON 3-Level TNPC datasheets	
Fig. 1	Typ. IGBT1 output characteristic
Fig. 2	IGBT1 rated current vs. Temperature I_C=f(T_C) [or I_C=f(T_s), depending on module type]
Fig. 3	Typ. IGBT1 & Diode2 turn-on/-off energy =f(I_C)
Fig. 4	Typ. IGBT1 & Diode2 Turn-on/-off energy = f(R_G)
Fig. 5	Typ. IGBT1 transfer characteristic
Fig. 6	Typ. IGBT1 gate charge characteristic
Fig. 7	Typ. IGBT1 switching times vs. I_C
Fig. 8	Typ. IGBT1 switching times vs. gate resistor R_G
Fig. 9	Transient thermal impedance of IGBT1 & Diode2
Fig. 10	Diode2 forward characteristic
Fig. 11	Typ. Diode2 peak reverse recovery current
Fig. 12	Typ. Diode2 recovery charge
Fig. 13	Typ. IGBT2 output characteristic
Fig. 14	IGBT2 rated current vs. Temperature I_C=f(T_C) [or I_C=f(T_s), depending on module type]
Fig. 15	Typ. IGBT2 & Diode1 turn-on/-off energy =f(I_C)
Fig. 16	Typ. IGBT2 & Diode1 Turn-on/-off energy = f(R_G)
Fig. 17	Typ. IGBT2 transfer characteristic
Fig. 18	Typ. IGBT2 gate charge characteristic
Fig. 19	Typ. IGBT2 switching times vs. I_C
Fig. 20	Typ. IGBT2 switching times vs. gate resistor R_G
Fig. 21	Transient thermal impedance of IGBT2 & Diode1
Fig. 22	Diode1 forward characteristic
Fig. 23	Typ. Diode1 peak reverse recovery current
Fig. 24	Typ. Diode1 recovery charge

Symbols and Terms

Letter Symbol	Term
2L	Two level
3L	Three level
AC	Alternating current
DC-	Negative potential (terminal) od a direct voltage source
DC+	Positive potential (terminal) of a direct voltage source
di/dt	Change of current per time
Err	Energy dissipation during reverse recovery (diode)
I_{AC}	RMS output current of a device
I_C	Continuous collector current
IGBT	Insulated Gate Bipolar Transistor
L_{CE}	Parasitic collector-emitter inductance
L_{sCE1}	Parasitic 3L commutation inductance short path
L_{sCE2}	Parasitic 3L commutation inductance long path
MLI	Multi Level Inverter
N	Neutral potential (terminal) of a direct voltage source; midpoint between DC+ and DC-
NPC	Neutral Point Clamped
PWM	Pulse Width Modulation
R_G	Gate circuit resistance
RMS	Root Mean Square
T_C	Case temperature
TMLI	T-type Multi Level Inverter
TNPC	T-type Neutral point Clamped
T_S	Heatsink temperature

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

References

[1] www.SEMIKRON.com
[2] A. Wintrich, U. Nicolai, W. Tursky, T. Reimann, "Application Manual Power Semiconductors", 2nd edition, ISLE Verlag 2015, ISBN 978-3-938843-83-3
[3] I. Staudt et al, "Numerical loss calculation and simulation tool for 3L NPC converter design", PCIM Nuremberg, 2011
[4] I. Staudt, "3L NPC & TNPC Topology", SEMIKRON Application Note, AN11001 – rev05, Nuremberg, 2015

IMPORTANT INFORMATION AND WARNINGS

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