

# Simulation Tool for IGBT modules

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## Abstract:

ABB has recently released a new simulation tool based on Microsoft Excel for dimensioning of two level voltage source IGBT converters.

The tool allows the calculation of switching and conduction losses under the assumption of sinusoidal output currents. Additionally static and transient temperature rises in the module and an optionally specified heatsink can be calculated. The losses in the IGBT and companion freewheeling diode are iteratively adjusted to the temperature rises.

Therefore the calculation results allow a quick selection of ABB IGBT modules for the planned application.

## Introduction:

The calculation of the conduction and switching losses of the IGBT and the freewheeling diode are done based on the application parameters.

As application parameters the DC-link voltage, output frequency, switching frequency, modulation index and the power factor  $\cos \phi$  can be specified.

If the maximum permissible output current has to be calculated the junction and case or heatsink temperature needs to be specified. In this case the permissible output current can be read out of a diagram or directly calculated by using the solver.

If the output current is given the simulation tool calculates with 10 iterations the losses and temperature rise of the module.

Additionally it is possible to calculate the temperature rise in an optionally specified cooler. In addition special overload conditions can be specified and the simulation tool calculates the temperature excursion during overload in the heatsink and the module. Again the losses are iteratively adjusted to the junction temperature.

## Loss Calculation:

The simulation tool offers a relatively exact and fast method for loss calculation.

The model data for the IGBT modules are based on their respective data-sheet values.

The calculations are done with a linear approximation of the devices forward characteristics and with a polynomial function of the IGBT and diode switching energy. Additionally the forward and switching-energy characteristics are temperature dependent.

The power dissipation calculation of the IGBT and diode are done by an average calculation for the conduction and switching losses over one period  $T_0$  of the output frequency. This method does not require adding up the switching energies [1].

**IGBT loss calculation:** Since the IGBT of one switch conducts only over one half period the conduction

losses are given by the integration of the forward losses ( $V_{CE0}$ ,  $r_{CE}$  including  $R_{CC}+R_{EE}$ ) up to  $T_0/2$ :

$$P_{cond\ IGBT} = \frac{1}{T_0} \int_0^{T_0/2} V_{CE0} + r_{CE} \cdot (\hat{i} \sin(\omega t))^2 \cdot \tau(t) dt$$

with  $\tau(t)$  as the function of pulse pattern with IGBT turned-on=1 and IGBT turned-off=0.  $\tau(t)$  can be substituted by a function of modulation ( $m$ ) and phase angle ( $\phi$ ).

With an infinite switching frequency we get the duty cycle variation over time (PWM pattern).

$$\tau(t) = \frac{1}{2} (1 + m \sin(\omega t + \phi))$$

Inserting  $\tau(t)$  into the formula and solving the integral we get the conduction losses:

$$P_{cond} = \frac{1}{2} (V_{CE0} \cdot \frac{\hat{i}}{\pi} + r_{CE} \cdot \frac{\hat{i}^2}{4}) + m \cdot \cos \phi \cdot (V_{CE0} \cdot \frac{\hat{i}}{8} + \frac{1}{3\pi} \cdot r_{CE} \cdot \hat{i}^2)$$

The simulation tool restricts the modulation index to  $m \leq 1$  which is the linear mode of the PWM.

The switching losses are the sum of all turn-on and turn-off energies at the switching events.

The measured turn-on and turn-off energies given in the data-sheet can be described as a polynomial function ( $E_{sw}=f(I)$ ):

$$E_{sw} = E_{on} + E_{off} = (a + b \cdot I + c \cdot I^2)$$

Since the DC-link voltage can vary in different applications the dependence of the switching energy on the DC-voltage needs to be considered. Within certain limits this dependence can be assumed linear:

$$E_{sw} = (a + b \cdot \hat{i} + c \cdot \hat{i}^2) \cdot \frac{V_{DC}}{V_{nom}}$$

To calculate the switching losses the switching energies have to be added up.

$$P_{sw} = \frac{1}{T_0} \cdot \sum_n E_{sw}(\hat{i})$$

whereas n depends on the switching frequency. Therefore we can calculate the switching losses as a function of phase-current and switching frequency.

$$P_{sw} = \frac{1}{\pi} \cdot f_{sw} \cdot (a + b \cdot \hat{i} + c \cdot \hat{i}^2) \cdot \frac{V_{DC}}{V_{nom}}$$

The total IGBT losses are the sum of the conduction- and switching losses:

$$P_{IGBT} = P_{cond} + P_{sw}$$

#### Diode loss calculation:

The diode losses can be nearly calculated the same way as the IGBT. Since the freewheeling diode conducts when the IGBT is turned-off the function of the pulse pattern has to be negated:

$$P_{cond} = \frac{1}{2} (V_{F0} \cdot \frac{\hat{i}}{\pi} + r_T \cdot \frac{\hat{i}^2}{4}) - m \cdot \cos\phi \cdot (V_{T0} \cdot \frac{\hat{i}}{8} + \frac{1}{3\pi} \cdot r_T \cdot \hat{i}^2)$$

In case of the diode the turn-on energy can be neglected. Therefore only the recovery energy counts. The recovery energy given in the data-sheet diagram can be described as a polynomial function:

$$E_{rec} = (a + b \cdot I + c \cdot I^2)$$

The recovery losses as a function of phase-current and switching frequency and  $V_{DC}$  can be written as:

$$P_{rec} = \frac{1}{\pi} \cdot f_{sw} \cdot (a + b \cdot \hat{i} + c \cdot \hat{i}^2) \cdot \frac{V_{DC}}{V_{nom}}$$

The total Diode losses are the sum of the conduction- and switching losses:

$$P_{Diode} = P_{cond} + P_{sw}$$

#### Thermal Calculation:

The loss calculation yields in average losses over one period of the output frequency. In fact the losses per switch only occurs during one half-period whereas during the other half period the antagonist switch is producing losses.

Figure 1 shows in the upper graph a PWM chopped current as it appears in case of a two level VSI. In addition the resulting junction temperature is shown (calculated with THIMP V3.08). It is obvious that the junction temperature oscillates with the frequency of the output current. In the lower graph the corresponding losses  $P_{smoothed}$  (THIMP) are shown. As a comparison the calculated average losses ( $P_{av}$ ) from simulation tool are given (dashed line).

If the junction temperature is calculated with  $T_{jav} = P_{av} \cdot R_{th}$  evidently the peak value of junction temperature exceeds the result of  $T_j$  calculated with the average losses  $P_{av}$ . Therefore the calculation of  $T_j$  with average losses yields in a optimistic value.

In order to minimize this inaccuracy the simulation tool calculates with  $P_{mod}$  which is two times the average losses  $P_{av}$  dissipated during one half period of the phase current. The resulting junction temperature  $T_{jmod}$  is shown in the lower graph of figure 1 and matches in terms of the peak and bottom values quite well with the real value of  $T_j$ .

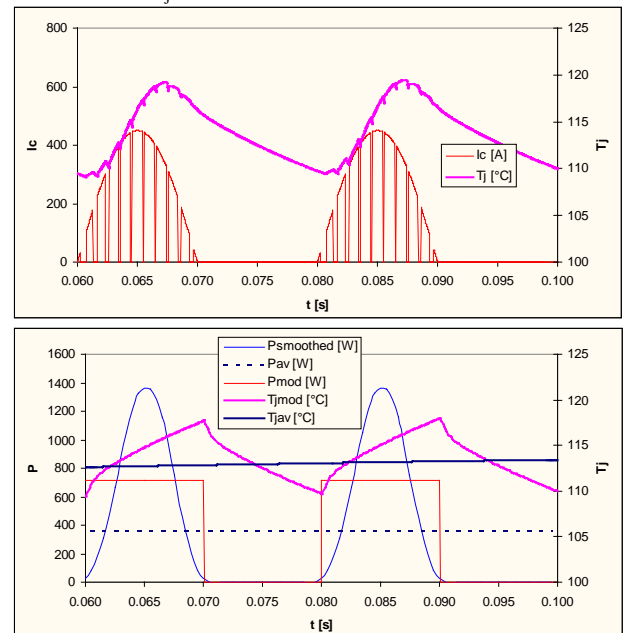


Figure 1: junction temperature as a function of  $f_0$

The maximum junction temperature  $T_{vj\ max}$  in function of the phase output current frequency  $f_0$  can be calculated if the transient thermal resistance is known:

$$T_{vj\ max} = 2 \cdot P_{AV} \cdot \sum_{i=1}^n R_i \frac{1 - e^{-\frac{2}{f_0 \cdot \tau_i}}}{1 - e^{-\frac{1}{f_0 \cdot \tau_i}}} + T_{ref}$$

With  $T_{ref}$  as the reference heatsink temperature  $T_h$  for base-less modules or case temperature  $T_c$  for based modules.

### Heatsink and Transient Calculations:

In addition to the module calculation the simulation tool allows the user to calculate the temperature rises and module losses of the IGBT-module together with a specified cooler.

The simulation tool uses a simplified approach to calculate temperature rises and cross-talk effects. This has the advantage that the calculations can be done with the given values in the module- and heatsink data-sheets.

More accurate methods based on finite element calculation require specific knowledge about module and cooler construction and need lots of time for parameter extraction.

On the other hand the simplified method of the simulation tool allows quick and accurate simulation without detailed knowledge on cooler and module construction.

### Thermal equivalent block diagram:

The simplification done in the simulation tool is the assumption of common reference temperature point where the temperature is assumed to be homogenous over the full area. In case of base-less devices this reference is the heatsink temperature (figure 2):

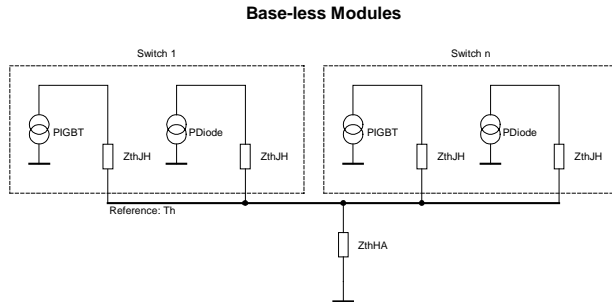


Figure 2: thermal equivalent block diagram for base-less devices

The static calculation of the temperature rise in the heatsink can be calculate with the thermal resistance of the cooler and the number of dissipating heat sources mounted on it:

$$T_H = T_A + (P_{IGBT} + P_{Diode}) \cdot n_S \cdot R_{thHA}$$

With  $n_S$  as the number of switches mounted on the cooler.

For based devices the reference is the case temperature. The thermal characteristics of devices with a base-plate (copper or AlSiC) is normally specified with a  $Z_{thJC}$  (thermal impedance junction – case) for the IGBT and Diode part. Additionally the interface resistance case-heatsink  $R_{thCH}$  is given for the whole module. Figure 3

shows the thermal equivalent block diagram for modules with base-plate:

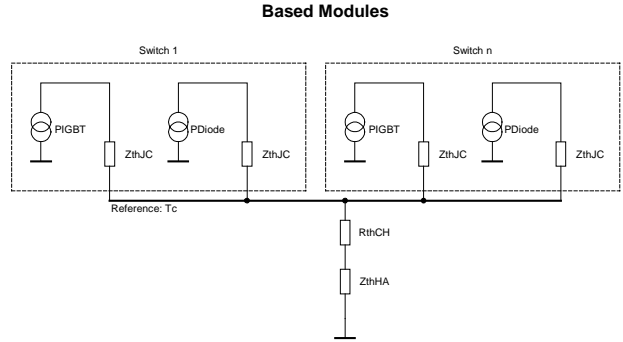


Figure 3: thermal equivalent block diagram for devices with base-plate

As in case of base-less modules the static calculation of the temperature rise in the heatsink can be calculate with the thermal resistance of the cooler and the number of dissipating heat sources mounted on it:

$$T_H = T_A + (P_{IGBT} + P_{Diode}) \cdot n_S \cdot R_{thHA}$$

Additionally the temperature rise in the interface  $\Delta T_{CH}$  needs to be calculated. Since it is possible more than one module is mounted on the heatsink and that the heat sources are distributed in several modules, as for example in a three phase inverter built with three half-bridge modules mounted on a single cooler, it becomes necessary to scale the interface resistance accordingly:

$$\Delta T_{CH} = (P_{IGBT} + P_{Diode}) \cdot n_S \cdot \frac{R_{thCH}}{n_M}$$

With  $n_M$  as the number of modules mounted on a single heatsink.

In order to calculate the temperature dependent semiconductor losses the simulation tool adjusts the junction temperature and the corresponding losses in several iterations. Depending on the module type and the calculation (with / without heatsink) the calculation starts with the initial conditions  $T_{vj} = T_A$ ,  $T_{vj} = T_H$  or  $T_{vj} = T_C$ .

### Transient Overload Calculation:

The simulation tool offers the possibility to additionally calculate the transient thermal behavior of the IGBT module and the heatsink. For the transient calculation overload conditions can be specified. In order to have full flexibility the start conditions of the temperature excursion calculation need to be specified. This includes the overload duration, the start junction temperature and the start case or heatsink temperature.

Therefore it is possible to study the transient thermal behavior from any temperature level and even the

thermal recovery behavior from an overload can be computed.

The transient temperature rise can be calculated with the thermal impedance.

$$Z_{th}(t) = \sum_{i=1}^n R_i \cdot (1 - e^{-t/\tau_i})$$

The temperature rise  $\Delta T(t)$  is a function of  $Z_{th}(t)$  and the temperature dependent power dissipation in the semiconductor  $P(T)$ .

$$\Delta T(t) = \left(-\frac{\Delta T_{start}}{R_{th}}\right) \cdot Z_{th}(t) + P(T) \cdot Z_{th}(t)$$

In order to include the starting conditions for  $\Delta T$  the first term is introduced.  $\Delta T_{start}/R_{th}$  describes the initial constant power that resulted in  $\Delta T_{start}$ . This deposited power influences the thermal behavior until  $Z_{th}(t)=R_{th}(t)$ .

The second term describes the heating with the temperature dependant power  $P(T)$ . Since  $T$  is as well a function of the dissipated power and the thermal impedance iterations are necessary to get an accurate result.

For the transient heatsink temperature we can write:

$$T_H(t) = T_A + \left(-\frac{T_{Hstart} - T_A}{R_{thHA}}\right) \cdot Z_{thHA}(t) + P(T) \cdot Z_{thHA}(t)$$

whereas  $P(T)$  depends on the number of switches mounted on the heatsink

$$P(T) = (P_{IGBT}(T) + P_{Diode}(T)) \cdot n_s$$

For the transient average junction temperature we can write:

$$T_{vjav}(t) = T_H(t) + \left(-\frac{T_{vjstart} - T_{Hstart}}{R_{thJH}}\right) \cdot Z_{thJH}(t) + P(T) \cdot Z_{thJH}(t)$$

In case of modules with a base plate  $T_H$  has to be replaced with  $T_C$  and  $R_{thJH}$  and  $Z_{thJH}$  have to be replaced with  $R_{thJC}$  and  $Z_{thJC}$  respectively. In addition the temperature drop across the interface  $\Delta T_{CH}$  has to be calculated. Since the interface has no heatcapacity this can be done similar to the static calculations (page 3). Therefore we are able to calculate the transient average junction temperature. As already mentioned the average junction temperature yields in too optimistic value if the temperature ripple in function of the output current needs to be considered.

To avoid a too high complexity the simulation tool uses a simplified approach that is valid in most relevant application cases.

The approach is to calculate the temperature ripple at the end of the overload pulse and add it to the calculated average temperature:

$$T_{vjmax}(t) = T_{vjav}(t) + (2 \cdot P(T) \cdot \sum_{i=1}^n R_i \frac{1 - e^{-\frac{0.5}{f_o \tau_i}}}{1 - e^{-\frac{1}{f_o \tau_i}}} + T_{ref}) - P(T) \cdot R_{th}$$

This is valid as long as the  $Z_{th}(t)$  of the module is close to its  $R_{th}$  value. For most modules this is the case between 0.5 and 1s. Below this time span the values for  $T_{vjmax}(t)$  are slightly optimistic. Therefore the simulation tool does not allow transient calculations with duration below 1s.

### Usage:

The simulation tool consists of two excel sheets. In the output sheet (figure 4) the application specific parameters such as output current, DC-voltage, output frequency, switching frequency, modulation, load power factor and the temperatures can be specified. Additionally a device has to be selected in the drop-down menu. The selected device is confirmed in the blue field and the electrical and thermal models of the device are loaded.

The calculation results are shown below and include conduction and switching losses as well as the maximum junction temperature and the output frequency dependent ripple of the junction temperature. With the button solve for  $I_{omax}$  the solver calculates the maximum permissible current if the case/heatsink and junction temperatures are specified. This feature requires the properly installed solver plug-in.

Simulation Tool for ABB IGBTs V 4.00, Sept. 2002

Select Device: 5516 0300 U120100 LoPaK5, SPT, 300A, 1200V

Enter application parameters:		limits	used values	Calculated results	
Output current I <sub>o rms</sub> [A]:	200	10 < I <sub>o rms</sub> < 424A	200	<b>I<sub>o max</sub> [A]:</b>	<b>250.2</b>
DC link voltage V <sub>dc</sub> [V]:	600	300V < V <sub>dc</sub> < 840V	600	Losses per IGBT & Diode [W]:	391.5
Output frequency f <sub>o</sub> [Hz]:	50	1Hz < f <sub>o</sub> < 1000Hz	50	IGBT total losses [W]:	318.7
Switching frequency f <sub>sw</sub> [Hz]:	4000	5 x 10 < f <sub>sw</sub> < 30000Hz	4000	T <sub>vj max</sub> IGBT [°C]:	125
Modulation index m:	1.00	0 < m < 1	1.00	Diode total losses [W]:	72.9
Load power factor cosφ:	0.85	-1 < cosφ < 1	0.85	T <sub>vj max</sub> Diode [°C]:	96
Th [°C]:	80	5°C < Th [°C] < 125	80		
Junction temperature T <sub>vj</sub> [°C]:	125	5°C < T <sub>vj</sub> < 150°C	125		
(only for diagrams and solver)		Gate resistor R <sub>G</sub> [Ohm]:	3.3		

Calculated Results:	
<b>Total switch losses(IGBT&amp;Diode) [W]:</b>	<b>281.3</b>
<b>T<sub>vj max</sub> [°C]:</b>	<b>112</b>

IGBT:		Diode:	
IGBT total losses [W]:	228.0	Diode total losses [W]:	53.2
IGBT conduction losses [W]:	156.3	Diode conduction losses [W]:	26.2
IGBT switching losses [W]:	71.7	Diode switching losses [W]:	27.0
T <sub>vj max</sub> [°C]:	112	T <sub>vj max</sub> [°C]:	91
Ripple ΔT <sub>vj</sub> [°C]:	5.1	Ripple ΔT <sub>vj</sub> [°C]:	2.6

Figure 3: Output sheet

Alternatively the maximum output current can be read out of the first diagram. The second diagram shows the temperature gradient and the ripple of the junction temperatures inside the module (figure 4).

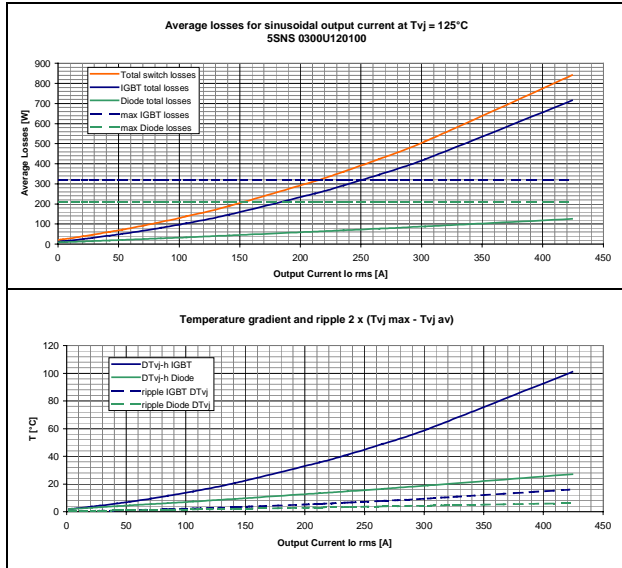


Figure 4: Diagrams with calculation results

The sheet heatsink and transient calculates the steady state and transient temperature excursions with the module and the heatsink (figure 5). The application specific parameters can be specified. The device to simulate is taken from the output sheet. In addition the heatsink, the ambient temperature and the number of switches and modules mounted on the cooler have to be specified. In order to calculate the transient heatsink behavior it is possible to specify up to  $n=4$  exponential terms for of  $Z_{th}$  of the cooler. If the  $Z_{th}$  of the cooler is not known the  $R_{thHA}$  can be specified in the first term ( $R_{th}$ ) and all other terms have to be set to zero (except the  $\tau$  that will be automatically set to 1 if not specified). The heatsink parameters have to be entered into the sheet heatsink\_spec.

If the necessary values are specified the simulation tool calculates the junction temperature and the corresponding losses of the IGBT and the freewheeling diode.

For the transient overload calculation a separate electrical load can be specified such as a possible overload or motor start conditions. To have full flexibility the starting temperatures for the  $T_{vj}$  of the IGBT and the Diode as well as the heatsink or case temperature can be entered. Therefore it is possible to simulate the transient behavior from any start condition and even thermal relaxation from overload can be computed.

The simulation tool reports the IGBT and Diode losses as well as the temperatures that have been computed after the specified overload duration has been elapsed. Additionally the transient temperature excursion over time will be shown in a diagram (figure 6).

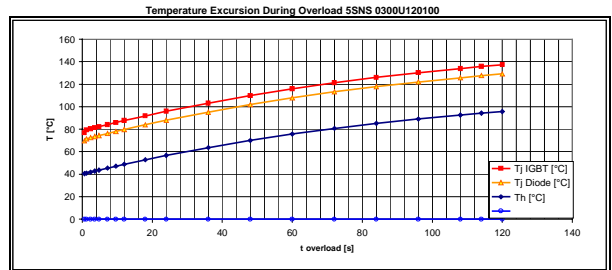
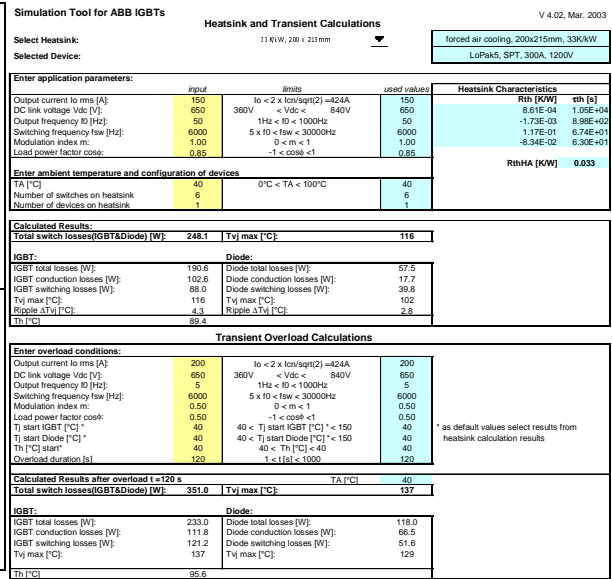


Figure 6: heatsink and transient calculations

### Conclusion:

The Simulation Tool presented offers a fast and simple but still accurate method to simulate the IGBT modules available from ABB under various application conditions. This even includes the possibility to calculate the transient thermal behavior together with a user-specified heatsink.

Right now the thermal and electrical models of the LoPak line up are available, this includes as well models for parallel connected LoPaks (as dual) that already have a derating included.

Therefore the Simulation Tool permits the user to select the right device for his application and furthermore gives already valuable application specific information on the behavior of the module in the planned application.

Nevertheless the described simplifications done by the simulation tool have to be considered in the simulation result judgement.

### References

1. D.Srajber, W.Lukasch, "The calculation of the power dissipation for the IGBT and the inverse diode in circuits with sinusoidal output voltage", *electronica'92, Proc.*, pp. 51-58
2. M.Rahimo, A.Kopta, R.Schnell, G.Debled, J.de Oñate, S.Linder, "New Industry Standard LoPak Modules with 1700V SPT-IGBT and Diode chip set", *Proc. PCIM'02, Nürnberg 2002.*

3. M.Rahimo, W.Lukasch, C. von Arx, A.Kopta, R.Schnell, S.Dewar, S.Linder "Novel Soft-Punch-Through (SPT) 1700V IGBT Sets Benchmark on Technology Curve", Proc. PCIM'01, Nürnberg, 2001.