Thermal Analysis of Semiconductors

Thermal simulation predicts the junction temperature and life time of semiconductors

The design of power converter includes necessarily the calculation of power loss and temperature rise in the semiconductors and heat sink. This article shows the procedure of evaluation junction temperature and life time of semiconductors.

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The design of power converter includes necessarily the calculation of power loss and temperature rise in the semiconductors and heat sink. For a reliable design the temperature ripple of the silicon should also be considered. The temperature ripple mainly determines the life time of the semiconductor (number of cycles to failure). The junction temperature is related to the heat sink temperature. Mostly the heat sources are not homogenous distributed over the heat sink. Therefore, the heat distribution on the heat sink must be known.

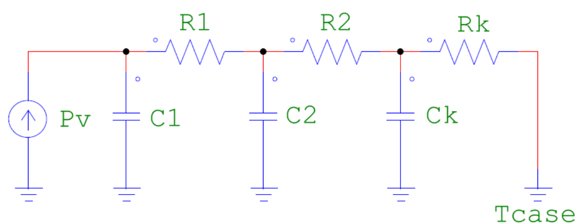


Figure 1a: Continued Fraction Model

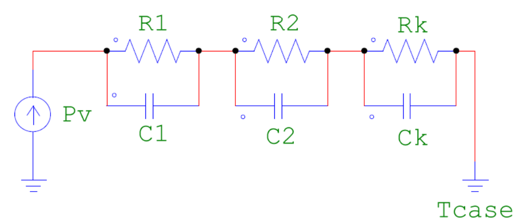


Figure 1b: Partial Fraction Model

Thermal model of the semiconductor

Numerical simulation of the junction temperature of semiconductors is possible by setting up a thermal model of the semiconductor and cooling system. Dynamic change of the junction temperature must be considered. Therefore a typical thermal model is composed of RC-networks. Figure 1a and figure 1b illustrates two possible electric equivalent circuits for numerical simulation of the thermal behaviour of a semiconductor device. In this model, the junction temperature is represented by a voltage increase relative to the case temperature, T_{case}. The model in Figure 1a is called the *continued fraction model*. This model reflects the physical layer structure of the semiconductor. The RC-elements are assigned to the layer structure of the semiconductor (chip, solder, substrate, base plate, thermal compound). Figure 1b shows a different approach, the so called *partial fraction model*. The RC-elements in this network have no physical meaning, except node PV-R1-C1 the junction temperature. The values of the RC-elements are extracted from the measured heating-up curve of the semiconductor. The values are extracted by a corresponding analysis tool. The advantage of the partial fraction model is that with an experimental setup the RC-elements can be calculated for every semiconductor without the need of additional data from the supplier.

Junction temperature simulation

The input to the thermal model is the power loss in the semiconductor. The power loss depends on the circuit topology and the application. In this paper, we are going to calculate the junction temperature of a semiconductor in a 3-Phase voltage source inverter (VSI). The calculation of the power loss is not shown in this paper. Reference [1], [2], gives further information.

Beside the average junction temperature, the temperature ripple of the semiconductor must be calculated. Every temperature change stresses the semiconductor device. The temperature fluctuations expose the internal connection in a semiconductor module (i.e. wire-bonds, solder connection of DCB and base plate, underside soldering of chips). The different length expansion of the layers causes stress during operation, which finally leads to a failure of the semiconductor module. The temperature model of a semiconductor as shown in figure 1a and figure 1b is a RC-network. The transfer function of the RC-network is frequency dependent. Due to this behaviour the junction temperature swing is a function of the output frequency of the 3-Phase VSI. In particular, low output frequencies must be considered because they are not smoothed out by the transient thermal impedance of the chip.

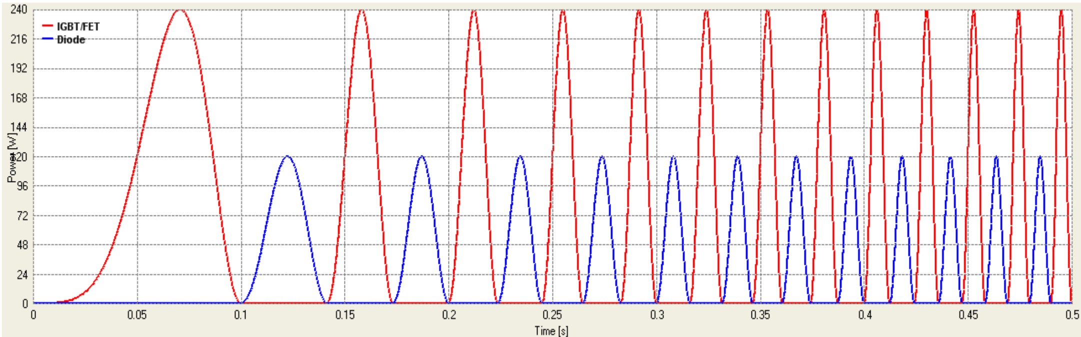


Figure 2: Power Cycle

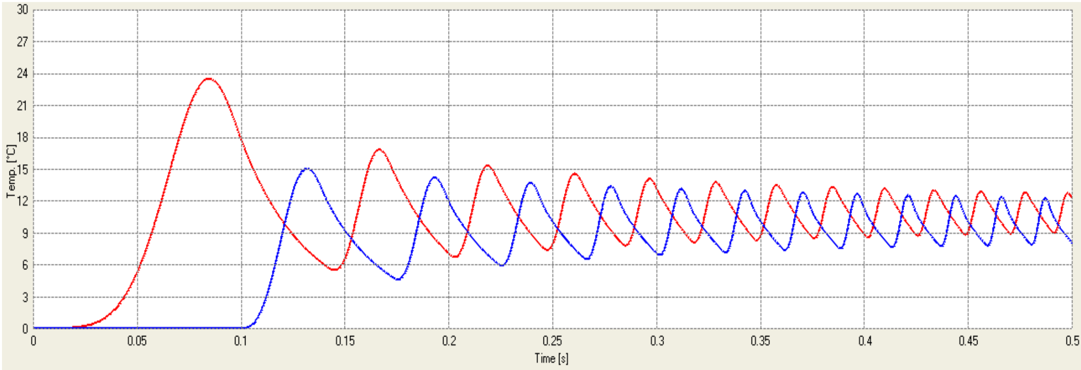
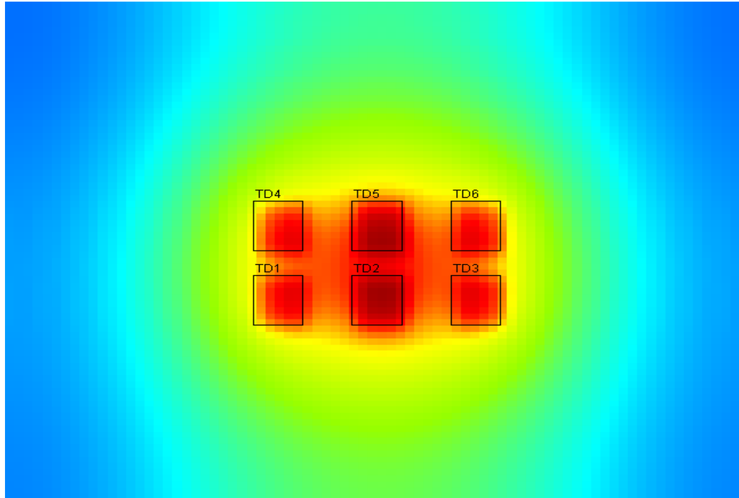


Figure 3: Temperature Swing

Figure 2 shows the power loss at the starting procedure of a three-phase motor. The motor current is held constant during start up. The motor is accelerated within 0.5s from 0Hz to 50Hz. The power loss was calculated for one IGBT and one freewheeling diode in an inverter leg. Figure 3 shows the relative temperature swing of the chip. At low frequency the maximum junction temperature fluctuation is18K, the minimum fluctuation 4K.

Case temperature

The lifetime of the power module not only depends on the temperature difference ΔT_j but also on the average junction temperature of the semiconductor. It makes a difference whether the temperature swing of 30K is between 60°C and 90°C or between 80°C and 110°C. It takes a much smaller number of cycles to failure if the absolute temperature is higher. The junction temperature is relative to the case temperature of the semiconductor module. The fact that the heat sources (semiconductors) are not evenly spread over the heat sink, the heat distribution of the heat sink must be simulated. The simulation tool used for the simulation in this paper represents the heat sink as a rectangular plate. One side is cooled by convection. On the other side rectangular heat sources are placed. The top of the heat sources and heat sink is isothermal.



Simulation Parameters:
Heat sink with the dimension of 200mm x 300mm. The base plate thickness is 15mm. Heat sink material is aluminium with a thermal conductivity of 360 W/(m*K). Power loss per IGBT (including freewheeling diode) 60W. This results in 240W total power loss. The heat sink is cooled by natural convection. The ambient temperature is 30°C.

Figure 4: Heat sink temperature distribution

Figure 4 shows the simulated heat distribution on the heat sink. The maximum temperature under the semiconductor chip TD5 is 87°C. This simulation shows the significance of simulating the heat sink temperature distribution.

Lifetime calculation

Semiconductor lifetime prediction requires a statistical approach. This demand can be met for example with a Weibull analysis of a group of samples. The Weibull distribution is a continuous probability distribution. It is often used in the field of life data analysis. A study of the power cycling lifetime of base plate modules was realised during the LESIT-project. In this study the number of cycles to failure N_f was expressed in the following form.

$$N_f = A * \Delta T_j^{\alpha} * \exp\left(\frac{E_A}{k_B * (T_m + 273K)} \right)$$

k_B	=	Boltzmann constant [J/K]
E_a	=	activation energy [J]
T_m	=	average junction Temperature [K]
ΔT_j	=	temperature ripple [K]
A,α	=	302500, -5.039

A short cycling time of <10s was used. This formula gives an indication for the life time. If available, one should use the cycle to failure data from the semiconductor manufacturer.

Conclusion

For a reliable design of the power converter it is important to calculate the semiconductors temperature. The significance of simulating the temperature distribution on the heat sink was shown. Taking the temperature ripple and the average temperature of the semiconductor in account leads to safer designs. With adequate simulation software it is possible to optimize the design during the development process in an early stage. All simulations in this paper were performed with SemiSimV1 [3].

References

[1] Realistic benchmarking of IGBT-modules with the help of fast and easy to use simulation-tool *R.Schnell, U.Schlapbach; ABB Switzerland*

[2] Power Cycling Lifetime of Advanced Power Modules for Different Temperature Swings *U.Scheuermann, U.Hecht; SEMIKRON*

[3] SemisSimV1, www.hsi-ag.ch

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