Counting Methods for Lifetime Calculation of Power Modules

Various counting methods are applied to extract amplitude and number of thermal cycles from a mission profile. Unfortunately the estimated lifetime may change, depending on the used method. To suggest the correct counting technique for lifetime calculation the finite element method (FEM) was used to simulate the thermo-mechanical stresses, experienced by the power module when it is submitted to a given thermal load.

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The lifetime prediction of power IGBT modules based on realistic mission profiles is an important issue for power electronic systems that are used in applications with high lifetime requirements. Among the most demanding are railway or hybrid electrical vehicles. Figure 1 shows a schematic with all steps that are necessary during this process [5].

The mission profile transfers into motor speed, varying phase currents and DC-link voltages in the inverter. In combination with the electrical properties of the power module a power loss profile can be calculated. In combination with the thermal behaviour of the power module and the cooling system these losses are generating temperature profiles of IGBTs and diodes. The details of the lifetime estimation approach have been described in [3,5] and are not repeated here.

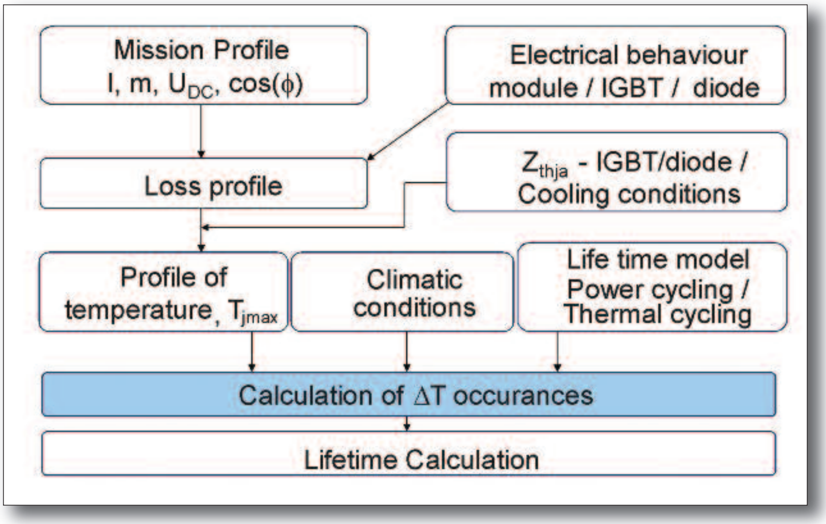


Figure 1: General approach for lifetime estimation

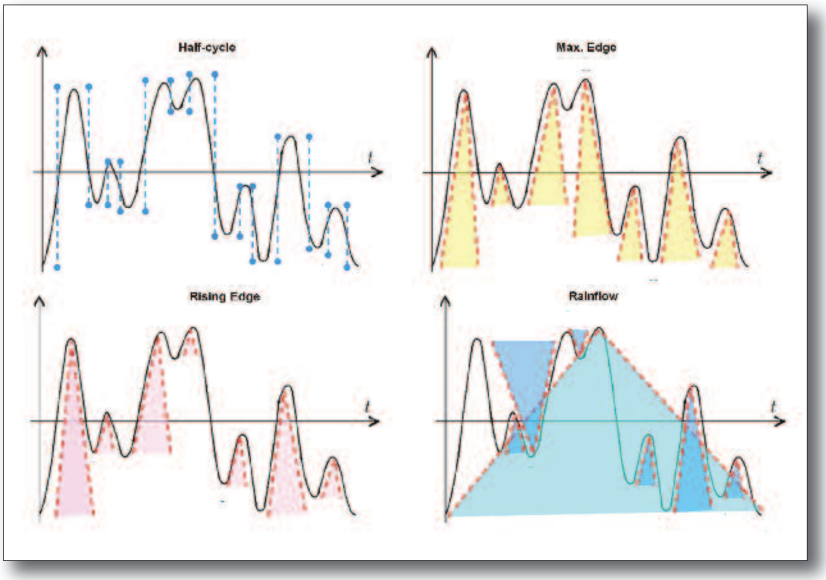


Figure 2. A graphical interpretation of different counting algorithms for an example of temperature waveform

Since the impact of ΔT has the dominant influence on reliability, it should be extracted correctly from the temperature profile. An important challenge of the process is the selection of cycle counting algorithm, because the estimated lifetime may vary, depending on the used method [4].

Various counting methods

There are lots of different counting methods like level crossing counting, peak counting, simple range counting and rainflow counting. The commonly used methods in the lifetime estimation, considered here, are:

- half-cycle peak through counting
- maximum edge peak through counting
- rising edge peak through counting
- rainflow algorithm.

The typical temperature profile is not a single, isolated temperature cycle, but a combination of many superimposed events. Entangled multiple cycles cause that their separation is not necessarily clear. However, different cycle counting algorithms interpret the cycles differently as depicted in Figure 2.

All peak-through counting methods analyze consecutive cycles, which correlates directly with the turn-on and turn-off the IGBT. In the half-cycle method, the different slopes are counted as a half cycle. In the maximum edge method, tone pair of rising and falling edge, is regarded as one cycle defined by maximum swing. For the rising edge method, every subsequent rising edge is counted as a cycle, while falling edge are ignored. The rainflow counting algorithm is

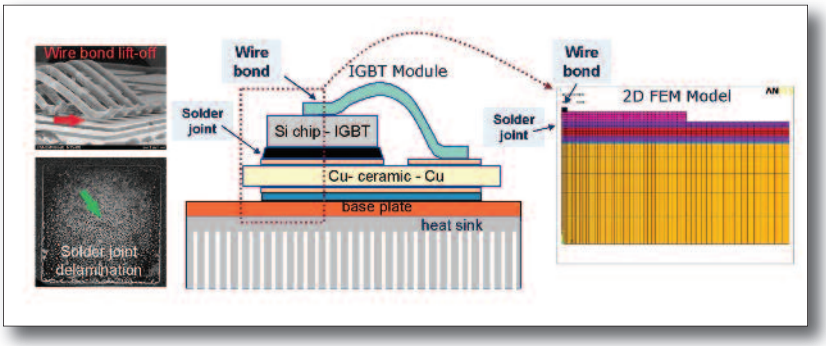


Figure 3: Major failure mechanisms (left), internal structure of the IGBT power module (middle) and FEM simulation model (right)

different from the peak through counting methods. It was developed earlier for the analysis of fatigue data in order to reduce a spectrum of varying stress into a set of simple stress reversals. In the context of lifetime estimation, the rainflow algorithm itself is interesting as a method to reduce a spectrum of varying temperatures to a set of simple temperature reversals. Practical definition of the rainflow cycle counting is explained in ASTM E-1049-85 (Reapproved 2005) [1,7].

FEM simulation of power cycling

The purpose of the FEM analysis is done to find the damage degree under cyclic thermal load like power cycling. The major failure mechanisms in the power module, due the power cycling, that have been taken into account are the fatigue of chip solder joint and the bond wire lift-off as depicted in Figure 3 (left). System solder delamination was not considered here.

Isolated power modules internally consist of a stack of different parts such as power semiconductor chips, substrates with metallization (DCB), base plate, bonding materials - solders and power interconnections - wire bonds and terminals. Based on the internal structure of the power module as sketched in Figure 3 (middle), a two dimensional, axis-symetric FEM ANSYS model was constructed, representing the vertical cross section of the device as shown in Figure 3 (right). In the simulation, nonlinear material properties were considered, especially the viscoplastic properties of solder joints and plastic, temperature dependent material properties for the aluminium wire bond.

The power cycling simulation was performed in two steps:

1. electro-thermal simulation to estimate the transient temperature distribution
2. thermo-mechanical simulation to calculate the amount of damage in the solder contact and bond wires under cyclic thermal load.

Depending on the load's magnitude, solder contact or bond wire undergo certain plastic deformation. Calculated plastic strain or deformation energy converted per temperature cycle sets an increment of damage. Crack propagation inside wire bonds and solder joints occurs in the region where the accumulated inelastic strain energy density per cycle _wp has its maximum. Therefore, the strain energy density, sometimes referred also as plastic work, was used as a measure and calculated from the area of the stress-strain hysteresis loop where plastic and creep damage occurs according to equation 1:

$$w_p = \oint_C \vec{\sigma}\, d\vec{\varepsilon}_p$$

In this formula, σ represents the stress and ε_p the plastic strain.

Counting methods investigation

In order to carry out a comparative analysis of the counting methods, appropriate thermal developments as in Figure 4 were considered.

The methodology of the correct counting technique determination is carried out in a sequence of steps:

- choice of suitable test cycles,
- FEM simulation of selected test cycles to get the Δwp value for wire bond and chip solder,
- application of the investigated counting algorithms to determine the particular temperature swings ΔT_i
- FEM simulation of these temperature swings ΔT_i to get the Δw_{pi}
- summation of the Δw_{pi} values to calculate the equivalent cycle number $\Delta w_{peqv} = (\Sigma_i \Delta w_{pi})$
- comparison of individual results and calculation of the relative error $\delta_{\%}$ between Δw_p and Δw_{peqv} according to equation 2:

$$\delta_{\%} = \left| \frac{\Delta w_p - \Delta w_{pavg.}}{\Delta w_p} \right| \cdot 100$$

Figures 5/6 show the relative error $\delta_{\%}$ by using various counting method for selected test waveforms with different combinations of amplitudes.

A significant dispersion of the results obtained from the different methods is obvious. Quantitative assess can be done based on the results summarized in Table

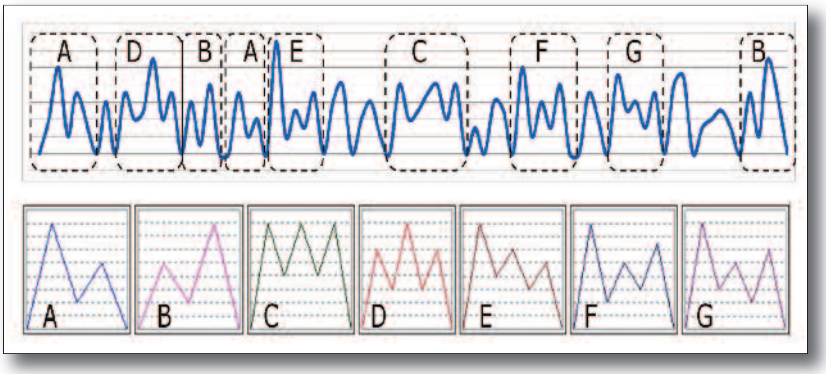


Figure 4: Example of mission profile (upper) and selected test waveforms (lower graph)

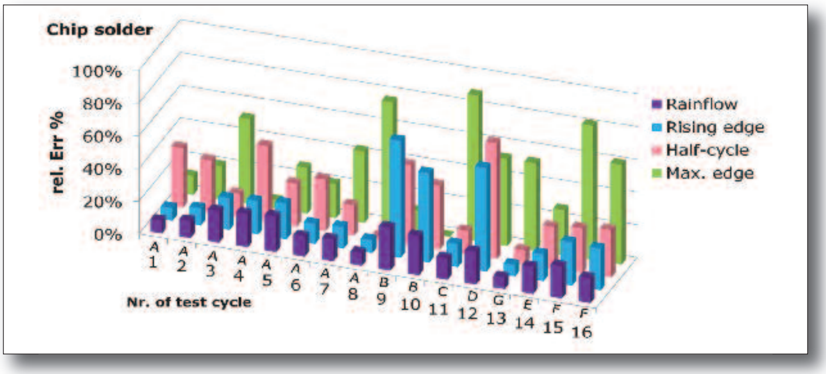


Figure 5: Relative errors ($\delta_{\%}$) in various counting methods for selected test waveforms with different combinations of amplitudes for chip solder

1, which contains the averaged values of relative errors for each counting method.

In addition, the different counting methods are compared based on a special case of a realistic short mission profile, given in Figure 7.

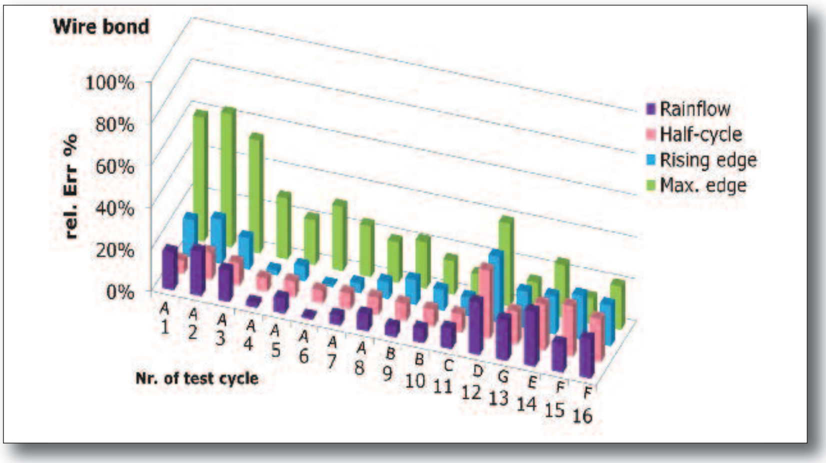


Figure 6: **Relative errors ($\delta_{\%}$) in various counting methods for selected test waveforms with different combinations of amplitudes for wire bonds**

$\delta_{\%avg}$	Rising edge	Half-cycle	Max. edge	Rainflow
Chip solder	25%	29%	44%	15%
Bond wire	15%	15%	28%	15%

Table 1: **Compilation of simulation results - averaged relative error $\delta_{\%avg}$**

The lifetime wear out in this case is calculated to be far less than the calculation of single selected waveform reveals. This is due to the superimposition of several individual cycles. The profile additionally contains a number of individual cycles. These individual cycles are interpreted identically, independent of the algorithm used.

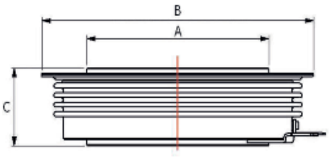
Table 2 contains the relative error of the calculation results for the short mission profile examined. This error turns out to be smaller than in the previous case of single selected waveform calculation.

The rainflow method shows the smallest error in most cases. On the basis of these results it can be concluded that the rainflow algorithm is advantageous over the peak through counting methods.

Conclusions

Simulation results show that every algorithm of temperature cycles brings some error. Based on the obtained results rainflow method can be suggested as the optimal one, since it gives the best results in terms of reduced error in most cases. The advantage of that method is that it captures not only small cycles, but the bigger one, which is often hidden in the

Part No.	V_{DRM} V	V_{RRM} V	I_{TGQM} @ C_S A	µF	V_T V	T_{JM} °C	R_{thJK} K/W	outline
G1000QC250	2500	18	1000	1.0	4	125	0.038	A
G1000QC450	4500	18	1000	1.0	4	125	0.038	A
G1000NC450	4500	18	1000	2.0	4.0	125	0.027	B
G2000HF250	2500	18	2000	4.0	2.8	125	0.022	C
G2000HF450	4500	18	2000	4.0	3.5	125	0.022	C
G2500HF250	2500	18	2500	6.0	3.1	125	0.022	C
G3000TF250	2500	18	3000	5.0	2.5	125	0.015	D
G3000TF450	4500	18	3000	6.0	4.0	125	0.015	D



Outline	A mm	B mm	C mm
A	38	60	26
B	47	75	28
C	66	112	26
D	75	108	26

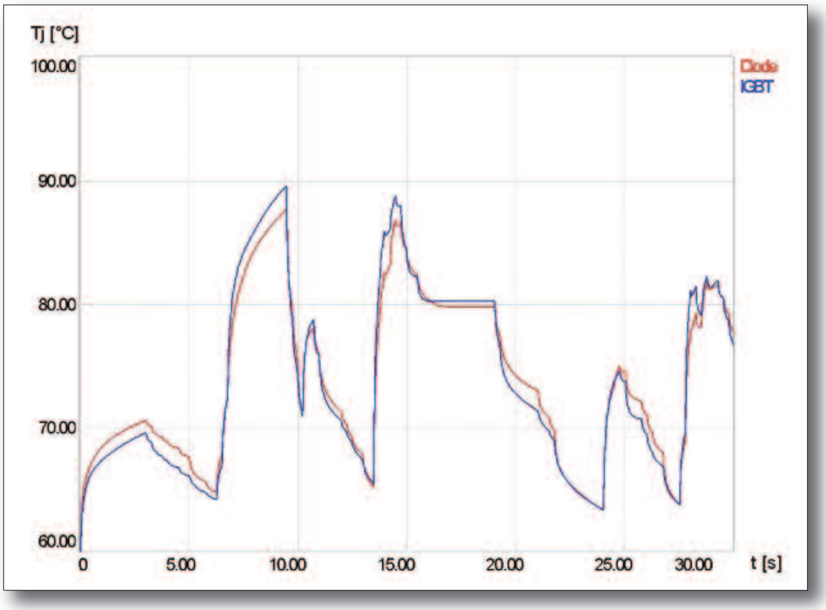


Figure 7: **Example of a short mission profile**

actual runs. In case of adverse ripple-shaped load cases, other investigated peak through counting algorithms miss the largest ΔT, which usually has the biggest influence on the lifetime. For these algorithms manual correction of automatically extracted cycles is required.

	Rising edge	Half-cycle	Max. edge	Rainflow
$\delta_{\%}$	19%	21%	27%	11%

Table 2: **Simulation results for example of mission profile (Figure 7) - relative error $\delta_{\%}$**

Literature

[1] ASTM International: E 1049-85 (Reapproved 2005) Standard Practices for Cycle Counting in Fatigue Analysis.

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[7] Rainflow Counting Algorithm for MATLAB. http://www.mathworks.com/matlabcentral/fileexchange/3026-rainflow-counting-algorithm