From vehicle drive cycle to reliability testing of Power Modules for hybrid vehicle inverter

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Abstract

In hybrid electrical vehicles (HEV) the battery, motor and inverter are the core elements of the electric drive train. In the inverter power semiconductors, usually packaged in a module, are used. To qualify such power modules for the use in HEV amongst others Power cycling and Thermal cycling tests have to be performed. These tests mainly ensure the reliability of the module regarding thermal stress conditions over the vehicle lifetime. This paper discusses the requirements on such power semiconductor modules in terms of reliability, and lifetime in HEV. A general approach is presented to evaluate duty cycles and thermal conditions and estimate required test cycles. Based on a water cooled Power module this approach is performed and test cycles are calculated.

1 Introduction

A main component of the hybrid drive system is the electric drive combined with the internal combustion engine. For variable speed operation of the electric drive the use of power electronics components is essential. Power electronics components in a hybrid electric vehicle have to fulfil requirements that are strongly dependent on the mounting conditions, cooling system and operation strategy. It significantly differs by level of mechanical shock, vibrations, absolute temperature and temperature cycling.

Amongst others power cycling and thermal cycling tests have to be performed to ensure the function over the vehicle lifetime.

Power Cycling and thermal cycling tests are performed under strong test conditions to reduce test time. A process is needed to convert real vehicle drive cycles into required test cycles. As development of the power electronics components and technology starts much earlier compared to the vehicle availability a virtual process utilizing simulation is advantageous.

2 Estimation of required test cycles from vehicle operation

The estimation of test cycles requires the knowledge of system information as well as information of the power electronics components. Figure 1 shows a schematic with all steps that are necessary during this process.

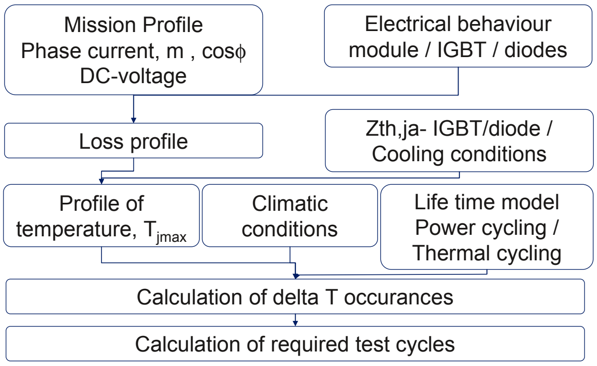

Fig. 1: general approach for estimation of required test cycles

The mission profile of the vehicle results in the motor speed and varying phase currents and DC voltages in the inverter. In combination with the electrical properties of the power module a 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 on the IGBTs and diodes. Considering the climatic conditions temperature cycling occurrences can be identified. Life time models are needed to transform thermal cycling during the vehicle operation and coolant temperature change into test cycles, with accelerated test conditions.

3 Calculation of loss profile

The loss profile is influenced by different parameters.

$$P = \mathrm{f}(\mathrm{I_L}, \mathrm{V_{DC}}, m, \cos(\varphi), \mathrm{f_s}, \mathrm{T_J}) \qquad (1)$$

Beside the current I_l and DC voltage V_{DC}, the modulation index and power factor, which is for sinusoidal waveform equivalent to the cos(φ), have a strong influence on the loss sharing between IGBT and diode. Also switching frequency and junction temperature have to be considered.

3.1 Calculation of modulation index and power factor

One commonly used type of motor speed adjustment of hybrid system uses a PWM inverter with PWM controller which can control both voltage and output frequency. The modulation index is used for Volts per Hertz control method. Below the base point, the motor operated with constant V_L/f_L ratio, where V_L is the amplitude of motor phase voltage and f_L is the synchronous frequency applied to the motor. Above this point, the motor operates under-excited.

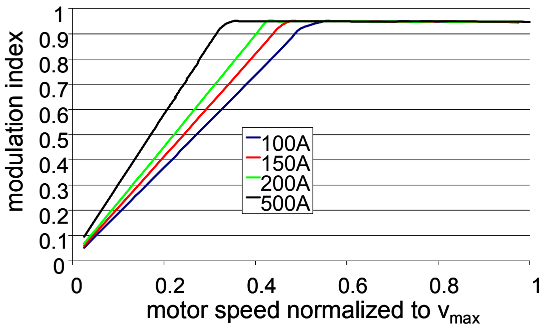

Fig. 2: modulation index as a function of motor speed and current

As show in figure 2, the modulation index can be described as a function of motor speed and current. It is necessary to consider this when calculating the IGBT and diode losses, as for low modulation index the losses are more evenly shared between IGBT and diode. The power factor is depending on the dimensioning and type of motor used in the hybrid system. It can be described as a function of motor speed and motor torque, respectively motor current. The power factor of the considered motor reduces with increasing motor speed at low current. This is shown in figure 3. It is complicated to describe the dependency in a closed formula. Therefore a look up table is utilized to implement calculation of modulation index and power factor.

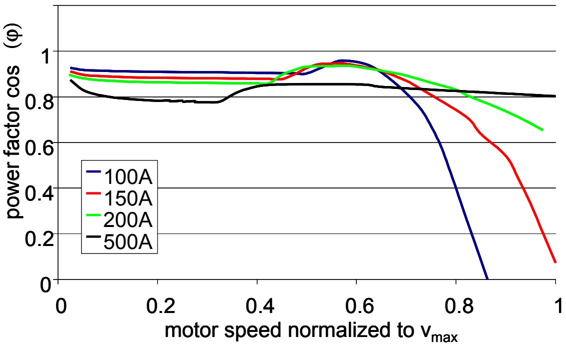

Fig. 3: power factor as a function of motor speed and current

3.2 Calculation of IGBT and diode losses

The calculation of power losses is based on averaging the conduction and switching losses for sine-triangle modulation assuming a sinusoidal output current. For the calculation of IGBT and diode losses a model based on linear approximations, e.g. for the device's forward characteristics, the derivation of switching losses and assumptions e.g. for the recovery energies are applied [1, 2, 3].

The conduction losses of the IGBT and Diode are calculated with formula 2 and 3, where r, V_{CE0}, r_D and V_{F0} are temperature dependent.

$$P_{IGBT\_DC} = \frac{I^2 r}{8} + \frac{I \cdot V_{CE0}}{2\pi} + m \cdot \cos(\varphi) \cdot \left(\frac{I^2 r}{3\pi} + \frac{I \cdot V_{CE0}}{8} \right) \qquad (2)$$

$$P_{Diode\_DC} = \frac{I^2 r_D}{8} + \frac{I \cdot V_{F0}}{2\pi} - m \cdot \cos(\varphi) \cdot \left(\frac{I^2 r_D}{3\pi} + \frac{I \cdot V_{F0}}{8} \right) \qquad (3)$$

For the IGBT switching losses a linear dependency from current and voltage gives a good approximation.

$$P_{IGBT\_SW} = \frac{f_{sw}}{\pi} \cdot \left(E_{on\_nom} + E_{off\_nom} \right) \cdot \frac{\hat{i}}{I_{nom}} \cdot \frac{V_{DC}}{V_{nom}} \cdot \left(\frac{T_J}{T_{nom}} \right)^{\alpha} \qquad (4)$$

For the dependency of Diode switching losses from current an extended function is used. This is necessary to describe these losses at low current operation. A bilinear approach from [1] would overestimate the losses for small currents.

$$P_{Diode\_SW} = \frac{f_{sw}}{\pi} \cdot E_{rec\_nom} \cdot \left(\frac{\hat{i}}{I_{nom}}\right)^{\kappa} \cdot \frac{V_{DC}}{V_{nom}} \cdot \left(\frac{T_J}{T_{nom}}\right)^{\alpha} \quad (5)$$

The coefficients for formula 1 to 5 can be easily extracted from Power module datasheet. Switching losses at nominal currents and as a function of current are included. Also the coefficients for the forward voltage can be extracted from the described output characteristics of the IGBT inverter. To prevent the use of an electrical-thermal coupled simulation model, a good approximation is to calculate the losses for the maximum operation temperature.

Figure 4 shows an example of a loss profile for a vehicle drive cycle. As the described curve mostly consists of motoring conditions, IGBT losses outbalance compared to diode losses.

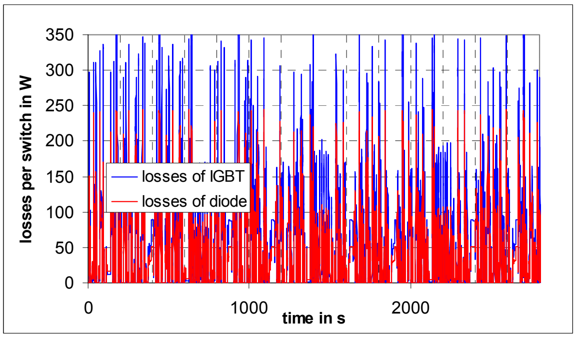

Fig. 4: example of a transient loss profile for a vehicle mission profile

4 Thermal model generation

To calculate a temperature profile from the losses, a thermal model of the power module including the cooling system is necessary. A direct cooled Power module with Pin-Fin base plate, as shown in figure 5, is investigated.

Fig. 5: investigated direct cooled HybridPACK 2 power module with Pin-Fin copper base plate

3D- transient FEM simulations are performed to extract the thermal model for the temperature on the IGBT and the diode. As degradation of DBC to base plate solder joint could be lifetime limiting for the power module, a thermal model for the solder joint is needed as well.

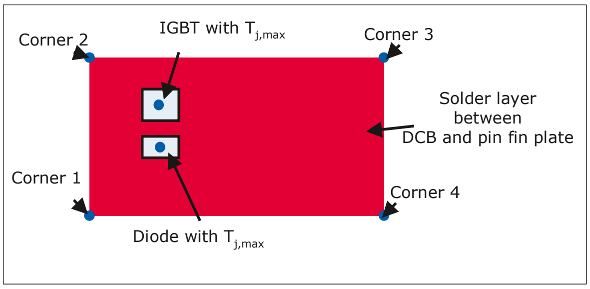

Fig. 5: temperatures of solder joint, which are considered for the thermal model

The temperature of the solder joint during operation of the power module isn't homogenous, especially for the direct cooled power module. Due to reduced heat spreading, only the solder directly below the chip is heated up. As shown in figure 6, the corners of the solder joint have low temperature increase. Typically degradation of the solder joints starts at the corners.

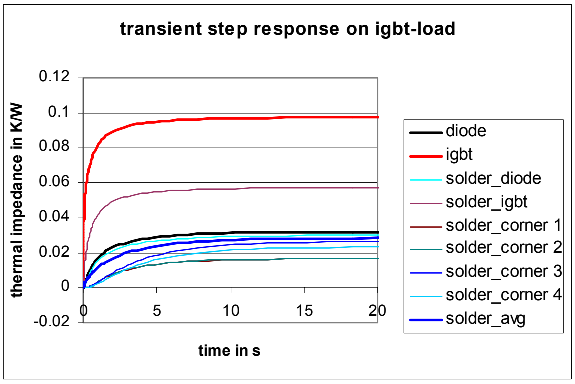

Fig. 6: transient step response of temperature on IGBT-load

To consider also the maximum temperatures below the chip an average temperature for the corner and below the chips is used in the thermal model.

$$T_{solder\_avg} = \frac{1}{6} \cdot (T_{s\_c1} + T_{s\_c2} + T_{s\_c3} + T_{s\_c4} + T_{s\_IGBT} + T_{s\_diode}) \quad (6)$$

The transient step response of the temperature on the diode results in higher temperature, as less silicon area is included in the power module. During the operation, losses in the diode generates a temperature increase on the IGBT.

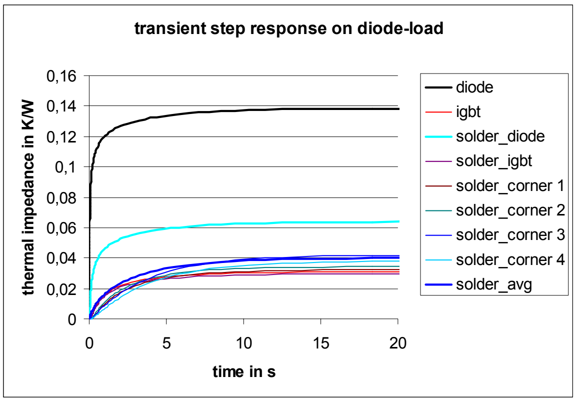

Fig. 7: transient step response of temperature on diode-load

This effect has to be included in the thermal model. The thermal model consists of capacitor/resistor pairs. Five pairs are needed to describe the transient behaviour of the IGBT and the diode. The coupling between IGBT and diode can be described with only on capacitor/resistor pair as well as the temperature behaviour of the average solder joint temperature.

Figure 8 shows the whole model, which is used for the temperature profile calculation. Simulations are performed with Simplorer, but the model can be implemented in several other Spice based simulation tools as well. On the one hand in the yellow coloured areas of the model the losses are generated by the IGBT, on the other hand in green coloured areas losses are generated by the diode.

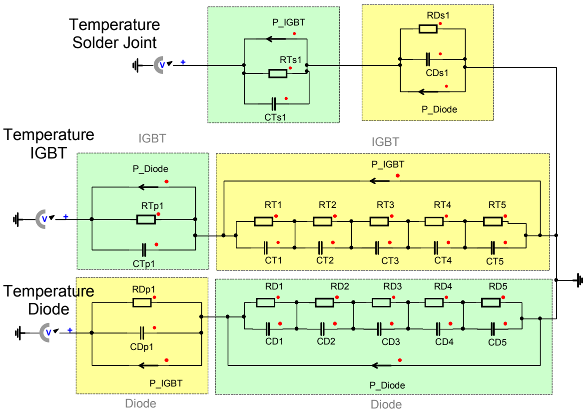

Fig. 8: transient step response of temperature on diode-load

To verify the model, infrared measurement of a power module without potting and lid were realized. Also the transient step response of the IGBT was measured to ensure the simulation model.

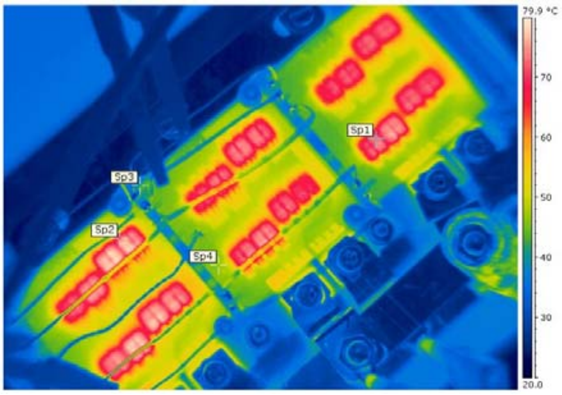

Fig. 9: Infrared measurement of power module while operating all IGBTs

5 Calculation of temperature profile and extraction of thermal cycles

With the thermal model and the loss profile a temperature profile for the IGBT, diode and the solder joint can be carried out. Although the losses in the IGBT for the example, shown in figure 10, are higher compared to the diode, the temperature level is similar, because of the different thermal resistance values. A maximum temperature increase of 15K for the average solder temperature occurs.

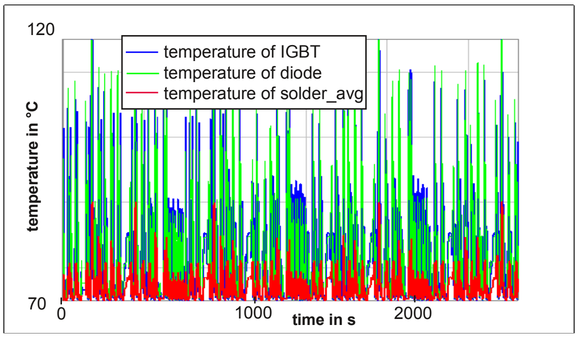

Fig. 10: example of a temperature profile for a vehicle mission profile

An automatic algorithm is implemented in Simplorer to extract temperature swings. Figure 11 describes how this information is extracted from the temperature profile. Additional information for the temperature cycle is useful, as the power cycling capability is also influenced by the duration of loss generation, the current and the junction temperature [5].

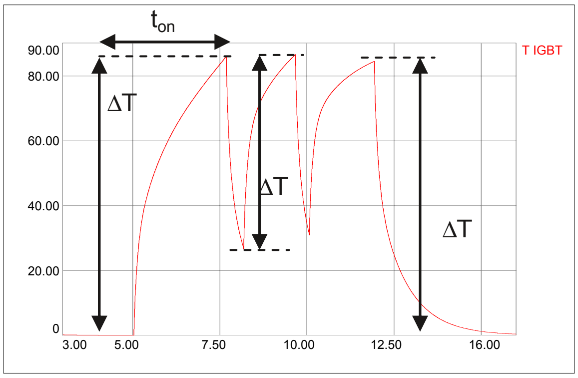

Fig. 11: extraction of ΔT and t_{on} from the simulated temperature profile

6 Conversion of duty cycle to test cycles

6.1 Conversion of IGBT and Diode Power Cycles

The lifetime limitation due to junction temperature swing is mainly related to wire bond lift off and differs from the mechanism of solder joint degradation [4]. Therefore different failure acceleration functions have to be taken into account when calculating test cycles. Formula 7 describes how each duty cycle can be transformed to test cycles with specific test conditions. The formula is based on a large number of power cycling tests performed with different power modules [5]:

$$\frac{n_{duty\_cycle}}{n_{test\_cycle}} = \frac{\Delta T_{duty}{}^{-3.483} \cdot e^{\frac{1917}{Tj,duty+273}} \cdot t_{on,duty}{}^{-0.438} \cdot I_{duty}{}^{-0.717}}{\Delta T_{test}{}^{-3.483} \cdot e^{\frac{1917}{Tj,test+273}} \cdot t_{on,test}{}^{-0.438} \cdot I_{test}{}^{-0.717}} \quad (7)$$

Assuming a test cycle with $\Delta T = 100K$, ΔT_{test} of 100K at T_{jmax}=150°C, $t_{on,test}$=2s at 800A the number of test cycles can be calculated by summation of all transformed duty cycles:

$$n_{test,sum} = \sum_{i=1}^{p} n_{test,i} = \sum_{i=1}^{p} n_i \frac{100^{-3.483} \cdot e^{\frac{1917}{150+273}} \cdot 2^{-0.438} \cdot 800^{-0.717}}{\Delta T_{j,i}{}^{-3.483} \cdot e^{\frac{1917}{Ti+273}} \cdot t_{on,i}{}^{-0.438} \cdot I_i{}^{-0.717}} \quad (8)$$

For 10000 occurrences of the temperature profile for a vehicle mission profile in figure 10 the number of test cycles is calculated. Following table shows an example of some calculated transformed duty cycles:

i	ΔT_i in K	$T_{j,i}$ in °C	I in A	ton in s	n_i	$n_{test,i}$
:	:	:	:	:	:	:
:	:	:	:	:	:	:
20	35	110	300	<2	30000	107
21	35	110	280	2<4<6	30000	102
22	35	115	280	6<8<10	60000	204
23	45	120	360	6<8<10	50000	1408
:	:	:	:	:	:	:
:	:	:	:	:	:	:

Table 1: example for ΔT occurrences during vehicle operation and transformation to test cycles

Assuming 10000 occurrences of the described vehicle profile in figure 10, the calculation results in approx. 4000 power cycles with ΔT_{test} of 100K at T_{jmax}=150°C, $t_{on,test}$=2s on time for the IGBT and the diode.

Passive temperatures due to heating up the coolant from ambient to operation temperature require additional test cycles. These cycles have a much longer cycling time. Formula 7 is developed for short time cycling operations. It is assumed, that power on time larger 15s have no effect on the power cycling capability.

T_IGBT_diode_max [°C]	125	125	125	125	125	125	125	125	125	125	125	125	
T_water_min = Tc_min [°C]	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	
delta Tc [K]	150	145	140	135	130	125	120	115	110	105	100	95	
Cycles per day	2	2	2	2	2	2	2	2	2	2	2	2	
days per year	5	10	10	20	25	30	45	50	50	50	35	35	365
Cycles per year	10	20	20	40	50	60	90	100	100	100	70	70	
Cycles per lifetime	150	300	300	600	750	900	1350	1500	1500	1500	1050	1050	15 years
equivalent number of ΔT100K, Tjmax=150°C	952	1632	1391	2356	2478	2485	3092	2825	2302	1858	1038	818	**23227**

Table 2: ΔT, occurrences in IGBT and diode during heating up of coolant and transformation to test cycles

11000 coolant temperature cycles are assumed over the vehicle lifetime. As shown in table 2 based on the formula a number of 23000 required power cycles are calculated. Therefore a total number of 27000 required power cycles is estimated.

6.2 Conversion of Solder joint thermal cycles

For solder joint reliability of leadfree solder joint a different acceleration exponent is reasonable for the transformation of test cycle to duty cycle. From [6] a range of values between 2 to 2.5 can be extracted. Formula 9 describes how thermal cycling of the solder joint can be transformed to test cycles.

$$\frac{n_{duty\_cycle}}{n_{test}} = \left(\frac{\Delta T_{duty\_cycle}}{\Delta T_{test}}\right)^{-(2\,..2.5)} \quad (9)$$

To reduce the effect of acceleration exponent for Power modules typically thermal cycles with

ΔT80K are performed. This amplitude is an average value for the temperature swing due to heating up the coolant from ambient. The ambient temperature is assumed to vary between -25°C to 30°C from winter to summer time. The temperature swing in the solder joint with a maximum value of 15K has a negligible effect on the required test cycle, but it increases the maximum temperature for the passive cycles to 85°C in the solder joint.

T_solder_max [°C]	85	85	85	85	85	85	85	85	85	85	85	85	
T_water_min = Tc_min [°C]	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	
delta Tc [K]	110	105	100	95	90	85	80	75	70	65	60	55	
Cycles per day	2	2	2	2	2	2	2	2	2	2	2	2	
days per year	5	10	10	20	25	30	45	50	50	50	35	35	365
Cycles per year	10	20	20	40	50	60	90	100	100	100	70	70	
Cycles per lifetime	150	300	300	600	750	900	1350	1500	1500	1500	1050	1050	15 years
equivalent number of ΔT80K for acceleration exponent :2	284	517	469	846	949	1016	1350	1318	1148	990	591	496	**9974**
equivalent number of ΔT80K for acceleration exponent :2,4	322	576	513	906	995	1041	1350	1285	1089	911	526	427	**9941**
equivalent number of ΔT80K for acceleration exponent :4	536	890	732	1193	1201	1147	1350	1159	879	654	332	235	**10309**

Table 3: ΔT, occurrences in the solder joint between DCB and Pin-Fin plate during heating up of coolant and transformation to test cycles

In Table 3 the required test cycles are calculated for three different acceleration exponents of formula 9. The resulting number of cycles is approx. 10000 and nearly independent of the exponent.

7 Summary and conclusions

In this paper a general approach is presented to evaluate duty cycles and estimate required test cycles for power modules in hybrid drive applications. The process offers to calculate test requirements at an early stage of the development process. Several simulation steps are performed including loss calculation, thermal simulation and thermal cycle extraction. The estimation of required test cycles is based on a lifetime model which reflects the capability of the investigated power module. Some correlation of variables used in the model restricts the model to ranges of test conditions of selected data. Therefore, authors strongly recommend not applying the model without consulting experts at Infineon Technologies.

For the investigated direct cooled power module a number of 27000 required power cycles are calculated. A number of approx. 10000 required thermal cycles with amplitude of ΔT 80K are calculated.

Acknowledgement:

The authors would like to thank S. Schennetten for determining power module loss parameters and T. Hong for thermal measurement.

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