Reliability estimation with uncertainties consideration for high power IGBTs in 2.3 MW wind turbine converter system

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A B S T R A C T
This paper investigates the lifetime of high power IGBTs (insulated gate bipolar transistors) used in large wind turbine applications. Since the IGBTs are critical components in a wind turbine power converter, it is of great importance to assess their reliability in the design phase of the turbine. Minimum, maximum and average junction temperatures profiles for the grid side IGBTs are estimated at each wind speed input values. The selected failure mechanism is the crack propagation in solder joint under the silicon die. Based on junction temperature profiles and physics of failure model, the probabilistic and deterministic damage models are presented with estimated fatigue lives. Reliably levels were assessed by means of First Order Reliability Method taking into account uncertainties.

1. Introduction

Over the past decades, wind turbine (WT) technology has developed enormously and the size of WTs has increased to the multi-megawatt level. In 1985, the peak power of WTs was in the range of 50 kW, whereas nowadays it reaches even 7000 kW [1]. It is anticipated that in the future, WTs with power ratings as high as 20,000 kW will be developed. The driving force behind the continuous increase in size is the cost of energy, which decreases as WTs get larger. With other words, large WTs produce cheaper energy than smaller WTs.

Insulated gate bipolar transistors (IGBTs) are one of the critical components in a wind turbine (WT) power converter systems. Standard wire-bonded IGBT has a multi-layered structure made of materials with various CTEs (coefficients of thermal expansion) like silicone, solder, copper, and ceramics [2]. WT power production is directly influenced by wind speeds, which define the IGBTs mission profiles. During its operation, an IGBT faces power losses in switching of high voltage and current, which causes temperature fluctuations in all layers of IGBT. Thus, temperature profiles are the one of the main stresses that an IGBT is facing during its useful life.

Three dominant failure mechanisms of standard wire-bonded IGBTs are bond wire lift-off, solder joints cracking under the chip and solder joints cracking under the ceramics. This research is focused on the solder cracking failure mechanism that propagates under the chip.

2. Wind turbine converter system design

A Siemens 2.3 MW WT was chosen for the study with the main parameters given in Table 1, see [3]. Since not many details of the power converter of the wind turbine were provided, it was necessary to do some basic power converter design and choose an appropriate IGBT for the selected WT.

The most commonly used converter configuration as two-level converter topology was chosen to generate three-phase line-to-line voltage at 690 Vrms [3], as shown in Fig. 1. Based on the rated active power of the wind turbine and the power factor range, the rated apparent power was calculated to be 2555 kVA. By taking into account the apparent power and rated voltage, the current rating of the converter was calculated to be 2138 A. Since the output AC line voltage was 690 Vrms, a DC link voltage of 1100 VDC was settled. Also, a simple inductive filter design was done by allowing a 20% voltage drop on the filter, resulting in an inductance of \(\frac{1}{2\pi f}\). The switching frequency of grid side inverter was set at 1950 Hz.

An appropriate IGBT module FZ3600R17HP4_B2 by Infineon [4], which satisfies the design requirements and is optimized for wind power application, is chosen in the case study of this paper. The selected IGBT has a maximum voltage rating of 1700 V and current rating of 3600 A. The voltage rating of IGBT is appropriate for working DC link voltages of 1100 V, because the failure rate due to cosmic radiation is kept at an acceptable level. The IGBT with a current rating of 3600 A was chosen in order to add safety margin to the design.

The high current rating of the FZ3600R17HP4_B2 module is achieved by connecting in parallel multiple low-current rating IGBT chips. The module contains both IGBTs and free-wheeling...
diodes (24 IGBTs and 12 diodes). In order to get a three-phase power converter, 12 FZ3600R17HP4_B2 modules are needed.

3. Junction temperatures estimation

When inputting the power curves of wind turbine, converter topology, the voltage and power ratings, as well as some information from the datasheet of chosen IGBT module, the electrical operation and condition of converter can be established. Next, the following steps were taken within the simulation software in order to estimate the IGBT junction temperature profile with the change of wind speed.

The IGBT loss model share the same idea as described in [5]. The loss in freewheeling diodes of IGBT module shares the similar calculation method as IGBT. It is noted that the switching loss profile of the chosen IGBT module only have the test condition at 125 °C on datasheet, therefore the loss models in this paper are considered temperature independent during the simulation, that means the loss may be more or less over-estimated depending on the temperature difference to 125 °C. The used thermal model for IGBT module is shown in Fig. 2, also see Table 2 and [6], where: $T_j$ is junction temperature, $T_c$ is case temperature, $T_h$ is heat sink temperature, $T_a$ is ambient temperature. The thermal impedance from junction to case $Z_{TD(j\rightarrow c)}$ is modeled as a multi-layers Foster RC network, as shown in Fig. 2. Each of the thermal parameters of the thermal model can be found from the manufacturer datasheets.

The resistance $R_w$ will decide the steady state mean value of junction temperature, and the thermal capacitance (with time constant $\tau$) will decide the dynamic change or fluctuation of the junction temperature.

It is noted that normally the IGBT manufacturer will only provide thermal parameters inside IGBT modules with Foster RC network (from junction to case). In order to establish the complete thermal models from junction to the ambient, the thermal impedance of $Z_{TD(j\rightarrow c)}$ has to be transferred to the equivalent Cauer RC network to facilitate the thermal impedance extension outside IGBT modules [7].

The temperature of heat sink $T_h$ is more stable (i.e. less fluctuated with larger thermal capacitance) in comparison with the junction temperature $T_j$ in properly designed heat sink system. Therefore, the heat sink temperature is set to the value directly related to the average loss of the whole IGBT module and the thermal resistance of heat sink. Yet, the heat sink temperature in a real application depends on ambient temperature and the heat sink system design.

The grid side IGBT junction temperature minimum, maximum and mean values were simulated and estimated for the wind speeds in the range of cut-in and cut-out wind speeds, assuming ambient temperature was 28 °C, (see Table 3).

For the given operational wind profile and Table 3, IGBT-operational junction temperature profiles were estimated (termed $T_{j\min}$, $T_{j\max}$ and $T_{j\text{mean}}$). An operational wind profile is defined as a profile

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WT rated power</td>
<td>2300 kW</td>
</tr>
<tr>
<td>2</td>
<td>PF range</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>Voltage level</td>
<td>690 V</td>
</tr>
<tr>
<td>4</td>
<td>Converter type</td>
<td>Full scale</td>
</tr>
<tr>
<td>5</td>
<td>WT type</td>
<td>Onshore/Coast</td>
</tr>
</tbody>
</table>

Table 1
Wind turbine main parameters.
during which a WT generates electricity. Thus, operational wind profile consists of wind speeds that were between cut-in and cut-out wind speeds. It was assumed that there was enough time for an ambient temperature to propagate into the IGBT module, during 3 h of operation. This would linearly affect IGBT-operational junction temperatures, e.g. if wind speed was 3 m/s and ambient temperatures data were available for 3 h averages at 10 m height, which were designated for a 5 MW power WT located near Thyborøn, Denmark with latitude 56.71° and longitude 8.20°. Wind profile power law was used to estimate the operational wind speeds at 100 m height with wind shear exponent of 0.1. IGBT-operational junction temperature profiles adjusted for the ambient temperatures are depicted in Fig. 3 for 150 h of operation at 100 m height.

4. Physics of failure in solder cracking under silicon die

In this research, reliability is assessed based on physics of failure approach. Major failure mechanisms in IGBT power modules are bond wire lift-off and solder cracking under silicon die and ceramics. In this paper, the failure mode is defined by SnAg solder cracking between the silicon chip and the direct copper bonded (DCB) ceramics.

The required number of cycles for a crack to reach the length \( L \) in the solder interconnect can be expressed by:

\[
N_f(\Delta\varepsilon_p) = \frac{L}{a(\Delta\varepsilon_p)^b}
\]

where \( L \) is the solder interconnect length in millimeters, \( a \) and \( b \) are constants, \( N_f \) is the required number of cycles to failure or number of cycles for the crack to reach \( L \) and \( \Delta\varepsilon_p \) is the average accumulated plastic strain per cycle.

If failure is defined as a 20% reduction of the total interconnect area, then the constants \( a \), \( b \) are estimated for SnAg solder interconnect between baseplate and ceramic, \( a = 0.00562 \) and \( b = 1.023 \) (see [8–10]). As far as this research is concentrated on crack propagation in solder joints under silicon die, it is assumed that solder thicknesses either between die and ceramic or ceramic and baseplate are almost the same.

During the operation the silicon (Si) die, solder (SnAg) between Si and copper (Cu) of upper layer of DCB ceramic are affected by high temperature loadings. By melting SnAg and Cu together a new intermetallic layer of \( \text{Cu}_5\text{Sn}_6 \) is formed, which is brittle and sensitive to operational temperatures (see [2]). High plastic strains will dominate because of high thermal mismatch between Si, \( \text{Cu}_5\text{Sn}_6 \) and Cu. This process initiate accumulated creep development and fatigue cracks propagation at the edges of solder joints, where shear stress is high.

To express accumulated plastic strain per cycle for SnAg solder by means of temperature loading, it was suggested by [11] to define it by:

\[
\Delta\varepsilon_p = A(\Delta T)^B(\alpha_{\text{Cu}} - \alpha_{\text{Si}}) e^{(\frac{Q}{R T_m})}
\]

where \( A, B, Q \) and \( R \) are constants, \( \alpha_{\text{Cu}}, \alpha_{\text{Si}} \) CTEs of Cu and Si, \( \Delta T \), \( T_m \) are temperate range and mean.

Based on finite element analysis data in [9]), the constants in (2) were estimated, as it is described in [11]. However, a miscalculation was observed in [11] reported values. The corrected values were estimated and reported in this paper, see Tables 4 and 5 (where “log” is a notation for natural logarithm). Based on a statistical analysis of the model in (2) all the constant terms were significantly different from zero with 2.5% level of significance, besides \( \log(A(\alpha_{\text{Cu}} - \alpha_{\text{Si}})) \) term. This indicates that “no intercept” model would be statistically an appropriate choice (see Table 5). The activation energy “\( Q \)” was estimated to be 0.55 eV, \( R_T^{\text{app}} = 99.88\% \) and the error term for “no intercept” model

### Table 2
Parameters for thermal model of the used IGBT.

<table>
<thead>
<tr>
<th>Thermal impedance</th>
<th>( Z_{\text{Th}(K/W)} )</th>
<th>( R_{\text{JCT}} ) (K/kW)</th>
<th>( R_{\text{D Th}} ) (K/kW)</th>
<th>( \tau_{\text{JCT}} ) (s)</th>
<th>( \tau_{\text{D Th}} ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector 1</td>
<td>0.544</td>
<td>0.001</td>
<td>1</td>
<td>0.0011</td>
<td>0.012</td>
</tr>
<tr>
<td>Sector 2</td>
<td>1.328</td>
<td>0.0122</td>
<td>2.19</td>
<td>0.012</td>
<td>0.0012</td>
</tr>
<tr>
<td>Sector 3</td>
<td>3.982</td>
<td>0.0071</td>
<td>5.11</td>
<td>0.0744</td>
<td>0.012</td>
</tr>
<tr>
<td>Sector 4</td>
<td>1.197</td>
<td>2.64</td>
<td>1.44</td>
<td>2.63</td>
<td>–</td>
</tr>
<tr>
<td>( R_{\text{BTh}} )</td>
<td>1</td>
<td>10</td>
<td>9.7</td>
<td>4</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 3
Wind speed vs. IGBT junction temperatures (°C).

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>( T_{\text{max}} )</th>
<th>( T_{\text{min}} )</th>
<th>( T_{\text{mean}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>33</td>
<td>32.5</td>
<td>32.8</td>
</tr>
<tr>
<td>4</td>
<td>36.6</td>
<td>35.7</td>
<td>36.2</td>
</tr>
<tr>
<td>5</td>
<td>42.8</td>
<td>41.0</td>
<td>41.9</td>
</tr>
<tr>
<td>6</td>
<td>51.9</td>
<td>48.8</td>
<td>50.4</td>
</tr>
<tr>
<td>7</td>
<td>61.6</td>
<td>57.1</td>
<td>59.4</td>
</tr>
<tr>
<td>8</td>
<td>75.5</td>
<td>69.0</td>
<td>72.3</td>
</tr>
<tr>
<td>9</td>
<td>90.0</td>
<td>81.3</td>
<td>85.7</td>
</tr>
<tr>
<td>10</td>
<td>95.0</td>
<td>85.5</td>
<td>90.3</td>
</tr>
<tr>
<td>11</td>
<td>97.5</td>
<td>87.7</td>
<td>92.6</td>
</tr>
<tr>
<td>12</td>
<td>98.5</td>
<td>88.4</td>
<td>93.5</td>
</tr>
<tr>
<td>25</td>
<td>98.5</td>
<td>88.4</td>
<td>93.5</td>
</tr>
</tbody>
</table>

### Table 4
Estimated parameters for the model described in (2), temperature in Kelvin.

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>Estimates</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \log(A(\alpha_{\text{Cu}} - \alpha_{\text{Si}})) )</td>
<td>–5.66</td>
<td>0.257</td>
</tr>
<tr>
<td>( B )</td>
<td>3.72</td>
<td>0.000</td>
</tr>
<tr>
<td>( Q/R )</td>
<td>4609.54</td>
<td>0.019</td>
</tr>
</tbody>
</table>

![Fig. 3. IGBT junction temperature profiles.](image-url)
was estimated to be LogNormal distributed with mean and standard deviation equal to 1.07 and 0.39, respectively.

5. Reliability estimation based on deterministic damage model

It was assumed that the selected IGBT consists of 24 parallel connected IGBT chips, composed from Infineon Technologies SIGC186T170R3 chips, see [12]. Based on product specification list, each chip dimension was defined as 13.63 mm in length and 13.63 mm in width. Failure of each chip was defined as 20% shrinkage of the total solder interconnected area under the chip, which defines crack length of 0.72 mm.

Based on rain-flow counting algorithm for each IGBT-operational junction temperature profile, the temperature means and temperature ranges were estimated. Deterministic accumulated damage was used to estimate reliability level for each temperature profile based on Palmgren–Miner rule, see [13].

Component stress is expressed by temperature fluctuations and pair of $\Delta T_i, T_{m_i}$ are defined as the temperature range and temperature mean at level $i$, so damage level by the time $t$ is expressed as:

$$ D(t) = \sum_{i} \frac{n_i(\Delta T_i, T_{m_i})}{N_i(\Delta T_i, T_{m_i})} $$  \hspace{1cm} (3)

and deterministic failure time would be defined by $t = t_f$, where $D(t_f) = 1$.

Combining (3), (2), and (1), deterministic damages were estimated for each IGBT-operational junction temperature profiles. With the increment of 30 h, cumulative damages were estimated from the beginning of temperature profiles to the end of each time interval, so that large fluctuations were taken into the account.

Based on threshold model defined by crack length of 0.72 mm and deterministic damage failure criteria $D(t) = 1$, the deterministic fatigue failure times were estimated, see Table 7.

6. Reliability estimation based on probabilistic damage model

As it was explained in [14,15], many parameters in damage accumulation model are to be estimated. Parameters estimation procedure contains uncertainty and variability that should be accounted for into the reliability estimation. In addition, any physical model attempts to approximate the physical phenomenon that it is modeled for, thus by using a physical model the uncertainty related to the model should be accounted as well. Uncertainties might be separated in two groups: aleatory and epistemic uncertainties. Aleatory uncertainties are related to the inherent variation of the environment and/or physical phenomenon, their spread cannot be reduced and their variability directly affecting on the outcome, e.g. variability of the wind speed at the given location and at the given height. Epistemic uncertainty is a variability related to the lack of knowledge and poor model, these uncertainty can be reduced by better models, by more measurements (samples), etc., e.g. variability related in accumulated plastic strain estimation by temperature mean and temperatures range by the proposed model in (2).

Structural reliability approaches incorporate uncertainties in reliability estimation through defined limit state function(s) as well as family distributions and variabilities of the model parameters. The updated limit state function was proposed by [14] to be defined by:

$$ g(t, \Delta m, \varepsilon_a, \varepsilon_m) = \Delta m - \sum_{i} \frac{n_i(\Delta T_i, T_{m_i}, \varepsilon_a, \varepsilon_m)}{N_i(\Delta T_i, T_{m_i}, \varepsilon_a, \varepsilon_m)} $$  \hspace{1cm} (4)
where $\Delta m$ was an uncertainty associated to Miner’s rule (linear damage model uncertainty), $\varepsilon_i$ was estimation uncertainty associated to the constant “$a$” in (1) and $\varepsilon_m$ was a model uncertainty defined in (2).

Coefficients of variations (COV), means and distributions are summarized in Table 6 (see conclusion for a discussion on the selected values).

First Order Reliability Method (FORM) is a method of estimating the reliability index ($\beta$) based on non-linear failure functions. This method allows estimating invariant reliability index irrespective to the limit state function (safety margin) formulation. This index also known as the Hasofer and Lind reliability index (see [13]). Independent stochastic variables that construct limit state function are transformed to the standard normal stochastic variables. Based on these variables, the limit state function is transformed to the standardized domain. In standardized domain, the reliability index is defined as the shortest distance from the origin to the limit state function. To find the shortest distance, the numerical differentiation with iterative algorithm is applied (see [13]). Cumulative probability from the standard normal distribution function at the negative reliability index estimates probability of failure. For the limit state function defined in (4), the cumulative distribution function is defined by:

$$F_Y(t) = P(g(t, \Delta m, \varepsilon_i, \varepsilon_m) \leq 0) = \Phi(-\beta)$$

where $\Phi$ is the standard normal distribution function and $\beta$ is a reliability index.

Defined limit state function in (4) was employed for reliability estimation by FORM. Available (total) wind profile was for 30 years period with 3 h averages, and thus IGBT-operational junction temperature profiles were available for this period as well. Several IGBT-operational junction temperature profiles were combined (held consecutively) to have enough loading profile to observe failures. Based on these profiles the rainbow counting algorithm was applied and pairs of $\Delta T_i, T_{mj}$ were estimated. The limit state function in (4) was updated in time domain based on the beginning of wind speed profile to the end of each time interval, so that large fluctuations were taken into the account. The difference quotient in numerical differentiation was set to $10^{-8}$ and error for reliability index estimation was set to $10^{-3}$. Reliability indices, cumulative failure probabilities and B10 (or L10, 90% reliability level) lives based on each operational junction temperature profile during the time were found (see Figs. 4 and 5 and Table 7). The reliability indices decrease in time for all exposed profiles, indicating an increase in probability of failure with time. The rates of decrease between exposed profiles are different due to the severity of them. This approach for reliability estimation takes into account the various parameter uncertainties related to the physics of failure models.

However, estimated B10 reliability levels are bigger than it was expected. The reason of it most likely is inaccurate estimated constants for (2) and (1). This might be corrected by experimental results or by more firm model development. Next, reliability is assessed by applying the described updated limit state function with uncertainties consideration in FORM.

7. Conclusion

Reliability estimation for the single failure mode of IGBT in WT application based on physics of failure model was performed. Uncertainties, related to the linear damage accumulation law, estimation of the accumulated plastic strain per cycle and the parameter “$a$”, were included in reliability estimation. It was shown that reliability levels get more conservative if uncertainties are accounted for in reliability estimation. In this research, FORM and updated limit state function were used for reliability assessment.

Described physics of failure model was for a failure mechanism defined as crack propagation in a solder joint between die and DCB upper layer. Failure was defined as 20% shrinkage of interconnection area. Therefore, estimated reliability levels are representative for the defined failure criteria only.

It is under the research and industry interest to identify the practical shrinkage area (the lowest allowable area that will define the failure), which should be determined from the failed components, observed from the field or laboratory experiments. Also, determine practical model(s), their constant(s) and/or define new physics of failure models. In addition, for the laboratory experiments it would be desirable to run at $T_{\text{max}}$ profile in order to estimate and/or calibrate parameters in shorter calendar-time.

Model parameters have an important part in reliability estimation, accurate parameters will lead to reliability estimation precision. The following is a summary for parameters associated in this research:

- parameters for (1) were established in [8], however no model error, MSE and/or coefficient of determination were reported.
- parameters for (2) were estimated based on the data provided in [9], however data in [9] have a single observation for each level and at least two observations are desired for each level to increase the model degrees of freedom.
- parameters for (4) are summarized in Table 6, $\varepsilon_i$ and $\varepsilon_m$ are related to the above bullets. Variability and distribution of $\Delta m$ are assumptions that have been made. However, the actual distribution and variability might be calibrated from the experimental values.

One of the limitations of this study is that only one of the failure mechanisms of wire-bonded IGBTs was considered. The bond-wire lift-off and the cracking of the solder joint under the ceramics were not considered in this paper, but it might be extended for future work.

Also, it is assumed that the temperature of the solder joint under the Si chip is the same as the temperature of the Si chip (junction temperature). This will certainly result in lower predicted lifetime(s). The accuracy of the lifetime estimation could be improved by developing a thermal model, which estimates the temperature of the solder joint under the chip.

Next, for further research it would be desired to investigate IGBTs reliability as a parallel system with chips and diodes subsystems by taking the correlation into account.

The approaches/methods presented in this paper could be extended to other WT types, if enough data about the mission profile, power converter and power devices are available.

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