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Prediction of Bond Wire Fatigue of IGBTs in a PV Inverter Under Long-Term Operation

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***Abstract*— Bond wire fatigue is one of the dominant failure mechanisms in IGBT modules. However, the bond wire lifetime is not easily predictable and measurable to date due to several challenges. To tackle this problem, this paper proposes a Monte Carlo based analysis method to predict the lifetime consumption of bond wires in a Photovoltaic (PV) inverter under long-term operation. The parameter distributions of IGBTs due to manufacturing variation and the annual stress profiles due to intermittent nature of solar irradiance and ambient temperature are taken into consideration. The proposed method enables a more realistic lifetime prediction with a specified confidence level compared to the state-of-the-art approaches. A study case on the IGBT modules in a 10 kW three-phase PV inverter demonstrates the procedure and the results of the analysis. Finally, the lifetime distribution of bond wires permits to estimate the risk of unreliability of a single IGBT in a Photovoltaic (PV) inverter.**

I. Introduction

Nowadays, special attention has been dedicated to the reliability and maintenance cost of grid-connected transformerless Photovoltaic (PV) inverters [1], [2]. The challenge is to satisfy the ambitious product requirements for the Photovoltaic market - long operating life under both normal and abnormal operations [3], [4].

Life limiting components of PV inverters have been widely discussed. According to a survey based on field experiences from semiconductor manufacturers, 31% of the 56 responders have found out that power semiconductor devices are the main contributor to failures in power converter applications, including PV inverters [5]. Insulated Gate Bipolar Transistors (IGBTs) are the most commonly used devices due to their high current density capability and ease of drive requirements; however, the reliability analysis of the IGBTs in PV inverters is usually not well treated.

Among different IGBT failure mechanisms, bond wire degradation is one of the dominant life limiting factors [6]. Thus, several approaches for the bond wire lifetime prediction have been presented in the literature. In the past, the Military-Handbook-217F [7] based on constant failure rate models was widely used to predict the lifetime of the components, which turned to be obsoleted in 1995. An updated version (Military-Handbook-217H) is further discussed in [8]. Nowadays, analytical models and physics-of-failure models are of more interest for the life assessment of power semiconductor modules, which are proved to be more accurate if properly used [4], [9], [10], [11] and [12].

The challenges to predict the IGBT lifetime in PV inverters lie in the following aspects: a) it is necessary to differentiate various wear out failure mechanisms and failure sites (e.g., bond wire, solder) [13], [14]; b) each lifetime model has its limitations due to specific technologies, failure mechanisms, and certain environmental and operational stresses (e.g., temperature range, cycle time of temperature excursions) [12]; c) the stress levels of IGBTs are varying with the mission profiles (i.e., solar irradiance and ambient temperature during the life cycle) due to the intermittency of solar power [15], [16]; and d) the end-of-life of a large population of IGBTs with same specifications (i.e., same product part number) varies in field operations due to variances in manufacturing process and statistical properties of lifetime models.

The research in [9], [10] and [11] discusses the differentiation of various failure mechanisms and reveals that the power cycling with heating times below one minute has an effect on the wear out of bond wires. A long-term mission profile based analysis approach has been presented in [15] and [16]. However, there is still a lack of study on the effect of variances in IGBT parameters and statistical properties of lifetime models, which is crucial to determine the wear out failure distribution of IGBTs along operation time. Each failure mechanism may be influenced by some uncertain parameters which can be treated as random variables following a certain probability distribution (e.g., normal, exponential, Weibull). The impact of the parameter variations in the output time to failure analysis can be evaluated by sampling each of the probability distributions applying the Monte Carlo method. In IGBTs, such parameter variations may be associated to: 1) operational and environment stresses of PV inverters (e.g., solar irradiance and ambient temperature), 2) lifetime of IGBTs with the same part number in a large population of PV inverters may be different due to variations of the materials properties, manufacturing processes and uncertainties in the applied lifetime model, and 3) degradation resulting in parameter time-dependent changes.

In PV applications, IGBTs that can fulfil a specific lifetime requirement are usually readily available. Thus, a practical issue for PV inverter designers is how to select the IGBTs with minimum cost and countable risk of unreliability. This paper proposes a Monte Carlo analysis based method to study the

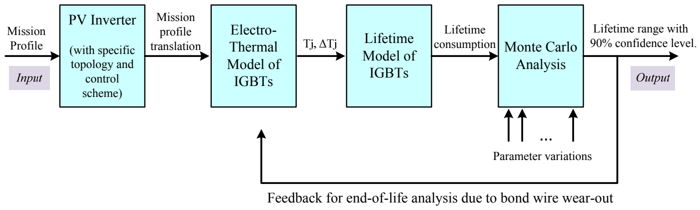

Fig. 1. Proposed Monte Carlo based method for bond wires lifetime analysis.

impact of parameter variations and the statistical properties of lifetime models, on the bond wire fatigue of IGBTs in a PV inverter. The presented study contributes to tackle the issue by predicting the bond wire lifetime range with a specified confidence level, allowing the accumulated failure analysis due to bond wire fatigue along with the operating time.

II. Proposed Monte Carlo Based Lifetime Prediction Method

The proposed Monte Carlo based method for bond wire lifetime analysis is shown in Fig. 1. The procedure includes four major steps. A long-term mission profile (i.e., solar irradiance and ambient temperature) is applied as the input. The output is the lifetime of bond wires of the IGBTs applied in PV inverters with a specified confidence level (e.g., 90%). Moreover, the importance of end-of-life analysis loop feedback (1) permits to extend the study to different IGBT candidates to assist the selection of IGBTs. The flow chart presented in Fig. 2 helps to clarify the steps of the proposed procedure.

A. Mission profile translation

In a real operating environment, power semiconductor devices are exposed to electrical and thermal stresses that are mainly influenced by the non-uniform ambient temperature and solar irradiances. Thus, a long-term mission profile (measured ambient temperature and solar irradiance) of the real field where the converter will perform is considered. The ambient temperature and the solar irradiance have been measured for one year with a sampling rate of 1 second per data at Aalborg University (Denmark) from October 2011 to September 2012 [17] and [18].

The long-term mission profile must be correctly transformed into the corresponding stress load of power semiconductor devices. Basically, the annual power loss of power semiconductor devices have been calculated by three steps:

1) A PV string model is applied to calculate the output power from the PV arrays [15]. The corresponding current and voltage values based on a 10 kW PV panel installation at different ambient temperatures and solar irradiances can be obtained.
2) The annual input power fed into the converter is acquired based on the available mission profile and the relationship between the output power of the PV array and the solar irradiance and ambient temperature. Each operation point from the mission profile is treated as follows: i) one of the four different ambient temperatures is selected as a function of the mission profile ambient temperature, the closest ambient temperature is chosen, ii) the input power fed into the converter is obtained through an interpolation as a function of the solar irradiance, for the ambient temperature previously selected.
3) The annual power loss of the converter is experimentally obtained and the annual power loss per single IGBT is obtained based on simulations, due to the inability to measure the power loss per chip. Further details of this procedure will be given in Section III.

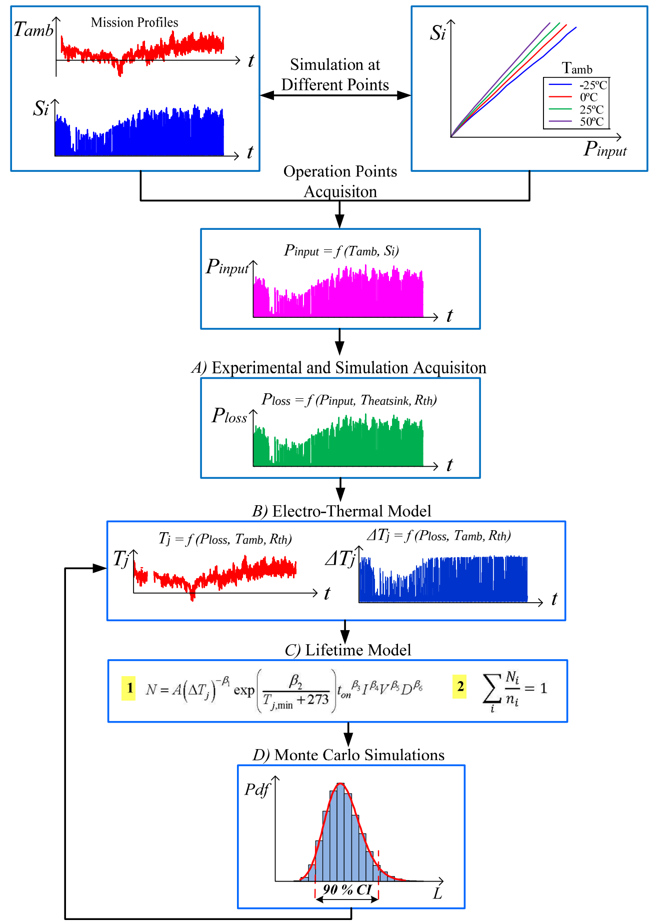

Fig. 2. Algorithm of the Monte Carlo based method for bond wires lifetime analysis: T_{amb} - ambient temperature, S_i - solar irradiance, P_{input} - inverter input power, P_{loss} - total inverter power loss, T_j - junction temperature, ΔT_j - junction temperature fluctuation, R_{th} - thermal resistance, L - lifetime, Pdf - probability distribution function.

B. Electro-thermal model

An electro-thermal model is applied to obtain the realistic thermal stress of a single IGBT. The IGBT junction temperature, T_j, and its fluctuation, ΔT_j, can be estimated according to the method in [17] and [19], where the thermal impedance from junction-to-heat sink, $Z_{th(j-h)}$, is modelled as a multi-layer Foster RC network, which is given in the IGBT module datasheet.

C. Lifetime model of IGBTs

Among the three well-known dominant failure mechanisms of IGBT modules, this study focuses on bond wire lift-off [4]. The number of cycles to failure, *N*, can be estimated based on the lifetime model presented in [12] for the 4^{th} generation of IGBTs as:

$$N = A \cdot (\Delta T_j)^{-\beta_1} \cdot \exp\left(\frac{\beta_2}{T_{j,min} + 273}\right) \cdot t_{on}^{\beta_3} \cdot I^{\beta_4} \cdot V^{\beta_5} \cdot D^{\beta_6} \tag{1}$$

where ΔT_j is the junction temperature fluctuation, $T_{j,min}$ is the minimum junction temperature, t_{on} is the heating time of the power cycling, V is the blocking voltage of the chip, D is the bonding wire diameter, I is the current per wire and A, β_1, β_2, β_3, β_4, β_5 and β_6 are the adjusted parameters published in [12].

By applying the Palmgren-Miner linear cumulative damage model [20], the accumulated damage for one year mission profile can be estimated.

D. Monte Carlo analysis

The previous lifetime model for bond wire lifetime assessment gives a fixed accumulated damage due to bond wire wear out. But the uncertainties in IGBT parameter variations and the statistical properties of the applied lifetime model should also be taken into account. Therefore, a statistical approach to analyse IGBTs lifetime performance subjected to parameter variations will be carried out in detail in Section III. The effect of these variations is analysed by means of Monte Carlo simulations. Finally, the lifetime of bond wires of the IGBTs applied in PV inverters with a specified confidence level can be estimated, as it is shown in Fig. 1

III. Analysis of IGBT Bond Wires Lifetime in the 10 kW PV Inverter

To demonstrate the method, a study case on a 10 kW three-phase 2 Level Voltage Source Inverter (2L-VSI) for grid-connected PV application is analyzed by simulations and experimental tests. Three 1200 V / 50 A 4^{th} generation of IGBT technology and aluminium bond wire packaging are adopted in the PV inverter. Fig. 3 and Table I show the topology and the specifications of the PV inverter, respectively. The PV inverter topology consists of a boost stage, a three-phase 2 Level Voltage Source Inverter (2L-VSI) and a passive LCL filter. The current controller consists of a Proportional Resonant (PR) controller with Harmonic Compensators (HC) [21]. The LCL-filter is designed according to [22]. Additionally, an annual mission profile [17] with a resolution of one second per data of solar irradiance and ambient temperature is used in the analysis.

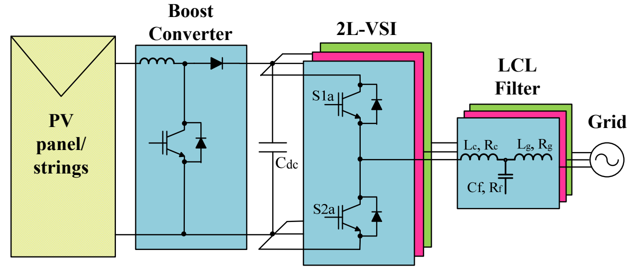

Fig. 3. 10 kW three-phase 2L-VSI topology.

TABLE I
Specifications of the three-phase 2L-VSI

Three-phase 2L-VSI design ratings	
Rated power	$P = 10kW$
Output phase voltage	$V_n = 230V$ (RMS)
Switching frequency	$F_{sw} = 7kHz$
IGBT module power ratings (SK50GB12T4T)	
Collector-emitter voltage	$V_{ce} = 1200V$
Collector current	$I_c = 50A$
LCL-filter parameters	
Inverter side	$L_c = 3.6mH$; $R_c = 0.04\Omega$
Grid side	$L_g = 8.6mH$; $R_c = 1.72\Omega$
Filter capacitor	$C_f = 4.7\mu F$; $R_f = 0.4\Omega$

A. IGBT Power Loss Analysis

The IGBT power loss is analyzed by simulations under different power levels based on the electrical characteristics from the IGBT datasheet. Therefore, a mapping relationship between the power loss and the inverter power level can be derived, allowing the translation of the annual mission profile into the power losses of the IGBT modules.

For the simulation results, the available power from the PV panels has been obtained by means of a PV string model that applies a BP365 module, as presented in [15]. By doing so, the corresponding current and voltage values for a 10 kW panel installation at four different ambient temperatures (-$25°C$, $0°C$, $25°C$ and $50°C$) and 16 different solar irradiances (0 W/m^2 to 1500 W/m^2, in steps of 100 W/m^2) have been obtained. Fig. 4 (a) and (b) shows the annual and daily inverter input power from the PV panels based on the mission profile, respectively. To avoid the overloading of the PV inverter, the maximum power limit is set as 11 kW (10% above the rated power).

The next step is to obtain the annual power loss of the IGBTs. Therefore, an experimental setup of the 10 kW three-phase 2L-VSI as shown in Fig. 5 is built up. The experimental setup has been tested at different power levels so the total power losses of the three 1200 V / 50 A 4^{th} generation of IGBT modules have been measured while the heatsink temperature is treated as constant, due to the large heatsink thermal capacitance [16]. Since it exists a dependence between the power losses and the heatsink temperature, its correlation has been experimentally calculated. Therefore, the total power losses of the IGBTs consisting the PV inverter can be represented as a function of the inverter input power and the heatsink temperature. Results are presented in Fig. 4 (c) and

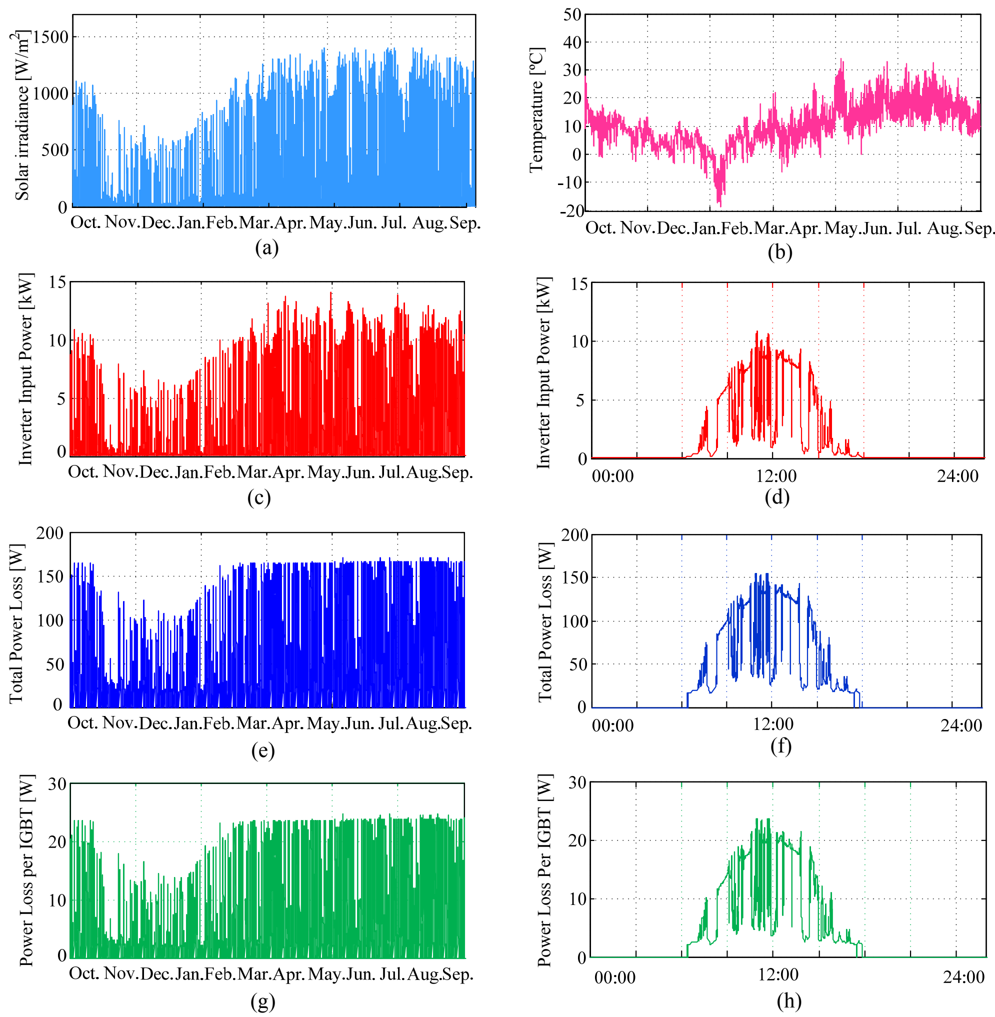

Fig. 4. Loading of the 10 kW Three-phase 2L-VSI (1 second per sampling data):(a) solar irradiance mission profile, (b) ambient temperature mission profile, (c) annual available power from PV panels, (d) daily available power for PV panels, (e) annual total power loss of the IGBTs, (f) daily total power loss of the IGBTs, (g) annual power loss profile of single IGBT and (h) daily power loss profile of single IGBT.

(d).

Furthermore, due to the inability to measure the power losses of a single IGBT (not including the free-wheeling diode) in the experimental setup, the 10 kW PV inverter has been analyzed by simulations in PLECS/Simulink.

Since the accuracy of the translation between the mission profile and the power losses per IGBT is important, experimental results of the 10 kW PV inverter are compared side-by-side with the simulation results in Fig. 6. It can be noted that the simulation results are well in agreement with the measurements, especially when the power is above 3 kW. It reveals the feasibility to obtain the power loss profile based on simulations that relies on the datasheet. Fig. 4 (e) and (f) shows the annual and daily power losses of a single IGBT based on the mission profile.

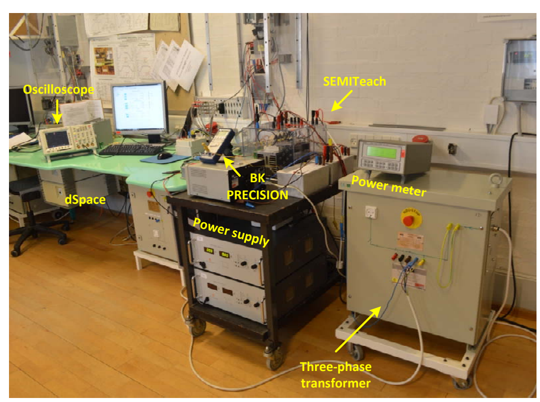

Fig. 5. Experimental setup of the three-phase 2L-VSI.

B. IGBT Thermal Stress Analysis

The three 1200 V / 50 A IGBT modules integrated in the 10 kW PV inverter are built without base plate [10]. The IGBT junction temperature and its fluctuation can be estimated according to the method in [17] and [19].

The estimated heatsink temperature, $T_{heatsink}$, and junction

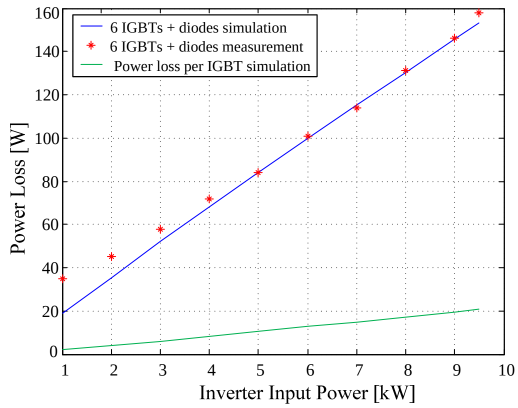

Fig. 6. Measured and simulated power losses.

temperature T_j for a year mission profile is shown in Fig. 7. The heatsink temperature is calculated based on the ambient temperature fluctuations from the mission profile data and the annual power losses obtained via experiments. The junction temperature is calculated based on the heatsink temperature and the power loss of a single IGBT which has been estimated via simulations.

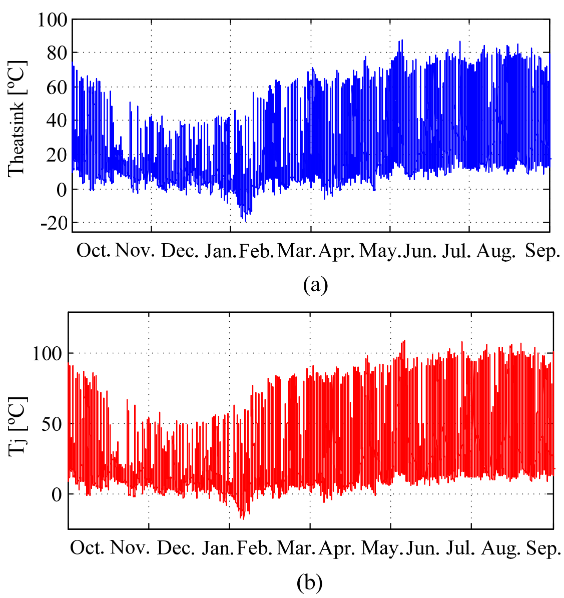

Fig. 7. Thermal loading of a single IGBT in the 2L-VSI PV inverter based on a year mission profile (1 second per sampling data), a) heatsink temperature and b) IGBT junction temperature.

C. Bond Wire Lifetime Consumption Analysis

In the real field, the solar irradiance and ambient temperature fluctuation causes non-uniform thermal stresses over the year depending on different seasons, weather conditions and locations. The knowledge of the mission profile for a particular site offers the possibility to calculate the lifetime consumption.

Bond wire degradation strongly depends on power cycling and low frequency thermal cycling in the sub-second to seconds regime. Typically, longer cycles (e.g., above 60 seconds) contribute to solder base degradation rather than bond wire degradation. Consequently, the lifetime consumption in percentage of the total available life is calculated for two types of temperature stresses: power cycling due to the line frequency and thermal cycling with heating time, t_{on}, less than 60 seconds due to the solar irradiance (SI) and ambient temperature T_{amb} fluctuations. Further details are given in the following to justify the reason of the applied lifetime model and the lifetime consumption analysis.

1) Justification of applied lifetime model: An analytical model has been applied to predict the bond wire lifetime consumption for an annual mission profile. Analytical models are easier to use because they do not require the knowledge of physical properties of the power semiconductor devices [23].

One of the most widely used analytical lifetime model to estimate the lifetime consumption for the 4^{th} generation of IGBTs is the Bayerer model is adopted in this paper [12].

Since the heating time, t_{on}, below one minute highly contributes to the bond wire end-of-life, the dependence of t_{on}, as a function of the number of cycles to failure is considered according to [24], which is given by,

$$\frac{N_{cyc}(t_{on})}{N_{cyc}(1.5s)} = \left(\frac{t_{on}}{1.5s}\right)^{-0.3} \quad ; \quad 0.1s < t_{on} < 60s \qquad (2)$$

2) Accumulated damage analysis of line frequency power cycling: By applying the Palmgren-Miner linear cumulative damage model [20], it is assumed that the damage is linearly accumulated. The whole life-cycle can be divided into fractions that can be summed up to obtain the accumulated damage due to line frequency power cycling as follows,

$$Damage_{50Hz} = \sum_i \frac{n_{50Hz}}{N_{50Hz}} \qquad (3)$$

where n_{50Hz} is the number of temperature cycles due to the line frequency cycling and N_{50Hz} is the number of cycles to failure for the same cycle type and same stress as n_{50Hz}. Failure occurs when the total accumulated damage reaches 1.

The number of cycles to failure has been calculated based on (1), (2) and the algorithm presented in Fig. 2. The junction temperature and its fluctuation is extracted from the mission profile for each measurement point, the heating time has a fixed periodicity (t_{on} = 0.01s) and the rest of the parameters (V, D, I) are kept constant. Results are summarized in Table II.

TABLE II
ANUUAL ACCUMULATED DAMAGE DUE TO LINE FREQUENCY AND LOW FREQUENCY THERMAL CYCLING.

Loading	t_{on}	Accumulated damage	Lifetime consumption
Line frequency	0.01 s	0.0257	2.57 %
T_{amb} & SI	[1-60] s	0.0027	0.27 %

3) Accumulated damage analysis of low frequency thermal cycling: The second type of cycling exposed by the IGBTs is caused from the solar irradiance and ambient temperature fluctuations. Since temperature cycles do not follow a repetitive pattern in terms of amplitude and duration, they are counted using a Rainflow counting algorithm [25]. Fig. 8 illustrates the distribution of junction temperature cycling obtained with the Rainflow counting algorithm. It is appreciated that most of the temperature cycles have a very low amplitude (ΔT_j), which means that the contribution of this type of cycling to the bond wire accumulated damage per year is trivial.

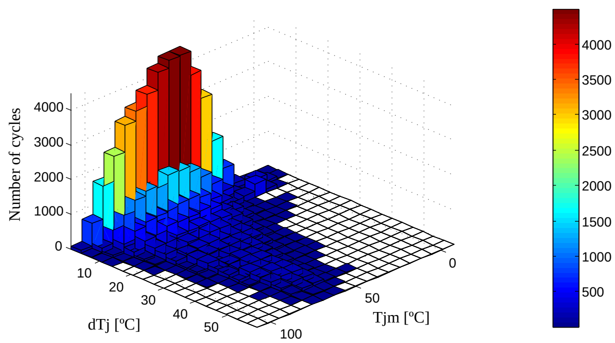

Fig. 8. Annual junction temperature counting based on a Rainflow algorithm.

Once again, the Palmgren-Miner cumulative damage model is applied to obtain the lifetime consumption due to low frequency thermal cycling by means of equation (4). Notice that only temperature cycles with heating time durations bellow 60 seconds are taken into account.

$$Damage_{SI\&T_{amb}} = \sum_i \frac{n_{SI\&T_{amb}}}{N_{SI\&T_{amb}}} \quad (4)$$

where $n_{SI\&T_{amb}}$ is the number of cycles due to low frequency thermal cycling and $N_{SI\&T_{amb}}$ is the number of cycles to failure for the same cycle type and same stress as $n_{SI\&T_{amb}}$. Results are summarized in Table II.

It is thus apparent that the accumulated damage corresponding to the low frequency thermal cycling (solar irradiance and ambient temperature) has an insignificant contribution to the bond wire end-of-life consumption for the mission profile considered.

D. Monte Carlo Based Analysis on the Variances in IGBT Parameters and Lifetime Model

This section investigates the reliability analysis of IGBTs considering the long-term operation and the relevant parameter variations. In order to obtain a realistic end-of-life range with a specified confidence level, two types of uncertainties are considered: 1) parameter uncertainties in the applied lifetime model, and 2) parameter uncertainties due to manufacturing process for the same IGBT part number. Regarding the first type of uncertainty, each lifetime model has its limitations due to the specific test conditions, device technologies and failure mechanism considered. The applied lifetime model in this study, the Bayerer model (1), estimates the power cycling capability for the new generation of 1200V-IGBT4 modules, the variables used in the model are limited to the test condition range, which is defined in [12], and also the model fitting coefficients are given within an uncertainty range. Therefore, the uncertainty of the fitting coefficients corresponding to the junction temperature and its fluctuation (β_1 and β_2) are taken into account. Regarding the second type of uncertainty, the end-of-life of a large population of IGBTs with the same specification and same part number varies in field operations due to variances in the manufacturing process. IGBT parameter variations are defined in the manufacturer datasheet with a typical, maximum and minimum value (e.g. on-state voltage, $V_{ce,on}$, gate-emitter threshold voltage, $V_{ge,th}$). $V_{ce,on}$ variations will be taken into account in this analysis, since they have a direct effect on the IGBT conduction losses, which leads to T_j and ΔT_j variations.

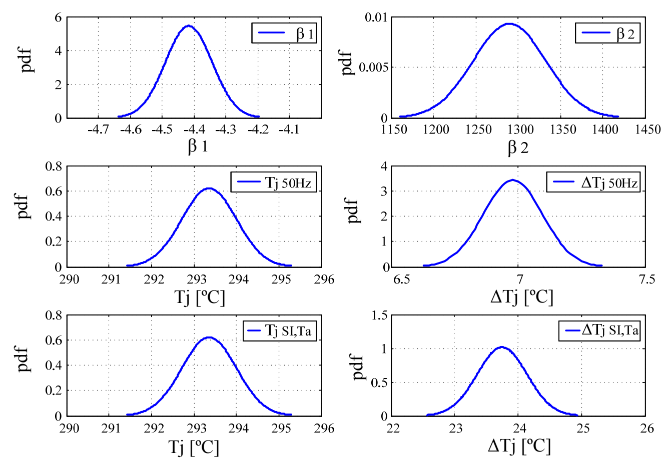

Fig. 9. Probability distribution functions of the parameters under analysis: β_1 and β_2 are the fitting coefficients of the applied lifetime model, $T_{j,50Hz}$ and $\Delta T_{j,50Hz}$ are the junction temperature and its fluctuation for the line frequency power cycling, and $T_{j,Si,Ta}$ and $\Delta T_{j,SI,Ta}$ are the junction temperature and its fluctuation for the low frequency thermal cycling .

The bond wire lifetime prediction is based on the previous analytical lifetime model of (1) in combination with (2), the Palgrem-Miner damage model (3) and (4), and the long-term mission profile. Parameter variations have been analyzed individually and jointly. All the parameters in the analysis are modelled by means of normal probability distribution functions which can be observed in Fig. 9. β_1 is assumed to experience a 5% variation and β_2 a 20 % variation according to [12]. Consequently, the typical, maximum and minimum value of the parameter $V_{ce,on}$ is extracted from the device datasheet. The fluctuation of the parameter $V_{ce,on}$ has been simulated leading to 5% variation of ΔT_j and a 0.66% variation of T_j for the power module in the analysis. Since the mission profile is continuously changing over the whole year, the dynamical mission profile stress has been converted into equivalent static values, which produce the same degradation [26]. Results are summarized in Table III. In order to obtain the static values, first, the number of cycles to failure due to line frequency power cycling is calculated from (3),

$$N_{50Hz} = \frac{1.57 \cdot 10^9}{0.0257} = 6.1 \cdot 10^{10}\, cycles\, per\, year \quad (5)$$

The equivalent junction temperature fluctuation due to line frequency power cycling is calculated from (1) and (2) as,

$$\Delta T_{j,50Hz} = 6.98°C \quad (6)$$

Th number of cycles to failure due to low frequency thermal cycling is calculated from (4) as,

$$N_{SI\&T_{amb}} = \frac{72264}{0.0027} = 2.6 \cdot 10^{7}\, cycles\, per\, year \quad (7)$$

The equivalent junction temperature fluctuation due to low frequency thermal cycling is calculated from (1) and (2) as,

$$\Delta T_{j,\,SI\&T_{amb}} = 23.75°C \quad (8)$$

TABLE III
EQUIVALENT STATIC VALUES FOR THE ANALYSIS ON THE VARIANCES IN IGBT PARAMETERS.

	Line frequency	T_{amb} & SI
Min. junction temperature ($T_{j,min}$)	20.36 $°C$	20.36 $°C$
Accumulated damage per year (D)	0.0257	0.0027
Number of cycles per year (n)	1.57 $\cdot 10^9$	72264
Heating time (t_{on})	0.01 s	23.71 s
Number of cycles to failure (N_f)	$6.1 \cdot 10^{10}$	$2.6 \cdot 10^7$
Junction temperature fluctuation (ΔT_j)	6.98 °C	23.75 °C

1) Individual parameter variation: In order to study the sensitivity of each selected variable into the bond wire accumulated damage, a sensitivity analysis is carried out by considering individual parameter variations, while maintaining the other parameters to the mean of their distributions. The average minimum junction temperature, $T_{j,min}$, the junction temperature fluctuation, ΔT_j and the applied lifetime model parameters, β_1 and β_2 have been modelled following normal probability distribution functions. Each distribution has been sampled using Monte Carlo simulations. The number of simulations depends on the desired accuracy of the output distribution, and therefore 10000 simulations have been chosen to build up the output accumulated damage distribution to assure high accuracy.

Since there are two types of thermal stresses considered, i.e., line frequency power cycling and low frequency thermal cycling, each consumption fraction shown in Table III is summed up to obtain the total bond wire accumulated damage as:

$$Damage = Damage_{50Hz} + Damage_{SI\&T_{amb}} = 0.0284 \quad (9)$$

Fig. 10 shows the individual parameter variations on the annual accumulated damage. As can be seen, the greatest

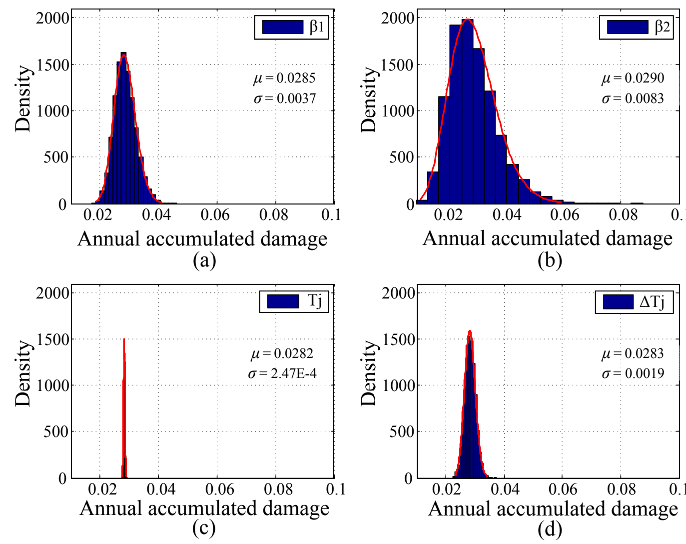

Fig. 10. Annual accumulated damage due to bond wire wear-out: a) lifetime model parameter β_1, b) lifetime model parameter β_2, c) minimum junction temperature, T_j and d) junction temperature fluctuation,ΔT_j.

standard deviations are observed for β_1 and β_2. It is now well heightened the degree of importance to consider the uncertainties of the applied lifetime model parameter. Whereas β_1 and β_2 have a standard deviation of 0.0037 and 0.0083 respectively. T_j and ΔT_j have a standard deviation of 2.5×10^{-4} and 0.0019, respectively.

2) Variation of all parameters: The second approach is to consider that all the parameters under analysis can suffer variations within the specified range.

The accumulated damage distribution due to bond wire wear out can be observed in Fig. 11 (a) with a sample of 10000 IGBTs. The accumulated failure due to bond wire of single IGBT lies between 0.017 - 0.048 accumulated damage (out of 1) with a 90% confidence level. 10% of the IGBTs are predicted to have an annual damage due to bond wire wear out less than 0.02 accumulated damage.

In order to get a clearer understanding of the above results, Fig. 11 (c) and (d) illustrates the end-of-life distribution of bond wires due to wear out. It can be noted that the estimated lifetime of a single IGBT is within 21 years to 60 years with a 90% confidence level. 1%, 5% and 10% of the IGBTs are predicted to have failure due to bond wire wear out after 17 years, 21 years, and 24 years.

IV. CONCLUSION

This paper presents a statistical approach for IGBT bond wire fatigue analysis and a guideline to evaluate its performance under relevant parameter variations. The impact of these variations is evaluated by means of Monte Carlo simulations, as a result the accumulated failure due to bond wire wear-out and lifetime range with a specified confidence level are obtained. A case study on a 10 kW PV inverter is discussed with an experimentally verified power loss profile. The bond wires in the IGBTs are estimated with a lifetime

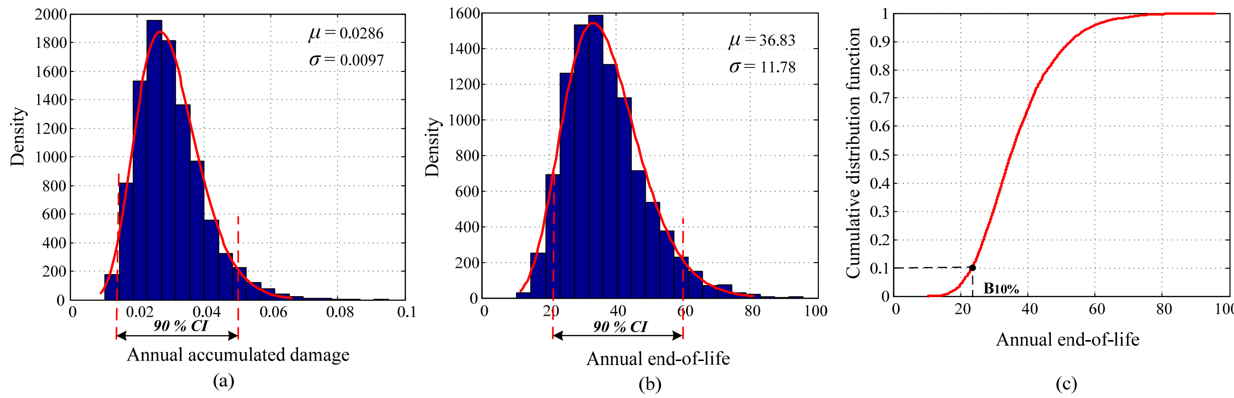

Fig. 11. Monte Carlo analysis based on bond wire wear out: a) accumulated damage probability distribution function, b) end-of-life probability distribution function, and c) end-of-life cumulative distribution function.

range from 21 years to 60 years with a 90% confidence level. The predicted accumulated failure along with the long-term operation allows the PV inverter designers to have a risk analysis of unreliability. As a result, depending on the design target (i.e., 10% risk of unreliability), the PV inverter designer can calculate which is the maximum design margin for bond wire lift-off failures and make sure that the IGBT selected fails only after the design margin. Moreover, the proposed method can be extended to other failure mechanism and to different IGBT candidates to assist the selection of IGBTs. Therefore, PV inverter designers can select the most cost-effective IGBTs based on the cost information and the reliability specifications at certain time, avoiding either lack of robustness or over-design with unnecessary cost increase.

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