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Quantitative Comparison of the Empirical Lifetime Models for Power Electronic Devices in EV Fast Charging Application

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***Abstract*—The load profile of the power converter in EV Fast charging applications involves a short high-current pulse for rapid charging of the EV battery leading to thermal cycles on the power electronic devices. These thermal cycles can cause thermo-mechanical fatigues, which consume the power devices' lifetime. Also, different timescales and magnitude of temperature swings lead to various failure modes. This paper compares different empirical lifetime models quantitatively in order to suggest the most appropriate model to predict the end of life of power electronic devices used in EV fast chargers. It is suggested that the selected model takes into account the most relevant failure mechanism based on the different timescales and magnitude of thermal cycles to indicate the lifetime of power electronic device used in a fast charger depending on the number of charging sessions.**

***Index Terms*—EV Fast charging applications, thermo-mechanical fatigues, empirical lifetime model.**

I. Introduction

Failures significantly impact the lifetime of power electronic converters during their operation [1], [2]. The main failure mechanisms influencing the lifetime of the power devices are thermo-mechanical fatigues, which make power devices in power converters extremely susceptible to these failures [3]. The wear-out failures in power devices are attributed to thermal stresses, which account for 55% of all stressors and cause thermo-mechanical fatigues [4]–[8]. Thermal cycles in power devices are characterized by repeated heating and cooling triggered by load variations, switching actions, and environmental factors. Due to the diverse coefficient thermal expansion (CTE) of the different layers in power devices, temperature fluctuations can cause bond-wire, solder, and chip metallization degradations, leading to thermo-mechanical fatigues [8]–[10].

Temperature swings are classified into short, medium/fundamental and long-term thermal cycles based on the time scale of fluctuations [11]. These Different timescales and magnitude of temperature swings lead to different failure modes [11]. As the thermal path of the power module acts as a low pass filter due to the thermal capacitance of layers, therefore impacts of the lower time scale of temperature swings (high-frequency) are less near the heatsink. Nevertheless, the high-frequency temperature swings are high at the junction, which can cause bondwire fatigue. On the contrary, the higher temperature swings time scales affect the solder joint of the module's baseplate [12]. Based on the power cycling tests, the short-term power cycles can cause the bondwire and die attach solder fatigue; however, long-term power cycles can lead to the DBC attach solder and thermal interface fatigues along with bondwire and die attach solder fatigues [13], [14]. In [15], it is suggested that lifetime tests for bond-wires can use short pulses of 1 sec, while failure associated with rest of the module which is thermally slower requires pulses of about 1 min.

Fast chargers for electric vehicles (EVs) has drawn much interest recently due to their ability to completely revolutionize the transportation sector. The load profile of the power converters in the charging process of EV Fast charging systems includes a high-current pulse to quickly charge the EV battery, which can last for a few minutes to an hour, depending on the state of charge. This results in thermal cycling of the power electronic components that may hasten their degradation. Consequently, failure mechanisms may arise due to these thermal cycles, ultimately leading to the end of the life of the power devices. This highlights the importance of evaluating the lifetime and reliability of the power components in EV Fast charging systems.

In the lifetime estimation of power devices based on the thermal cycles, which are the main contributor to thermo-mechanical fatigues impacting the device's reliability, the empirical lifetime models are utilized to calculate the number of cycles to failure [10], [16]. Since data collection for reliability assessment of power devices takes many years in the field, empirical lifetime models are one of the ways to estimate the end of life of the power devices under cyclic thermal loading that was proposed based on the accelerated power cycling tests

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[10], [16], [17]. These models account for factors that affect the lifetime of a power component. When conducting power cycling tests, these variables are taken into account. LESIT model is the first presented empirical lifetime model, in which only the impact of the magnitude of the temperature swing (ΔT_j) and the medium temperature ($T_{\text{j,medium}}$) is considered [18]. This model is applied when the power device's main failure mode is the bond wire lift-off. Also, this model does not explicitly discuss the duration of the thermal cycles, and it estimates the lifetime of the standard modules with Al_2O_3 substrates. Then CIPS 2008 lifetime model was proposed, which considered the impacts of other effective parameters on the end of life of devices, such as heating time (t_{on}), the diameter of the bonding wires (D), the blocking voltage of the device (V), and current per bond stitch (I) [19]. This model is also used for the standard modules with Al_2O_3 substrates. It is suggested that the fatigue in the base plate to substrate solder for longer t_{on} can limit the device's lifetime, and the relevant impact may not be covered in the model accurately. In [20], [21], a correction factor for the CIPS 2008 model based on the different heating times is used, which can be a suitable lifetime model for the various time scales of thermal cycles and for situations where the bond wire and also solder joint are the main failure modes. Skim model is proposed for solder-free modules, so this model may give different results when the solder joint failure is the main failure mechanism and estimates the device's lifetime based on the bondwire degradations [22].

As mentioned, timescales of thermal swings and the magnitude of temperature swings cause various failure modes. For example, low-magnitude thermal cycles at lower time scales (a few ms) lead to bond wire fatigue while high-magnitude temperature variation in a minute up to hour scale, which happens per charging session, can stress the solder joint of the base plate. Since the t_{on} corresponding to the charging sessions in EV fast chargers is long, DBC-attached solder fatigue can be expected to have a significant contribution towards the device failure. This paper investigates the impact of time scales of thermal cycles on the lifetime of the devices by comparing the lifetime models. Specifically, investigation of the t_{on} in relation to the thermal time constant of different layers, where the particular failure modes occur, is crucial. This dependence for different lifetime models is compared quantitatively in Section II. Thereafter, in Section III, the lifetime of IGBT switch for a dc fast charging application is discussed using the chosen lifetime model. Finally, the main idea presented in this paper are concluded in Section IV.

II. Quantitative Comparison of Different Lifetime Models

This section compares the number of cycles to failure for standard IGBT modules by the proposed empirical lifetime models in the literature. The impact of important parameters, such as ΔT_j and t_{on} are explored in this section. Based on these comparisons, the most relevant lifetime model is selected for fast charging application. In these comparisons, LESIT, CIPS 2008, and CIPS 2008 with correction factor models, which are shown in (1), (2), and (3) are compared [18]–[21].

The LESIT project [18] proposed a model described in (1) to estimate the lifetime of IGBT modules with Al_2O_3 DBC substrates based on fast power cycling tests with t_{on} and t_{off} in the range of 0.6-4.8 s and 0.4-5 s, respectively.

$$N_{\text{f}} = A\Delta T_{\text{j}}^{\alpha} e^{(\frac{E_a}{k_B T_{\text{j,m}}})} \tag{1}$$

In this model, the impacts of the ΔT_j and medium junction temperature ($T_{\text{j,m}}$) are considered on the lifetime of the IGBT, considering bond wire lift-off as the main failure mode. Herein, constant $A = 3.025 \cdot 10^5\,\text{K}^{-1}$, activation energy $E_a = 9.89 \cdot 10^{-20}\,\text{J}$, Boltzmann constant $k_B = 1.38 \cdot 10^{-23}\,\text{JK}^{-1}$, and constant $\alpha = -5.039$ are used [23]. The model is based on the assumption that fast power cycling tests produce approximately the same damage as slower ones, which we know inadequately includes the failures associated with solder joints [15]. Nevertheless, it does provide an useful first approximation, as [18] suggests that the LESIT model is descriptive in the sense that it does not consider actual failure mechanisms and the device structure.

The so called CIPS lifetime model presented in [19] is given by (2), wherein the impact of additional parameters, such as t_{on}, current per bond stitch I, bond-wire diameter D, and the device's blocking voltage (V/100) using a large data set of power cycle data for standard modules with Al_2O_3 ceramic in DBC with different structures.

$$N_{\text{f}} = A\Delta T_j^{\beta_1} e^{(\frac{\beta_2}{T_{\text{jmin}}+273})} t_{\text{on}}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6} \tag{2}$$

The values of constants $\beta_1 - \beta_6$, are listed in Table I [19].

TABLE I: Parameters for CIPS Lifetime model

β_1	β_2	β_3	β_4	β_5	β_6
-4.416	1285	-0.463	-0.716	-0.761	-0.5

It can be inferred from the value β_3 that while the value of N_{f} reduces with increasing t_{on}, this decrease is less significant for higher values of t_{on}. This relationship makes sense considering the first order approximation of the thermal response of various layers in the semiconductor module. However, the paper indicates that the model may be inaccurate for longer pulse widths, where the fatigue of substrate to base plate solder limits the lifetime associated with ΔT_{j}. In such case, CIPS model with correction factor is useful in the lifetime estimation of power devices based on different time scales of thermal cycles is indicated in (3) [20], [21].

$$\frac{N_f(t_{\text{on}})}{N_f(1.5)} = \begin{cases} 2.25 & t_{\text{on}} \leq 0.1s \\ (\frac{t_{\text{on}}}{1.5})^{-0.3} & 0.1s \leq t_{\text{on}} \leq 60s \\ 0.33 & t_{\text{on}} \geq 60s \end{cases} \tag{3}$$

Where $N_f(t_{\text{on}})$ and $N_f(1.5)$ are the number of cycles to failure at a t_{on} and 1.5 seconds, respectively.

A comparison of lifetime estimated with LESIT, CIPS 2008, and CIPS 2008 with a correction factor with different t_{on} is shown in Fig. 1. These curves are based on the variation in

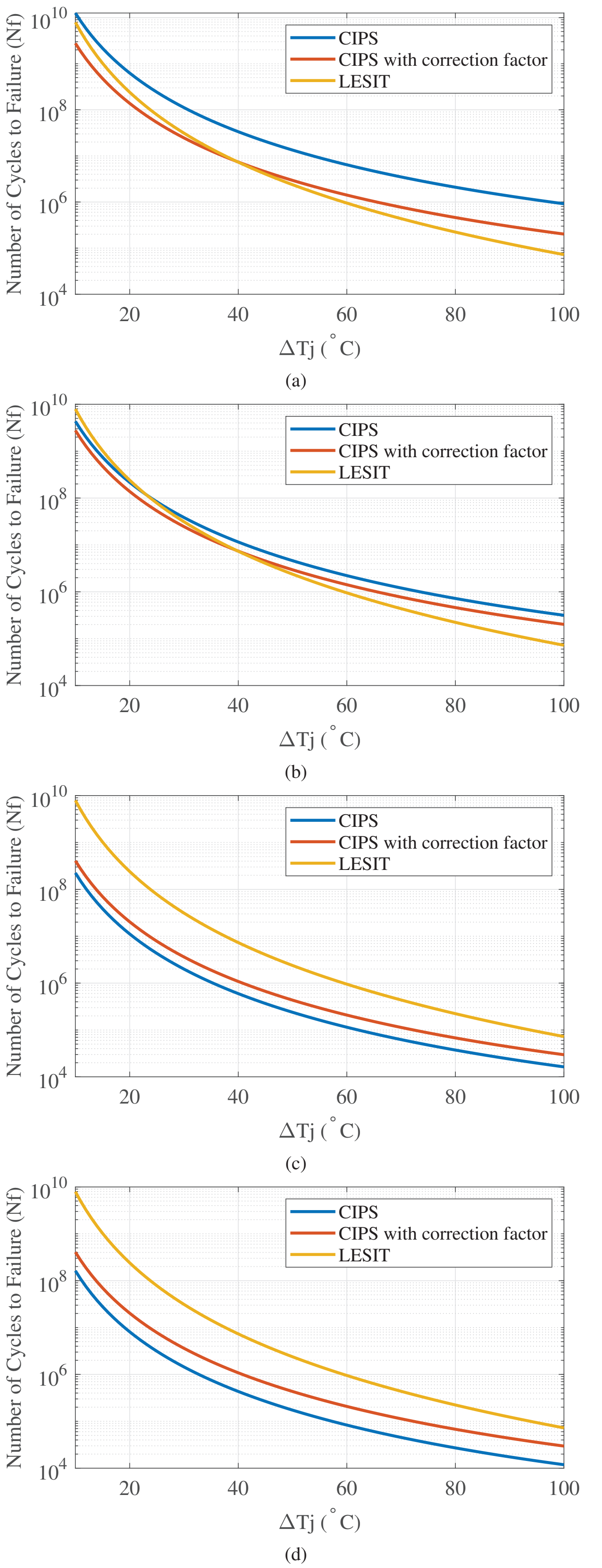

Fig. 1: Comparison of LESIT, CIPS, and CIPS with correction factor lifetime models at a different t_{on}. a)t_{on}=0.01s, b)t_{on}=0.1s, c)t_{on}=60s, and d)t_{on}=120s.

ΔT_{j} at the constant medium temperature ($T_{\text{j,medium}} = 56°\,\text{C}$). Also, the lifetime model parameters are considered based on the [18], [19] and the parameters $I = 20\,\text{A}$, $V = 12$, $D = 500\,\mu\text{m}$ are considered for the CIPS 2008 lifetime model.

It can be observed that the estimation of N_{f} for CIPS with correction factor is close to the LESIT model for smaller t_{on} in both Fig. 1(a) and (b). As discussed, the failure associated with wire bond life-off is dominant for this t_{on} because these are closer to the semiconductor junction at which power loss occurs. Note that as t_{on} increases from 0.01 s to 0.1 s, the change in estimated lifetime is marginal for CIPS with correction factor as compared to the CIPS model, a trend which seems more reasonable considering the physical phenomenon that the solder layers may not see significant temperature swings for on time below 100 ms because these are lower than the first order approximation of the device's thermal time constant.

For longer t_{on}, the failure modes associated with solder layers come into picture because the temperature swings now have time to reach the layers that are further away from the junction. It is for these values, as observed in Fig. 1 (c) and (d), that the LESIT model significantly diverges from both CIPS and CIPS with correction model. For example, the estimated N_{f} is almost an order of magnitude higher with LESIT model for ΔT_{j} in the range of $40 - 60°\,\text{C}$. Again, considering the physical expectation that temperature swings must reach different layers slower as compared to those closer to the junction, it is reasonable to expect that the estimated N_{f} should be sensitive to t_{on} up-to approximately 5 times the thermal time constant of the first order approximation of the device from its junction to heat-sink.

Fig. 2 compares the CIPS and CIPS with correction models with varying (t_{on}) for different ΔT_j with the same medium temperature ($T_{\text{j,medium}} = 56°\,\text{C}$).

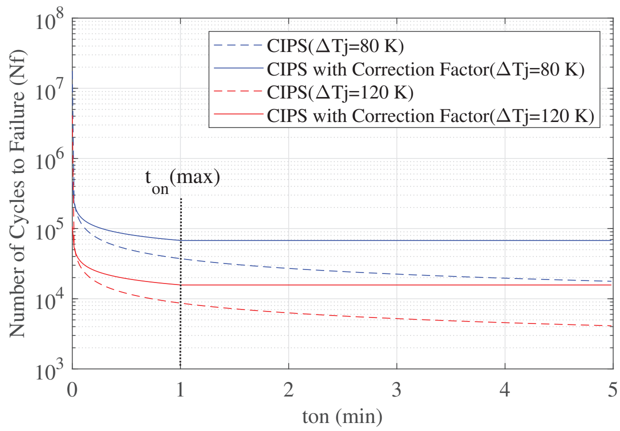

Fig. 2: Comparison of CIPS 2008 and CIPS 2008 with a correction factor.

It can be observed that N_{f} is lower for CIPS model as compared to the one with correction factor and this difference grows with higher t_{on}. The estimated lifetime is constant for $t_{\text{on}} > t_{\text{on}}(\text{max}) = 60\,\text{s}$ for the latter as indicated in (3), which makes physical sense as temperatures of all internal layers of the semiconductor device can be expected to reach steady-state for the same junction losses with heating time longer than t_{on}(max). On the other hand, while the CIPS model becomes flatter with higher t_{on}, it increasingly deviates from the value predicted by CIPS with correction model. Though only t_{on} upto 5 min is shown, the difference can be significant for higher values. Since fast charging sessions usually occur at a time scale of few minutes to an hour, CIPS with correction model is chosen for lifetime estimation of the power electronic component. The exact t_{on}(max) is necessary to design accelerated lifetime tests such that the obtained failure data is independent of the chosen cycle time. This value depends on the device structure and further experimental tests are necessary for deriving a more accurate empirical lifetime model for power electronic switches. It is possible that some decrease in N_{f} is always observable with increasing t_{on} due to higher average temperature, but this discussion is beyond the scope of this paper. Nevertheless, future research must be conducted to incorporate these dependencies empirically.

III. Lifetime of IGBT Devices in DC Fast Charging Station

As illustrated in the previous section, the CIPS model with correction factor can be an appropriate model to estimate the lifetime of power modules in EV Fast charging applications. Therefore, this section estimates the lifetime value for the standard IGBT module in EV Fast charging applications for two specific junction temperature swings with the same medium temperature by CIPS lifetime model with a correction factor.

As mentioned, junction temperature fluctuations are the main parameters that can cause thermos-mechanical fatigue, impacting the device's lifetime. Also, the temperature profile is changed based on the mission or load profile of the application, which is the main reason for the temperature swings in different applications. As mentioned before, the load profile of the fast charging applications includes rapid high-temperature swings during the charging of EV batteries, and the heating time in such applications is longer. As well as, the number of thermal cycles is directly related to the number of charging sessions. Therefore, the lifetime estimation of the IGBT module should be based on the load profile. As soon as the junction temperature swings ΔT_{j} and $T_{\text{j,medium}}$ are defined from the device's temperature profile during the EV battery's charging session. The empirical lifetime models are employed to drive the number of cycles to failure.

In this study, the power module's number of cycles to failure (N_{f}) for two junction temperature cycles (ΔT_{j} = 60° C, 80° C) at the same medium temperature ($T_{\text{j,medium}}$ = 80° C) based on the EV Battery charging load in which the heating time in each charging session is 30 minutes are estimated and illustrated in Table I. The parameters of the lifetime model are considered based on [19]. Also, the current per bond wire (I) and Voltage range (V/100), and diameter of bondwire (D) are assumed to be 20 A, 12 V, and 300 μm.

TABLE II: Number of cycles to failure (N_f) of IGBT module Based on CIPS Lifetime Model with correction factor

	$\Delta T_j = 60^oC$, $T_{\text{jmean}} = 80^oC$	$\Delta T_j = 80^oC$, $T_{\text{jmean}} = 80^oC$
N_f	1.9479×10^5	6.2092×10^4

In order to determine the accumulated damage of each power device (D), Miner's rule is employed, shown in (4) [24]–[26]

$$D = \sum_{i=1}^{n} \frac{n_i}{N_{f_i}} \quad (4)$$

where n_i is the number of thermal cycles during a year, which corresponds to the i_{th} thermal cycle, and N_{f_i} , is the number of cycles to failure, which was calculated from the lifetime model using (2), and (3) and shown in Table II.

The end-of-life of the power component, represented by L_c(year), can then be calculated using Equation (5). The value of D represents the accumulative damage of the device, and by adding it up until it equals one, the lifetime of the IGBT module is estimated.

$$L_c = \frac{1}{D} \quad (5)$$

As the number of thermal cycles is closely related to the number of charging sessions in the EV charger applications, So in the presented study, the estimation of the IGBT module damage and lifetime is conducted based on the number of charging times. The assumption is that each charging session lasts 30 minutes, and the number of charging sessions per day ranges from 5 to 40. It is further assumed that the components have the same junction temperature at the start of each charging session, equal to a fixed ambient temperature. This approach provides valuable insights into the accumulated damage and lifetime of the IGBT module under various charging times. Figs. 3 and 4 indicate the accumulated damage and lifetime of the IGBT module in EV chargers based on daily EV charging times at two temperature cycles with the same medium temperature.

The results of this section demonstrate that the power module's lifetime is severely affected by the number of charging times in EV applications. According to the figures, more charging sessions increase thermal cycles, which shorten the module's lifetime. Moreover, this paper emphasizes the need to carefully consider temperature cycling and its duration influences on the module's lifetime when designing and implementing EV charging systems.

Overall, this study offers insightful information about the factors influencing the lifetime of EV charging modules and notes the significance of taking these factors into account in future research and development efforts. However, the suggestions in this paper need experimental validation to get more insights about the failure mechanism that can occur in EV fast chargers due to the thermal cycles.

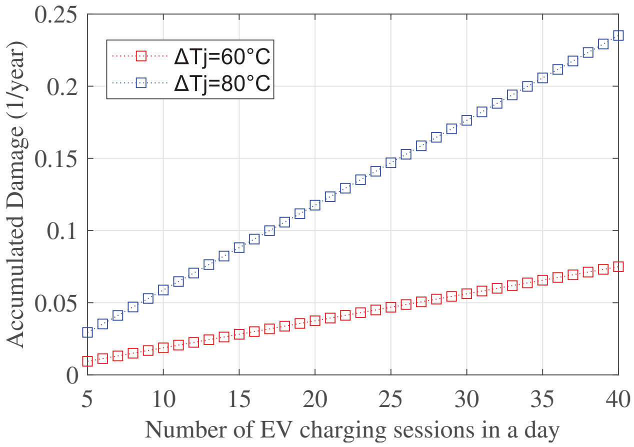

Fig. 3: Damage of a power device in one year based on the number of charging sessions

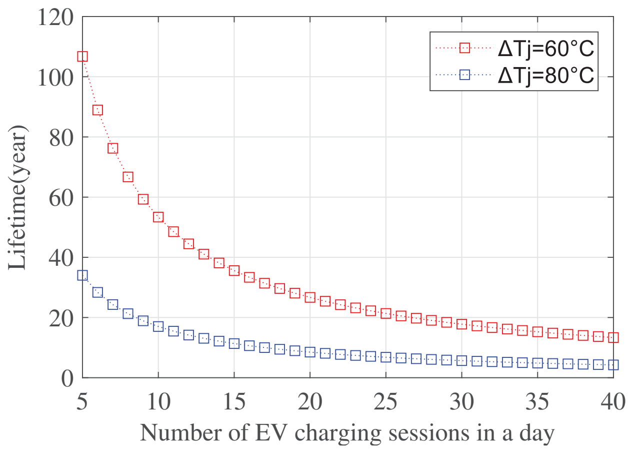

Fig. 4: Lifetime of a power device based on the number of charging sessions

IV. Conclusions and Future Work

In this study, a quantified comparison of LESIT, CIPS and CIPS with correction model is carried out. Literature suggests that fatigue in DBC attached solder layer of the semiconductor module is a dominant failure mode for longer on-time temperature cycles. Based on the idea that temperature swings can reach these layers at-most by five times the thermal time constant of the first order approximation of the device's thermal circuit, CIPS with correction model is selected as an accurate representation for damage calculation in fast charging application. This is because the model is the only one out of those compared, that is sensitive to t_{on} but becomes independent of it above 60 s. It is highlighted that the maximum heating time beyond which the estimated device lifetime becomes independent of its on-time must be determined empirically. These results indicate that the lifetime of a single power electronic switch module reduced by more than 85 % when number of charging sessions per day increased from 5 to 40 for $\Delta T_{\mathrm{j}} = 60°$ C. The insights offered in this paper are suggestive, and need experimental validation as future work, particularly considering the on-time of the temperature cycle in relation with the thermal time constant of different layers where the specific failure modes occur.

References

[1] M. Ahmadi, A. Shekhar, and P. Bauer, "Impact of the various components consideration on choosing optimal redundancy strategy in mmc," in *2022 IEEE 20th International Power Electronics and Motion Control Conference (PEMC)*. IEEE, 2022, pp. 21–26.

[2] M. Ahmadi, A. Shekhar, and Bauer, "Reconfigurability, modularity and redundancy trade-offs for grid connected power electronic systems," in *IEEE 20th International Power Electronics and Motion Control Conference (PEMC)*. IEEE, 2022, pp. 35–41.

[3] S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran, and P. Tavner, "Condition monitoring for device reliability in power electronic converters: A review," *IEEE Transactions on Power Electronics*, vol. 25, no. 11, pp. 2734–2752, 2010.

[4] J. Falck, C. Felgemacher, A. Rojko, M. Liserre, and P. Zacharias, "Reliability of power electronic systems: An industry perspective," *IEEE Industrial Electronics Magazine*, vol. 12, no. 2, pp. 24–35, 2018.

[5] R. Burgos, G. Chen, F. Wang, D. Boroyevich, W. G. Odendaal, and J. D. Van Wyk, "Reliability-oriented design of three-phase power converters for aircraft applications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 48, no. 2, pp. 1249–1263, 2012.

[6] X. Perpina, X. Jorda, M. Vellvehi, J. Rebollo, and M. Mermet-Guyennet, "Long-term reliability of railway power inverters cooled by heat-pipe-based systems," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 7, pp. 2662–2672, 2011.

[7] F. Carastro, A. Castellazzi, J. Clare, and P. Wheeler, "High-efficiency high-reliability pulsed power converters for industrial processes," *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 37–45, 2012.

[8] V. Smet, F. Forest, J.-J. Huselstein, F. Richardeau, Z. Khatir, S. Lefebvre, and M. Berkani, "Ageing and failure modes of igbt modules in high-temperature power cycling," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4931–4941, 2011.

[9] P. Ghimire, A. R. de Vega, S. Beczkowski, B. Rannestad, S. Munk-Nielsen, and P. Thogersen, "Improving power converter reliability: Online monitoring of high-power igbt modules," *IEEE Industrial Electronics Magazine*, vol. 8, no. 3, pp. 40–50, 2014.

[10] A. Morozumi, K. Yamada, T. Miyasaka, and Y. Seki, "Reliability of power cycling for igbt power semiconductor modules," in *Conference Record of the 2001 IEEE Industry Applications Conference. 36th IAS Annual Meeting (Cat. No.01CH37248)*, vol. 3, 2001, pp. 1912–1918 vol.3.

[11] G. Zhang, D. Zhou, J. Yang, and F. Blaabjerg, "Fundamental-frequency and load-varying thermal cycles effects on lifetime estimation of dfig power converter," *Microelectronics Reliability*, vol. 76-77, 07 2017.

[12] K. Ma, M. Liserre, F. Blaabjerg, and T. Kerekes, "Thermal loading and lifetime estimation for power device considering mission profiles in wind power converter," *IEEE Transactions on Power Electronics*, vol. 30, no. 2, pp. 590–602, 2015.

[13] J. Lutz, "Semiconductor power devices: Physics, characteristics, reliability," *Springer*, 2018.

[14] A. V. Hornkamp and M., "Igbt modules: Technologies, driver and application," *Infineon Technologies AG, Neubiberg, Germany*, 2017.

[15] N. Kaminski, "Load-cycling capability of hipaks," in *Application Note 5SYA 2043-01*. ABB, 2004.

[16] A. Bryant, P. A. Mawby, P. Palmer, E. Santi, and J. Hudgins, "Exploration of power device reliability using compact device models and fast electro-thermal simulation," in *Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting*, vol. 3, 2006, pp. 1465–1472.

[17] D. Hirschmann, D. Tissen, S. Schröder, and R. W. De Doncker, "Reliability prediction for inverters in hybrid electrical vehicles," in *2006 37th IEEE Power Electronics Specialists Conference*, 2006, pp. 1–6.

[18] M. Held, P. Jacob, G. Nicoletti, P. Scacco, and M.-H. Poech, "Fast power cycling test of igbt modules in traction application," in *Proceedings of Second International Conference on Power Electronics and Drive Systems*, vol. 1, 1997, pp. 425–430 vol.1.

[19] R. Bayerer, T. Herrmann, T. Licht, J. Lutz, and M. Feller, "Model for power cycling lifetime of igbt modules - various factors influencing lifetime," in *5th International Conference on Integrated Power Electronics Systems*, 2008, pp. 1–6.

[20] AN2019-05, "Pc and tc diagrams," *Infineon Technologies AG, Munich, Germany*, 2019.

[21] S. Peyghami, H. Wang, P. Davari, and F. Blaabjerg, "Mission-profile-based system-level reliability analysis in dc microgrids," *IEEE Transactions on Industry Applications*, vol. 55, no. 5, pp. 5055–5067, 2019.

[22] U. Scheuermann and R. Schmidt, "A new lifetime model for advanced power modules with sintered chips and optimized al wire bonds," 05 2013.

[23] R. Amro, J. Lutz, and A. Lindemann, "Power cycling with high temperature swing of discrete components based on different technologies," in *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551)*, vol. 4, 2004, pp. 2593–2598 Vol.4.

[24] M. A. Miner, "Cumulative damage in fatigue," *J. Appl. Mech.*, vol. 12, no. 3, pp. 159–164, 1945.

[25] H. C. Yildirim, G. B. Marquis, and Z. Barsoum, "during a year, which corresponds to the," *International Journal of Fatigue*, vol. 52, pp. 57–67, 2013.

[26] H. Huang and P. A. Mawby, "A lifetime estimation technique for voltage source inverters," *IEEE Transactions on Power Electronics*, vol. 28, no. 8, pp. 4113–4119, 2013.