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Load Profile Based Reliability Assessment of IGBT Module in Full-bridge DC/DC Converter for Fast Charging of EVs

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***Index Terms*—Reliability, Thermal stress, Lifetime, IGBT**

***Abstract*—EV Fast chargers are crucial to alleviate the driving range anxiety for E-mobility applications. A typical converter load profile consists of a short high-current pulse to rapidly refill the EV battery followed by a cooling-off period once the charging is completed. Power electronic components experience thermal cycles as a result, which can hasten the degradation of such components. In this context, the reliability evaluation of the power electronic converters enabling fast EV charging is of importance. This paper presents the reliability assessment of the IGBT module in EV Fast chargers to show how the load profile of the charger impacts the device's lifetime.**

I. Introduction

Off-board Fast chargers are suggested for EVs for long-distance travels due to the restricted capacity of on-board chargers. These chargers can quickly deliver the necessary dc power for EV batteries through power converters. Off-board chargers also help EVs with their size and weight problems. As well they assist EVs in overcoming their weight and size issues. With power ranging from 50 kW to 350 kW, these chargers can fully recharge EVs in about 30 minutes. Due to the fact that AC-connected fast chargers have more power conversion stages than DC-connected fast chargers, they are less efficient and more complex than DC-connected fast chargers despite having some advantages in terms of converter technology availability, protection devices, and approved standards. DC-fast chargers are therefore more cost-effective and also address synchronization problems [1], [2]. The benefits of DC Fast chargers have lately caused these chargers to advance and gain significance. The standard DC fast chargers include two stages of power conversion: the first stage is AC/DC power conversion, which also requires the use of PFC for power factor correction, and the second stage is a DC/DC conversion step to meet the necessary DC voltage for the EV battery [2], [3]. A line-frequency transformer or high-frequency transformer in an isolated DC/DC converter is used to create galvanic isolation between the grid and the EV battery. Additionally, multi-parallel modules are employed to supply the energy needed by high-power DC fast chargers [2].

Power converters are comparatively more vulnerable to failures during their operation, which is remarkably impacting the reliability of power electronic systems [4]–[6]. Among the parts of power converters, power semiconductors, and capacitors are the most susceptible to failure [7], [8], [9], [10], [11]. Thermo-mechanical fatigues are the primary failure modes in power devices that impact the reliability of the power converter. Thermal stresses cause these fatigues, which are a factor in wear-out failures. According to the studies, wear-out failures in power devices are caused by thermal stresses, which make up 55% of all stressors [12]–[16]. Power converters produce power losses while operating, which causes thermal cycles of repeated heating and cooling caused by changes in the load, switching actions, and environmental conditions. Since power devices are made of many layers with different coefficient thermal expansion (CTE), temperature swings can lead to thermo-mechanical fatigues such as bond-wire fatigues, solder fatigues, and degradation of chip metallization. Based on the time scale of temperature variations, temperature swings in power devices are divided into short (micro seconds-seconds), medium (seconds-minutes), and long-term (minutes-months) thermal cycles [17]. The short-term temperature swings are related to the switching frequency of the converter. Thermal cycles induced by load changes of the converter are called fundamental or medium-term thermal cycles. Also, Environmental variables, such as ambient temperature changes, contribute to long-term thermal cycles [18]. All of the mentioned thermal cycles can be the origin of the thermo-mechanical fatigues due to the mismatch of the coefficient of thermal expansion (CTE) between module layers which would consume the life of the power converters [18].

In EV Fast charging systems, a typical converter load profile involves a short high-current pulse to quickly charge the EV battery, followed by a cooling-off time after the charging is finished. This process leads to thermal cycles on power electronic components that can accelerate the breakdown of such devices. Therefore, some failure mechanisms can occur due to the thermal cycles, which result in the component's end of life. Therefore, discovering the reliability of the power converters depending on the load profile in EV Fast charging systems is crucial.

This paper presents the reliability assessment process of power semiconductors and estimates the lifetime of the IGBT module in the Full-Bridge converter based on the charging profile of EV in section II. The summary of this investigation is presented in Section III.

II. Load profile based Reliability Assessment of power converters

A. Methodology for Reliability Assessment of power semiconductors

Power semiconductors are the parts of power converters that are particularly susceptible to thermal stress, which results in thermo-mechanical fatigue, as was discussed in the section above. That's why power semiconductors have to be designed at a strength level to endure applied stresses over the course of their intended lifetime [8]. By utilizing the mission/load-profile-based reliability technique, this paper assesses the reliability of the converter's components for EV DC fast charging applications. The stress sources on the power devices should be converted into thermal stresses. The lifetime and reliability of the power components can then be calculated using experimental models and Monte Carlo simulations. The process of model-based reliability assessment of power electronic components is depicted in Figs 1, 2, and 3.

As is shown in Fig 1, the first stage in the reliability assessment of power converters is converter modeling depending on the application, mission/load profile, converter topology, control, and modulation techniques. The electrical stress of each relevant component is provided at this step. Also, Component-level modeling, which is connected to various sorts of components, is the process' second step of reliability assessment of power components. In this stage, the electrical stresses defined by the stage before are utilized to calculate the power losses of each component, including conduction losses and switching losses in power devices. Following

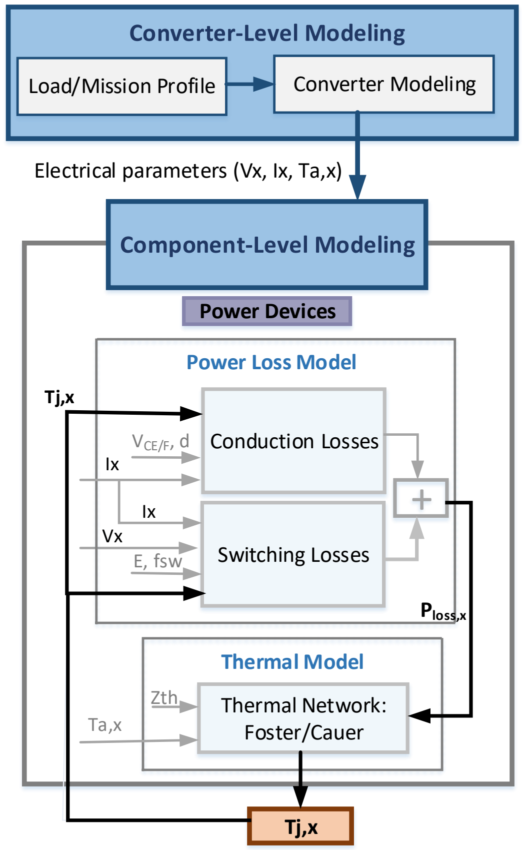

Fig. 1. First and second stage of model-based reliability assessment process

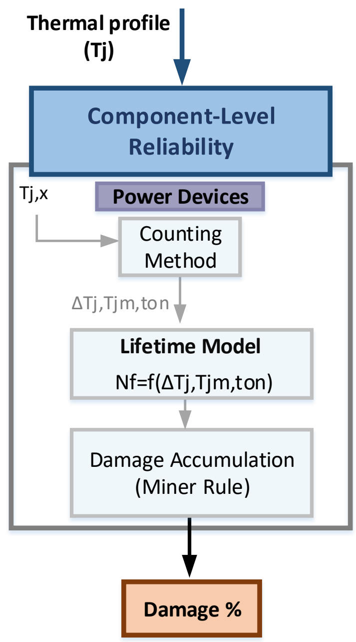

Fig. 2. The third stage of model-based reliability assessment process

this, the thermal loading of each component (junction temperature profile) is extracted using electro-thermal (Foster/Cauer) networks which are dependent on the power device features or their thermal impedances. The inputs of thermal networks are the components' power losses. Fig. 1 provides a detailed representation of this step.

The third step of the model-based reliability assessment process is the component-level reliability stage which is shown in Fig. 2. Such as the previous stage, this one is reliant on components. The extracted thermal loading, which is the junction temperature for power semiconductors, is defined as an input at this stage to estimate the consumed lifetime or Damage of the components. In power electronic applications like PV, Wind systems, MMC applications, etc, the load and mission profile variations lead to a complicated profile of junction temperature in power devices, making it difficult to find out the different ΔT_{j}s during operation. Therefore, counting algorithms like the Rainflow method are implemented to determine the number of cycles in the specific T_{j} and T_{jmean}. After defining the thermal cycles which are impacted the lifetime of the device, the Empirical lifetime models are employed in this step to derive the number of cycles to failure, which were discovered by the huge sets of data from power cycling experiments. These models take into account variables that may affect a component's reliability and were considered in power cycling tests. As well, these models are one of the methods that were presented based on the power cycling tests to estimate the end of life of the power devices under cyclic thermal loading as the field data collecting for reliability evaluation of power devices take several years. There are several lifetime models proposed in papers, including the LESIT [19], CIPS 2008 (Bayerer) [20], corrected CIPS 2008 [21], [22], and the Skim models [23]. These models are based on the main failure mechanisms. For instance, the LESIT model is more appropriate when bondwire failure is the primary cause of fatigue [24]. When the heating time has a greater influence on the failure mechanisms or the solder joint failure together with bondwire failures is the predominant failure mechanism, the CIPS 2008 lifetime model is applicable [20], [24]. Corrected CIPS 2008 is a reasonable lifetime model for the various temperature cycle time scales as well as for conditions where the bond wire and solder joint failure modes are the primary failure mechanisms [22], [25]. After the estimation of the number of cycles to failure by lifetime models, each device's accumulated damage is estimated using the Miner rule [25], [26].

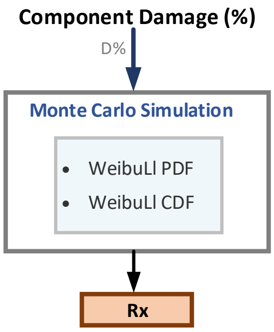

Fig. 3. The final phase in the model-based reliability assessment procedure of power semiconductor

At the last step of component-level reliability assessment, the components' PDF (Probability density function) and CDF (Cumulative distribution function) is extracted using Monte Carlo simulation to consider the uncertainties [27]. So, Reliability of the each component is estimated based on this stage which is shown in Fig. 3. In order to find the reliability of the power converter (system-level reliability), a series reliability block diagram (RBD) connection is used to assess the reliability of the power electronic system with n components [28]. This process is the final step of the reliability assessment of power electronic systems with different components. In this paper, the reliability of the power switches based on the load profile power cycles for EV DC fast charging applications is discovered.

B. Case study and simulation results

To fulfill the EV battery power, DC/DC converters are employed in the second power conversion stage of DC Fast chargers. Isolated and Non-Isolated converters are the two categories for DC/DC converters [3]. A full-bridge (FB) DC/DC converter is one the most widely utilized isolated DC/DC converters as an interface in DC fast charging stations to charge the EV batteries. The loading stresses of the power components vary due to the various load profiles. Therefore, the modeling of the power converter should be based on the load profile to extract the stresses on the power semiconductors. Fig. 4 shows the converter's load profile, which is the profile to charge a 400 V, 50.36 kWh battery.

In this paper, a phase-shift Full-Bridge DC/DC (PSFB) converter with the battery load profile was simulated in PLECS-BLOCSET to assess the reliability of the power components based on the charging profile of the battery. Fig. 5 shows the structure of the phase-

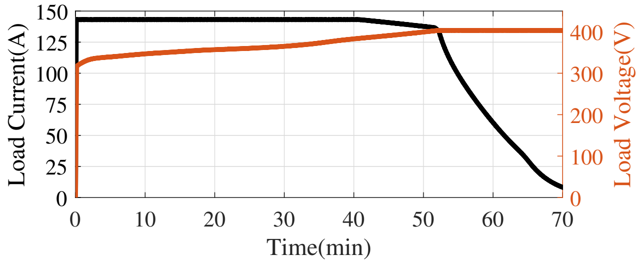

Fig. 4. A load Profile of the power converter in one session of charging the battery.

shifted full-bridge DC/DC converter and in Table I, the specifications of this converter are listed.

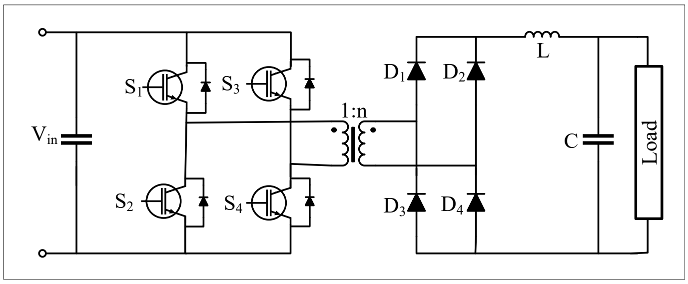

Fig. 5. Topology of the Isolated 55 kW Full-bridge DC/DC power converter used for fast charging of the EV.

TABLE I
SPECIFICATIONS OF THE FB DC/DC CONVERTER

Converter parameters	**Value**
Rated power (P_o)	55 kW
Input voltage (V_{in})	600 V
Output voltage (V_{out})	400 V
Switching frequency (f_{sw})	10 kHz
Inductance (L)	9.2 mH
Capacitor (C)	410 µF
Transformer ratio (n)	1:0.8
IGBT	FF200R12KE3

The FF200R12KE3 IGBT module is selected for the converter and Power losses (conduction and switching losses) of the IGBT module were calculated based on the given data in the datasheet of the device by using the lookup tables in PLECS. The values of the fourth-order Foster network of the IGBT module are given in its datasheet which is used to make a thermal network. Also, the thermal resistance of the thermal grease was defined as 0.01 K/W in the datasheet. The thermal resistance of the heatsink is considered as 0.03 K/W. By Considering ambient temperature is constant at 25°C, the junction temperature profile was extracted from the thermal network of the module and it is shown in Fig. 6.

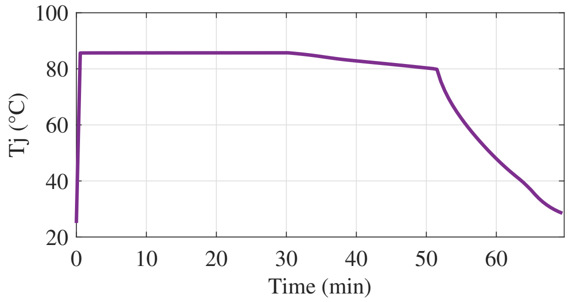

Fig. 6. Junction temperature profile of the IGBT module based on the load profile of the converter.

Depending on the duration of the power cycles, thermal stresses produced by them can cause various thermo-mechanical fatigues [17]. As bondwires are near the junction and the thermal stress can't reach the DBC solder at such short durations (a few ms), thermal cycles at shorter intervals (a few ms) only affect the bond wire and die attach solders. The LESIT model and the CIPS model with correction factor are the best suitable models for such shorter heating durations or when the bondwire failure mechanism is the primary failure mode [29]. On the other side, DBC attach solder, and the thermal interface failures along with the bondwire failures are also caused by fundamental and long-term temperature cycles (minutes to hours). Since the LESIT model doesn't take into account the length of thermal cycles, therefore it just considers the bond wire failure mechanism as the main cause of fatigue and overestimates the number of cycles to failure at higher heating times which means it can't take into consideration DBC solder joint fatigue [29]. CIPS and its corrected model have a more realistic lifetime prediction than the LESIT model while the failure of the DBC solder attaches is the most relevant failure mechanism in the system due to their dependency on the thermal cycle duration. Therefore, based on the application, a suitable lifetime model should be selected to estimate the device's lifetime related to the most pertinent failure mechanism. Due to the longer length of the temperature cycles (t_{on}) caused by charging sessions in EV fast chargers, the DBC-attached solder is impacted by thermal cycles as well. The corrected CIPS lifetime model was proposed for different time scales by researchers. This model overpredicts the number of cycles to failure for higher values of the t_{on} in comparison to the CIPS model. As a few minutes after the heat reaches the baseplate, the DBC solder joint breaks, and the device's end-of-life happens [29]. So the corrected CIPS lifetime model is the more appropriate model in this study and is used to find the number of cycles to failure. The CIPS and its corrected Model are expressed as (See (1) and (2)) [20], [21], [22]:

$$N_f = A \Delta T_j^{\beta_1} {t_{on}}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6} e^{\left(\frac{\beta_2}{T_{jmin}+273}\right)} \tag{1}$$

$$\frac{N_f(t_{on})}{N_f(1.5)} = \begin{cases} 2.25, & \text{if } t_{on} \leq 0.1s. \\ (\frac{t_{on}}{1.5})^{-0.3}, & \text{if } 0.1 < t_{on} < 60s. \\ 0.33, & \text{if } t_{on} \geq 60s. \end{cases} \tag{2}$$

Where N_f is the number of cycles to failure, ΔT_j is a temperature fluctuation, T_{jmin} is the minimum junction temperature, and t_{on} is the on-time. The other factors, A, $\beta_1 - \beta_6$ are the parameters that are given in [20]. Additionally, I is the chip's current per bond stitch, V is the device's voltage range (V/100), and D is the bond wire's diameter in micrometers. These parameters in this study are assumed to be 20 A, 12 V, and 250 μ, respectively.

Using Miner's rule (Eq. (3)), the annual damage of the device is calculated as follows [26]:

$$D = \sum_{j=1}^{n} (\frac{n_j}{N_{fj}}) \tag{3}$$

Where n_j is the number of power cycles and N_{fj} is the number of cycles to failure at jth power cycle.

Then, by adding up the D until it approaches unity, which is when the device's end-of-life reaches, the expected lifetime of the IGBT module is determined. So, the power component end-of-life (LF) is calculated by Eq. (4).

$$LF = \frac{1}{D} \tag{4}$$

The static lifetime data values for the case study have been estimated using the mentioned lifetime estimation method, and they are presented in Table II. As the number of cycles varies depending on the number of charging sessions, therefore the static values of the IGBT Damage and end-of-life are estimated based on the number of charging sessions which are shown in Fig.7 and Fig.8. The minimum and maximum number of charging sessions in a day are considered in a range of 5 to 19.

TABLE II
STATIC LIFETIME VALUES OF THE IGBT MODULE IN FB DC/DC CONVERTER

Junction temperature fluctuation ΔT_j (°C)	60.72
Mean junction temperature Tjm (°C)	55.36
On-state time ton (second)	4199.8
Number of cycles to failure (Nf)	28.263×10^4

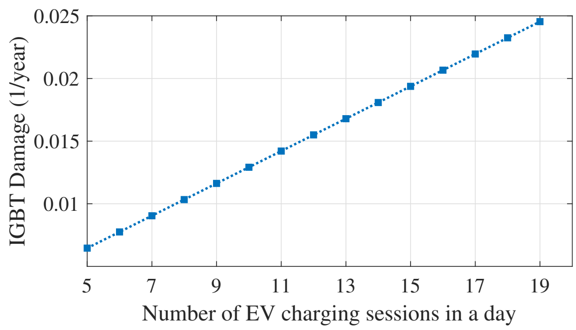

Fig. 7. IGBT Damage in one year based on the number of charging sessions.

C. *Monte Carlo analysis and reliability of the IGBTs*

In the preceding section, we predicted the lifetime data in an ideal scenario in which all IGBTs degrade at the same rate. However, in reality, uncertainties emerge as a result of differences in the parameters of the lifetime model and the production process of the component. So, this section focuses on investigating the reliability of the IGBTs considering uncertainties by using the Monte Carlo method [27], [30].

The constant parameters in the lifetime models, derived from accelerated aging tests using a specific number of testing samples, are subject to uncertainties. To address this, a normal probability density function (Pdf) is used to distribute the parameters in the lifetime

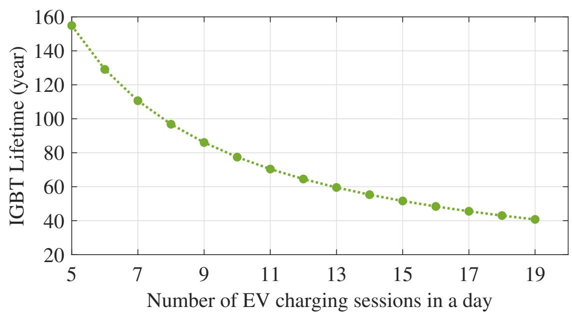

Fig. 8. IGBT lifetime (year) based on the number of charging sessions.

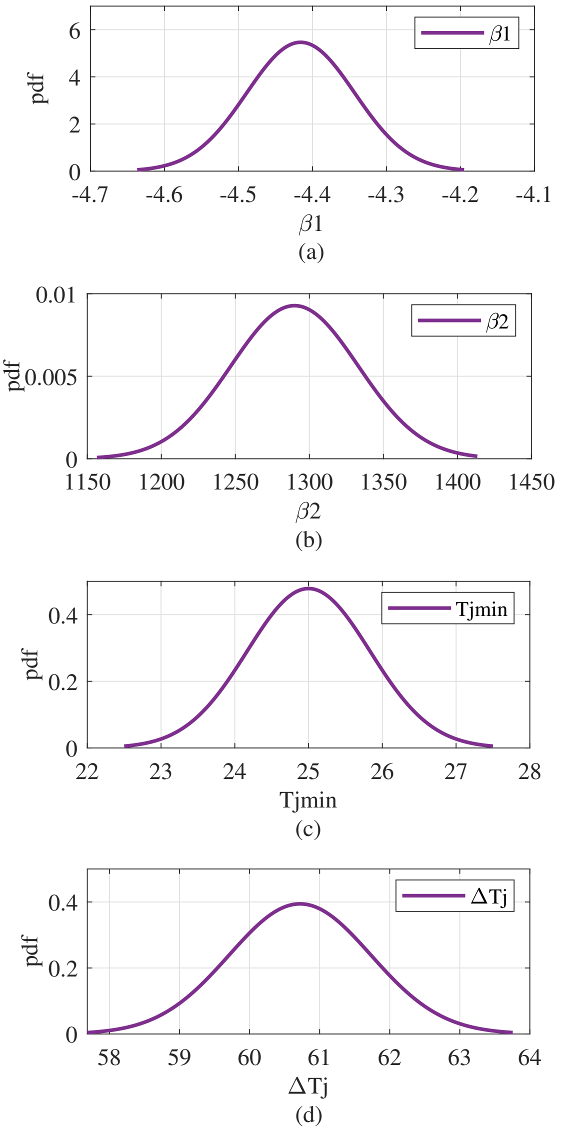

Fig. 9. Probability density functions of the parameters: a)β_1, b)β_2, c),T_{jmin} and d)ΔT_j.

model. We assumed that β_1 and β_2 have 5% and 10% variations. Also, Another type of uncertainty arises due to variances in the production process of the component, which results in variations in the minimum junction temperature and junction temperature fluctuation. So it is assumed that there is a variation of 5% for ΔT_{j} and 10% for T_{jmin}. The Probability density functions of the parameters (β_1, β_2, T_{jmin} and ΔT_{j}) are extracted and shown in Fig. 9.

In order to assess the precise lifetime of the system, a Monte Carlo simulation is applied by considering parameter changes (β_1, β_2, ΔT_{j} and T_{jmin}) [27]. The range of variation for each parameter were shown in Fig. 9. It should be noted that the number of charging

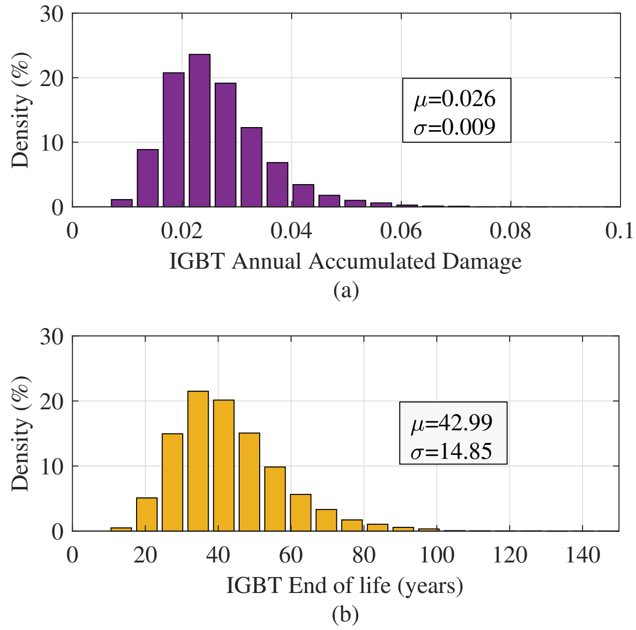

Fig. 10. Monte-Carlo analysis. a) Accumulated damage probability distribution function. b) End-of-life probability distribution function.

times affects the module's lifetime, with more charging sessions resulting in more thermal cycles and ultimately reducing the module's lifetime. In order to use the Monte-Carlo method and determine the reliability of the component, the maximum number of charging sessions has been taken into account in this section which in this particular case, the maximum number of charging sessions is considered 19. Fig. 10 (a) and (b) demonstrate the accumulated damage and end-of-life distributions for IGBT which were extracted based on the Monte-Carlo analysis. The mean value and standard deviation are μ and σ, respectively. The Reliability function of each IGBT in the studied converter is estimated based on the Monte-Carlo and Weibull distribution [30], also to evaluate the reliability of all IGBTs together in this system the RBD method is used [25], [28]. The estimated reliability and B_{10} of each IGBT and all IGBTs are depicted in Fig. 11. Based on this figure, the B_{10} lifetime of each IGBT is 22.52 years, indicating that 10% of IGBTs deteriorate after that period.

III. Conclusion

This paper presents a quantitative lifetime and reliability analysis of the IGBT module in a 55 KW phase shifted FB DC/DC converter used for EV DC chargers. The analysis was conducted based on the load profile of the DC fast charging for EVs, taking into account the

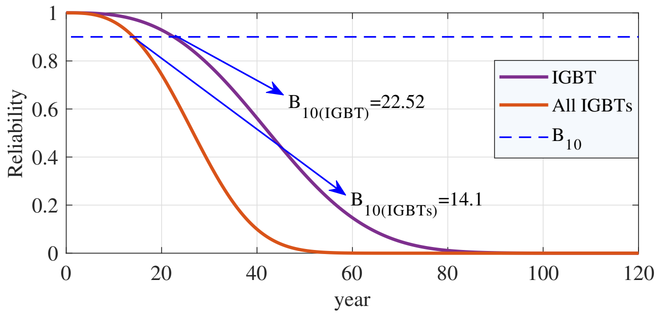

Fig. 11. Reliability and B_{10} of each IGBT and all IGBTs in PSFB DC/DC converter.

effect of thermal cycles during charging. Additionally, the Monte Carlo analysis was used to incorporate parameter differences in the lifetime model and production process of the IGBT module. Based on the results, the B_{10} lifetime of each IGBT was estimated to be 22.52 years, meaning that 10% of IGBTs will deteriorate after that time. These results highlight the substantial effect of temperature cycles resulting from EV charging applications on the device's lifetime. It also underscores the significance of load profile-based reliability evaluation in DC fast charging applications, given that the number of charging times and rapid high-temperature swings during the charging of an EV affect the module's lifetime. Also, results illustrate that more charging periods lead to more thermal cycles and ultimately reduce the module's lifetime.

References

[1] S. Srdic and S. Lukic, "Toward Extreme Fast Charging: Challenges and Opportunities in Directly Connecting to Medium-Voltage Line,"IEEE Electrification Magazine,vol.7,NO.1, PP.22-31, 2019.

[2] D. Ronanki,A. Kelkar and Sh. S. Williamson, "Extreme Fast Charging Technology-Prospects to Enhance Sustainable Electric Transportation",Energies, vol.2, No.19, 2019.

[3] S. G. Liasi, F. Kardan, and M. T. Bina, "Power Electronics Converters for EVs and Wireless Chargers: An Overview on Existent Technology and Recent Advances," Power Electronics for Green Energy Conversion, John Wiley & Sons, Ltd, 2022, ch. 14, pp. 475-517.

[4] S. Peyghami, P. Palensky and F. Blaabjerg,"An Overview on the Reliability of Modern Power Electronic Based Power Systems" IEEE Open Journal of Power Electronics, Vol.1, pp.34-50,2020.

[5] M. Ahmadi, A. Shekhar, and P. Bauer, "Impact of the various compo- nents 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.

[6] 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.

[7] Sh. Yang, A. Bryant, Ph. Mawby, D. Xiang, Li. Ran and P. Tavner,"An Industry-Based Survey of Reliability in Power Electronic Converters",IEEE Transactions on Industry Applications,vol.47,pp. 1441-1451,2011.

[8] 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.

[9] 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, Nov. 2010.

[10] F. Chan and H. Calleja, "Reliability Estimation of Three Single-Phase Topologies in Grid-Connected PV Systems," IEEE Transactions on Industrial Electronics, vol. 58, no. 7, pp. 2683-2689, 2011.

[11] S. E. De León-Aldaco, H. Calleja, F. Chan and H. R. Jiménez-Grajales, "Effect of the Mission Profile on the Reliability of a Power Converter Aimed at Photovoltaic Applications—A Case Study," IEEE Transactions on Power Electronics, vol. 28, no. 6, pp. 2998-3007, 2013.

[12] 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

[13] 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

[14] 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

[15] 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

[16] V. Smet et al., "Ageing and Failure Modes of IGBT Modules in High-Temperature Power Cycling," in IEEE Transactions on Industrial Electronics, vol. 58, no. 10, pp. 4931-4941, 2011

[17] G. Zhang, D. Zhou, J. Yang, F. Blaabjerg,"Fundamental-frequency and load-varying thermal cycles effects on lifetime estimation of DFIG power converter", Microelectronics Reliability, Vol. 76–77, 2017, pp. 549-555

[18] 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

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

[20] R. Bayerer, T. Herrmann, T. Licht, J. Lutz and M. Feller, ”Model for Power Cycling lifetime of IGBT Modules - various factors influencing lifetime,” 5th International Conference on Integrated Power Electronics Systems, Germany, 2008, pp. 1-6.

[21] “Technical Information IGBT Modules Use of Power Cycling Curves for IGBT 4,” Appl. Note AN2010-02, Infineon, Neubiberg, Germany, 2012.

[22] Infineon Technologies AG,”, PC and TC Diagrams” Infineon AN2019-05, Munich, Germany, Tech. Rep., 2019.

[23] U. Scheuermann, R. Schmidt,”A New Lifetime Model for Advanced Power Modules with Sintered Chips and Optimized Al Wire Bonds,” PCIM Europe (Power Conversion Intelligent Motion), Nuremberg, pp.810-817.

[24] A. Abuelnaga, M. Narimani and A. S. Bahman, ”A Review on IGBT Module Failure Modes and Lifetime Testing,” in IEEE Access, vol. 9, pp. 9643-9663, 2021, doi: 10.1109/ACCESS.2021.3049738.

[25] 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.

[26] M. A. Miner, “Cumulative damage in fatigue,” J. Appl. Mech., vol. 12, no. 3, pp. 159–164, 1945.

[27] J. McPherson, Reliability Physics and Engineering, 2nd ed. Switzerland: Springer Int., 2013.

[28] R. Billinton and R. N. Allan, “Reliability evaluation of engineering systems: concepts and techniques,” 1992.

[29] F. Kardan, A. Shekhar, P. Bauer, ”Quantitative Comparison of the Empirical Lifetime Models for Power Electronic Devices in EV Fast Charging Application” 11th International Conference on Power Electronics- ECCE Asia, Jeju, Korea (South), 2023.

[30] W. Weibull, “Statistical distribution function of wide applicability,” ASME Journal of Applied Mechanics, vol. 18, no. 3, pp. 293–297, Sep. 1951.