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End-of-Life Comparison of Full-Bridge and Half-Bridge DC/DC Converter Switches Used for EV Charging

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***Abstract*—EV fast chargers are essential in addressing the concern of limited driving range for E-mobility applications. However, the load profile of a converter for fast charging involves a high-current pulse that can last for a few minutes to efficiently replenish the EV battery, which is followed by a cooldown period after the charging process is finished. This results in thermal cycles that can lead to thermo-mechanical fatigue and degradation of power electronic components, thereby impacting device lifetime. This paper presents a comparative study on the reliability of power devices in isolated half-bridge and full-bridge DC-DC converters in EV fast chargers. The study focuses on the differences in thermal stresses that Si switches experience in each converter during charging cycles and how it impacts the end-of-life of each device. This study provides valuable insights for selecting reliable power converters for EV fast charging applications.**

***Index Terms*—EV fast chargers, Thermo-mechanical fatigue, IGBTs' lifetime**

I. INTRODUCTION

Power converters generate power losses during operation, leading to thermal cycles of repeated heating and cooling due to changes in the load, switching actions, and environmental conditions. As power devices consist of multiple layers with different Coefficients of Thermal Expansion (CTE), temperature swings can cause thermo-mechanical fatigues such as bond-wire fatigues, solder fatigues, and degradation of chip metallization [1]. So, during the operation of power converters, failures are more likely to occur, which can significantly impact the reliability of power electronic systems [1]. Power semiconductors and capacitors are particularly susceptible to failure [2] and thermo-mechanical fatigues are the primary failure modes in power devices due to the thermal stress that can affect the reliability of the power converter [2]. The studies have revealed that thermal stresses account for 55% of all stressors and are responsible for wear-out failures in power devices, as stated in references [3]–[7].

The life of power converters is affected by various types of temperature swings, including short-term, fundamental, and long-term thermal cycles, classified according to their time scale of fluctuations [8]. Short-term temperature swings are linked to the converter's switching frequency, while fundamental thermal cycles result from load changes. Long-term thermal cycles are influenced by environmental variables such as changes in the ambient temperature [9]. These thermal cycles can cause thermo-mechanical fatigues that lead to different failure modes, reducing the converters' lifetime [9]. The thermal capacitance of layers in the power module's thermal path functions as a low-pass filter, reducing the effects of temperature swings with lower time scales (high-frequency) closer to the heatsink. However, high-frequency temperature swings are more significant at the junction, causing bondwire fatigue. In contrast, temperature swings with higher time scales affect the module's baseplate solder joint [6]. Power cycling tests reveal that short-term power cycles result in bondwire and die attach solder fatigue, while long-term power cycles cause DBC attach solder and thermal interface fatigues in addition to bondwire and die attach solder fatigues [7], [8], [10].

To enable long-distance travel for electric vehicles (EVs), off-board fast chargers are recommended over on-board chargers due to their limited capacity. These chargers utilize power converters to deliver DC power to EV batteries rapidly and alleviate size and weight issues. With power ranging from 50 kW to 350 kW, they can fully recharge EVs in approximately 30 minutes. Although AC-connected fast chargers possess certain advantages such as converter technology availability, protection devices, and approved standards, they are less efficient and more complex than DC-connected fast chargers, which are more cost-effective [11], [12]. In the context of EV Fast charging systems, the load profile of a typical converter involves a high-current pulse that lasts for a few minutes to facilitate rapid charging of the EV battery, followed by a cooling-off period upon completion of the charging process. This cyclical operation creates thermal cycles on power electronic components that may hasten their failure [13], [14]. As a result, the devices can experience failure mechanisms triggered by thermal cycling such as thermo-mechanical fatigues, leading to their end-of-life. It is therefore essential to determine the reliability of power converters in EV Fast charging systems based on the load profile.

The aim of this paper is to compare the reliability of

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isolated half-bridge (HB) and full-bridge (FB) DC-DC converters in EV fast chargers, given that power devices in each converter experience different thermal stresses depending on the converter's load profile and topology. In section II of this paper, the reliability evaluation process of power switches is explained and the lifetime of IGBT switches in HB and FB converter for EV chargers is estimated. Section III provides the conclusion of this study.

II. LIFETIME ESTIMATION OF IGBT MODULE IN HB AND FB DC/DC CONVERTERS

A. Power Converters in DC Fast Chargers of EVs

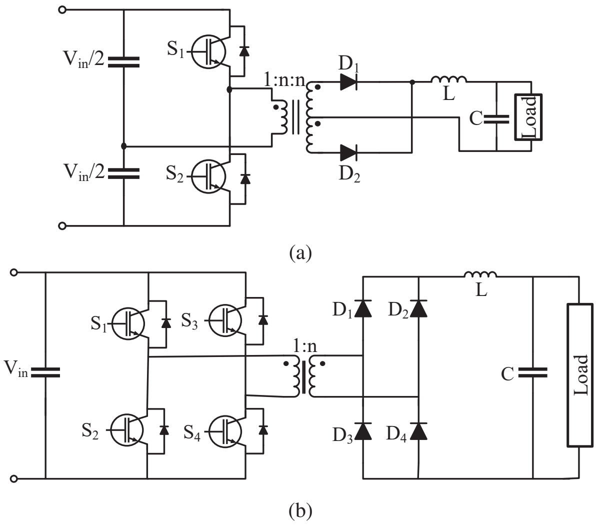
In standard DC fast chargers, there are two power conversion stages. The initial stage involves AC/DC power conversion and necessitates power factor correction (PFC). The second stage entails a DC/DC conversion process to provide the required DC voltage for the EV battery [12]. As mentioned, DC/DC converters are critical components in the DC fast charging of EVs and are utilized to regulate the voltage levels and maintain a constant power flow from the charging station to the EV battery. So the reliability and effectiveness of these converters have a significant impact on the overall reliability of the EV charging system. Thus, investigation of the reliability of DC/DC converters is crucial for improving the performance and reliability of DC fast charging stations for EVs.

In the DC fast charging of electric vehicles (EVs), both Isolated and Non-Isolated DC/DC converters are employed, depending on the application requirements. Non-isolated DC/DC converters are generally used in EV Fast chargers where a line-frequency transformer is connected between the grid and AC/DC converter, which meets a floating power supply to the EV battery [15]. Some conventional Non-isolated DC/DC converters for EV Fast chargers are presented in [12]. The simple DC/DC converter from the battery point of view in EV Fast chargers is a bidirectional boost converter where the output voltage of the AC/DC converter is higher than the battery voltage. One of the drawbacks of this converter is power rating limitation due to the flowing current through the one power semiconductor. There is also a need for a large-size of the inductor to minimize the current ripples [12]. Paper [16]–[18] proposed a unidirectional and bidirectional three-level boost converter that can be used in EV Charging systems that provide lower harmonics. Also, the current ripples can be small alongside the small inductor size. Nonetheless, this converter can negatively affect the battery system due to the high electromagnetic interference (EMI) [16], [17], and [19]. Isolated DC/DC converters are the familiar interface in EV Fast charging systems that protect the battery from the high-frequency transformer. In this case, there is no need for a line-frequency transformer between the grid and AC/DC converter. Different kinds of Isolated DC/DC converters for EV Fast charging are proposed in [12], [20]. Generally, Isolated DC/DC converters are preferred in the DC fast charging of EVs due to their ability to provide complete electrical isolation between the input and output circuits. Isolation is critical in high-voltage and high-power applications to ensure the safety of charging station operators and EV users. Also, these converters offer improved noise immunity and galvanic isolation, which enhances the reliability and performance of the charging system. Among the different types of isolated DC-DC converters, the hard-switching-based half-bridge (HB) and soft-switching-based Full-Bridge (FB) DC/DC converters are widely used in EV fast chargers due to their advantages. In this paper, we compare and evaluate the reliability of Isolated HB and FB DC-DC converters for EV fast chargers.

B. Reliability analysis and comparison of IGBT modules in HB and FB DC/DC converters in EV Chargers

Power semiconductors are a critical component of power converters and are highly susceptible to thermal stress, which results in thermo-mechanical fatigue, as previously discussed [21]. Therefore, the reliability of power electronic converters heavily depends on the reliability of these power semiconductors. In this paper, we investigate the lifetime of power components, considering the thermal stresses resulting from thermal cycles. Our study aims to analyze the impact of related factors, especially switch electrical stress, on the lifetime of power semiconductors and provide insights into designing and selecting reliable power converters for EV charging applications by comparing the half-bridge and phase-shifted Full-bridge DC/DC converters.

In this paper, the load profile-based reliability of IGBT modules in Half-Bridge (HB) and phase-shift full-bridge (PSFB) DC/DC converters is compared. Fig. 1 illustrates the structure of the HB and PSFB DC-DC converters, and in Table I, the specifications of these converters are indicated.



(a)

(b)

Fig. 1: Structure of the Isolated 55 kW HB and FB DC/DC power converters used for charging the EV a) HB DC/DC Converter b) FB DC/DC Converter.

As mentioned in the previous section, temperature cycling is a significant concern for the reliability of power converters and can be caused by changes in the load/mission profile and environment. So, the first step to assessing the reliability of power components is to model the power converters by analyzing the load/mission profile and extracting the electrical stresses of the components since the loading stresses of the power components vary due to the various load profiles.

In this paper, the reliability of IGBT modules in HB and PSFB DC/DC converters based on the charging profile of the battery is estimated and compared. The converter's load profile, which is the profile to charge a 400 V, 50.36 kWh battery, is shown in Fig. 2. The models of the converters based on this load profile are implemented in PLECS-BLOCSET, and the electrical stresses of the IGBT (IGBT's voltage and current) in both converters are shown in Fig. 3.

TABLE I: SPECIFICATIONS OF THE HB AND PSFB DC/DC CONVERTERS

Converter parameters	Value for HB	Value for PSFB
Rated power (P_o)	55 kW	55 kW
Input voltage (V_{in})	600 V	600 V
Output voltage (V_{out})	400 V	400 V
Switching frequency (f_{sw})	10 kHz	10 kHz
IGBT Module	FF200R12KE3	FF200R12KE3
Transformer ratio (n)	1:1.6	1:0.8
Inductance (L)	5 mH	9.2 mH
Capacitor (C)	45 µF	410 µF

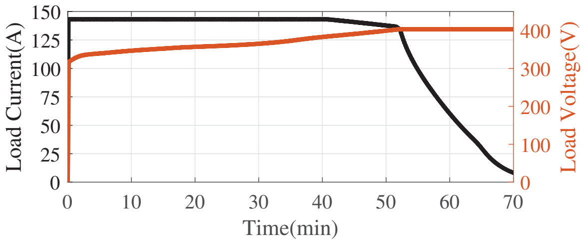
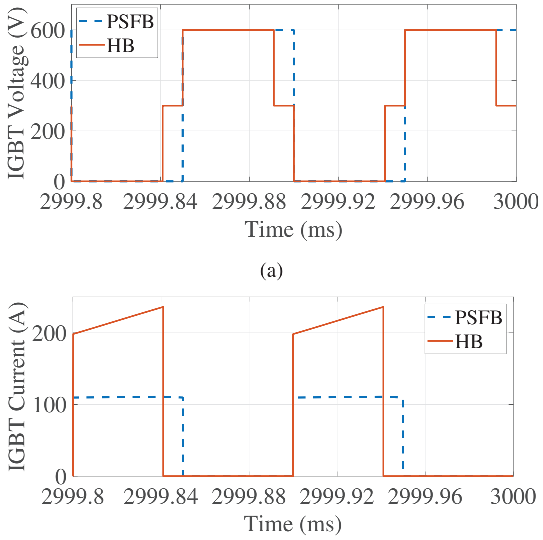


Fig. 2: The load profile of the power converter during a single battery charging session.



(a)

(b)

Fig. 3: IGBT voltage and current stresses in HB and PSFB converters a)Voltage stress of IGBT b) Current stress of IGBT.

After extracting the components' electrical stresses by converter modeling based on the load profile, the components are modeled to find out their thermal profiles, which is the second process of the power converter reliability analysis. During this process, the electrical stresses determined in the previous step are used to compute the power losses of each component, taking into account both conduction losses and switching losses. Then, electro-thermal networks, which depend on the features of the power devices, are used to extract the thermal loading of each component, which is the junction temperature profile in power devices. The thermal networks take the components' power losses as inputs.

In this study, the FF200R12KE3 IGBT power module is chosen for both converters based on safety margins, and the reliability of this module will be estimated and compared for these converters in the rest of the paper. To calculate the power losses of the IGBT module, the data provided in the device's datasheet and the lookup tables in PLECS/BLOCKSET is utilized. The datasheet of the IGBT module provides the Foster thermal network, which is used to construct the thermal description in PLECS/BLOCKSET. The datasheet also specifies a thermal resistance of 0.01 k/W for the thermal grease. Additionally, the thermal resistance of the heatsink was determined to be 0.03 k/W. Based on the constructed thermal description and assuming that the ambient temperature remains constant at 25°C, the junction temperature profile of the IGBT module for both converters was driven, as illustrated in Fig. 4. As it can be seen the IGBT junction temperature profiles are following the load profile of the converter, which was shown in Fig. 2. Additionally, based on this graph, the maximum junction temperature of the IGBT in HB is greater than the PSFB due to the higher losses in HBs' IGBT brought on by higher electrical stress.

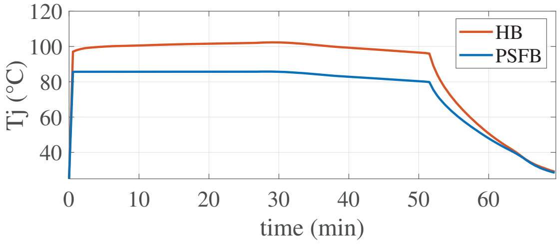


Fig. 4: The Load-varying based junction temperature of IGBT power module for both HB and PSFB DC/DC converters.

Since temperature swings due to load changes in EV charging have a far larger amplitude than temperature fluctuations caused by converter switching activity during EV rapid charging, the most significant factor contributing to IGBT life consumption in EV charging converters is temperature variations caused by load changes. So, the lifetime of the power module is determined in this paper based on temperature variations brought on by changes in the load.

After estimating the junction temperature profile, predicting the component's number of cycles to failure (N_f) is the next phase in the reliability evaluation procedure for power components. The extracted junction temperature of the power semiconductors is defined as an input of this process in order to derive the N_f by empirical lifetime models. Various lifetime models have been developed based on extensive data obtained from power cycling experiments. These models consider different factors that can impact the reliability of components, which were taken into account during the power cycling tests. Several papers have proposed lifetime models, including LESIT, CIPS 2008 (Bayerer), corrected CIPS 2008, and the Skim models, which are based on the main failure mechanisms [22]–[25]. For example, the LESIT model is suitable when bondwire failure is the main cause of fatigue [22]. On the other hand, the CIPS 2008 lifetime model is more applicable when heating time plays a significant role in the failure mechanisms or when solder joint failure and bondwire failures are the predominant failure mechanisms [23]. The corrected CIPS 2008 model is a reasonable choice for various temperature cycle time scales and conditions where bond wire and solder joint failure modes are the primary failure mechanisms [13], [26]. So, in order to accurately estimate the lifetime of the device, it is crucial to select a suitable lifetime model that corresponds to the most relevant failure mechanism. In the case of EV chargers, the charging sessions lead to longer temperature cycles (t_on), which in turn impact the solder attached to the DBC (Direct Bond Copper). Also, a corrected CIPS lifetime model considers different time scales and takes into account the specific characteristics of the power device under study. Consequently, the corrected CIPS lifetime model is deemed the most suitable in this study and utilized to determine the number of cycles to failure. (1) and (2) show the CIPS (Bayerer) and corrected CIPS lifetime models.

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

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

Where N_f is the number of cycles to failure, ΔT_j is the temperature swing, T_jmin is the minimum junction temperature, and t_on is the heating time. The other factors, A, $\beta_1 - \beta_6$ are the parameters that are given in [23]. Also, 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, which are assumed to be 20 A, 12 V, and 250 μ, respectively, in this paper. Also, t_on is 4199.8 s based on the load profile. So the estimated number of cycles to failure based on the CIPS corrected model for the device under study in both HB and PSFB DC/DC converters are illustrated in Table II.

Miner's rule is used to calculate the annual accumulated Damage of the device after predicting the device's number of cycles to failure and the number of thermal cycles [27]. The load/mission profile fluctuations in power electronic applications, such as PV, MMC, and Wind applications, cause a convoluted junction temperature profile in power switches, making it challenging to determine the various ΔT_js through activity. As a result, counting methods such as the Rainflow algorithm are used for calculating the number of cycles in a given T_j and T_jmin. (3) shows Miner's rule, which is used to find the annual damage of the device.

TABLE II: IGBT MODULE NUMBER OF CYCLES TO FAILURE IN HB AND PSFB DC/DC CONVERTERS

Lifetime parameters	**Value for HB**	**Value for FB**
ΔT_j(°C)	77.4	60.72
T_jmean (°C)	63.7	55.36
Number of cycles to failure (N_f)	9.6769×10^4	28.263×10^4

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

Where n_j is the number of cycles occurring and N_fj is the number of cycles to failure at the jth power cycle.

The predicted lifetime of the IGBT module is then found by adding up the D until it equals unity, which is when a device hits its end-of-life. So, using (4), the devices' end-of-life (LF) is determined.

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

Since the number of cycles experienced by the device in this study is contingent upon the number of charging sessions, the static values of IGBT damage and end-of-life have been estimated based on the corresponding number of charging sessions. The estimated static values by using (3) and (4) are depicted in Fig. 5 and Fig. 6. It is important to note that the range of charging sessions considered in this study spans from a minimum of 5 sessions per day to a maximum of 15 sessions per day. This range captures the variation in charging activity observed in the case study. These figures compare the IGBT Module damage and lifetime in HB and PSFB DC/DC converters.

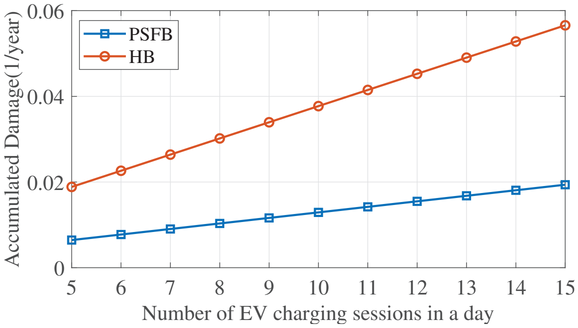


Fig. 5: IGBT accumulated Damage comparison in HB and PSFB DC/DC converters based on the number of charging sessions.

The power component's reliability evaluation process ends with the consideration of uncertainties to determine the components' cumulative distribution function (CDF) and B_{10} lifetime (the point at which 10% of the devices fail) by Monte

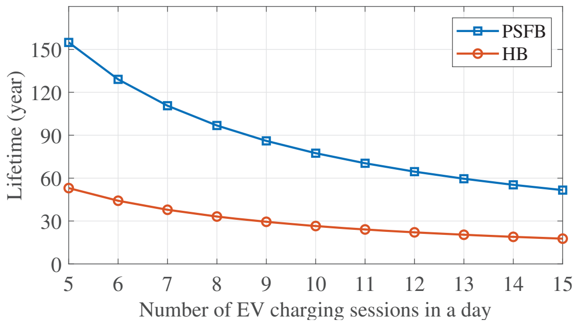


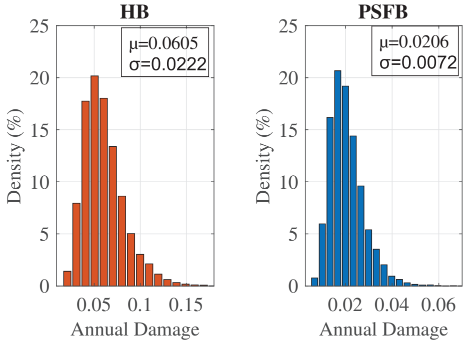
Fig. 6: IGBT lifetime comparison based on the number of charging sessions in HB and PSFB DC/DC converters.

Carlo methods and Weibull distribution [28], [29]. The IGBT lifetime data in the previous part were estimated assuming that all IGBTs deteriorate uniformly, nevertheless, in reality, there are uncertainties regarding the constant variables in the lifetime models that have been determined from accelerated aging tests employing a particular amount of testing samples. In addition, variations in the component's manufacturing process bring another type of uncertainty, which influence the minimum junction temperature and junction temperature fluctuation. So, to determine the precise devices' lifetime, the accumulated damage probability distribution function and end-of-life probability distribution function are driven by considering these uncertainties, and these functions are extracted by the Monte Carlo method [28]. So, In this study, a Monte Carlo simulation is applied and the variations are considered for β_1, β_2, ΔT_{j} and T_{jmin} which are 5%, 10%, 5%, and 10%, respectively.

It should be pointed out that the quantity of charging sessions influences the lifetime of the module, more charging times lead to more thermal cycles, which eventually shorten the lifetime of the module. Therefore, in this paper to extract the IGBT's accumulated damage and end-of-life distributions, the maximum number of charging sessions has been considered which is 15 per day in this study.

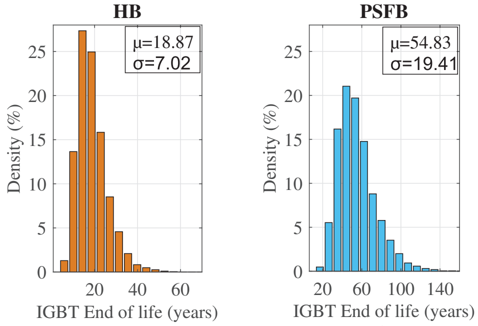
Fig. 7 compares the accumulated damage probability distribution function of the IGBT module in HB and PSFB DC/DC converters which were extracted based on the mentioned variations by Monte Carlo analysis. As well as the IGBTs' end-of-life probability distribution function comparision in HB and PSFB DC/DC converters are illustrated in Fig. 8. Where μ and σ are the mean value and standard deviation, respectively.

Finally, the Reliability of each IGBT is driven by using the Weibull distribution [29] and compared for both converters in Fig. 9 (a). According to this figure, the B_{10} lifetime of each IGBT, which denotes that 10% of IGBTs degrade after that period, is 9.52 and 28.46 years in HB and PSFB DC/DC converters, respectively. Also, to see the whole IGBTs reliability in both converters RBD (Reliability Block Diagram) method [30] was used since PSFB has two more IGBTs than the HB converter which can decrease the system-level reliability of the converter. The reliability comparison of whole IGBTs in HB versus PSFB converter is indicated in Fig. 9 (b).



(a) (b)

Fig. 7: Accumulated damage probability distribution function of IGBT Module, a) in HB, b) in PSFB DC/DC converters.



(a) (b)

Fig. 8: End-of-life probability distribution function, a) in HB, b) in PSFB DC/DC converters.

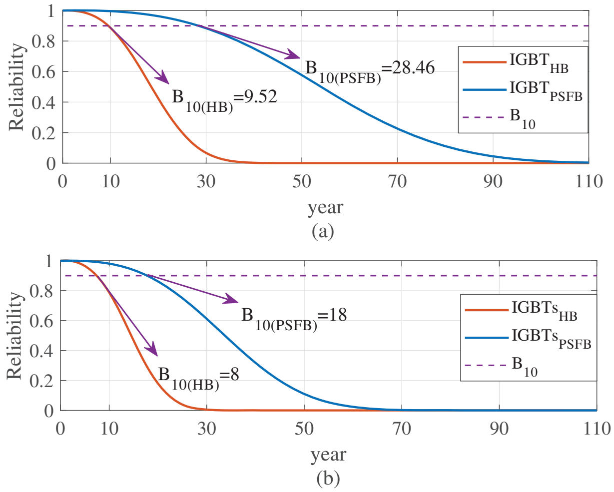


Fig. 9: Comparison of component Reliability function, a) Reliability and B_{10} comparison of each IGBT in HB and PSFB DC/DC converters, b) Reliability and B_{10} comparison of whole IGBTs in HB and PSFB DC/DC converters.

Due to the fact that the switch in the HB DC/DC converter experiences twice the current stress compared to the PSFB DC/DC converter for identical input, output voltage, and power and this point reveals in Fig. 3, it was anticipated that the switch in the HB converter would have a shorter lifetime compared to the PSFB converter. This expectation regarding the lifetime difference is supported by the results obtained in this study (see Fig. 6 and Fig. 9 (a)), as the estimated B_{10} lifetime for each IGBT in the PSFB converter is approximately three times greater than that of the HB converters' IGBT. This can be attributed to the higher power losses in the HB converter than the PSFB converter, leading to increased junction temperature swings and a higher mean junction temperature on the switch which were indicated in Fig. 4. These factors contribute to a decrease in the switch's lifetime of the HB.

III. CONCLUSION

In this paper, IGBT modules in 55 kW HB and PSFB DC/DC converters used in EV DC chargers are compared in terms of their quantitative lifetimes. The reliability analysis focuses on the load profile of DC charging for EVs, considering the impact of thermal cycles during charging. The B_{10} lifetime of each IGBT was calculated to be 28.46 years for the PSFB converter and 9.52 years for the HB converter. This stark contrast emphasizes the substantial influence of temperature cycles resulting from the electrical stress on the IGBT. It was discovered that the lifetime of the PSFB IGBT is three times longer than the HB IGBT for this identical case study. Therefore the lower current stress on the IGBT of PSFB in comparison to HB makes it more reliable. These findings highlight the significance of considering reliability-based criteria when selecting converters for DC charging applications. It underscores the importance of understanding the impact of electrical stresses on device lifetimes and the need for reliable converter designs in the context of EV charging systems.

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