

Article

Comparative Damage Analysis of Critical Sub-Profiles in Random Mission Profile of Electric Drive Power Converters Under Controlled Thermal Conditions

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Abstract

This paper presents a signal-processing methodology for assessing thermal stress and fatigue damage in IGBT modules. This study utilizes junction temperature data from operational frequency converters at a belt conveyor station rather than conventional approaches. These in situ measurements ensure that thermal profiles accurately reflect actual loading conditions. A reliability framework based on mission profiles assesses the contribution of each operational regime. We examine transient overloads, steady-state operation, and periods of low load specifically. We apply Miner's rule and rainflow counts to the analyzed temperature profiles. This enables the assessment of accumulated damage in each operational segment. The primary finding indicates that a minimal duration of operational time constitutes the majority of total lifetime utilization. This disproportionate impact is attributable to transient overloads. This study quantitatively evaluates this phenomenon using Rainflow analysis to disaggregate mission profiles. The proposed framework enhances the precision of reliability engineering. It provides a valuable foundation for enhancing maintenance planning and control strategies in practical scenarios.

Keywords: mission profile; IGBT modules; damage analysis; rainflow method; generic lifetime model

1. Introduction

Electric drive power converters are essential in industrial automation, transportation, and energy conversion applications. Their operational lifetime is a critical factor for overall system reliability and cost [1]. As stated in [2], the power converter is one of the most sensitive subsystems regarding reliability.

Reliability assessment of power semiconductor components has historically relied on constant-load models, which provide a useful reference base by evaluating component endurance under fixed, often adverse, electrical and thermal stresses [3]. To assess overall system availability, statistical reliability models, such as those that calculate failure rates in time (FIT) or mean time between failures (MTBF), are a standard industry tool [4]. In the reliability assessment of the belt conveyor drive system presented in the paper [5], statistical models were applied to calculate failure rates in FIT and mean time to failure (MTTF) values for key components such as power electronics, induction motors, and mechanical transmissions. These calculations demonstrate the practical application of



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industry-standard reliability metrics to evaluate and compare the operational performance of different drive configurations under realistic mining conditions. The paper [6] provides a comprehensive overview of how reliability, availability, and maintainability are defined and applied to high-power variable-speed drive systems, using failure rates expressed in FIT and MTBF as fundamental metrics. The authors emphasize that these statistical models are essential for evaluating system performance and for establishing a common understanding between customers and suppliers when specifying reliability requirements. The publication [7] supports this approach by offering a detailed statistical analysis of failures in adjustable speed drives (ASDs). It uses Mean Time Between Failures (MTBF) calculations to compare the reliability of ASD-fed motors and direct-on-line motors in the chemical industry. The authors demonstrate that efficient engineering practices can significantly enhance the estimated MTBF of ASDs, making it more aligned with the reliability standards required for conventional motor installations.

Traditional lifetime estimation methods often rely on constant or simplified load assumptions. These approaches can be inaccurate. They may underestimate the damage caused by specific, short-duration operational events embedded within the broader profile. Model-based methods yield more accurate reliability predictions by combining empirical accelerated test results with the physics of failure for components. This method also accounts for how product-level stresses affect individual components [8].

Empirical models are developed based on experience and large databases obtained from accelerated aging experiments conducted over many years for different module technologies [8]. The accuracy of these models can only be guaranteed when they are applied under conditions similar to those in which they were originally created [9].

Empirical lifetime models make it possible to estimate the number of cycles to failure (N_f) for a single load cycle, which is characterized by the thermal cycle depth (ΔT), the maximum temperature ($T_{\max}$), and the heating duration (T_{on}). Such periodic cycling is mainly applicable in controlled thermal cycling tests that provide the failure data used to build these models. In real operating conditions, however, load cycles are rarely uniform or strictly periodic. Therefore, it becomes essential to break down realistic thermal load profiles of power modules into simpler sub-cycles that can be analyzed using these empirical models. Authors in [10] directly address this issue by comparing several lifetime models for IGBT power modules. They show how rainflow counting algorithms can break down realistic in-service thermal load profiles. This includes minor stress cycles, enabling accurate lifetime prediction. The authors show that neglecting the cumulative effect of non-uniform, low-amplitude thermal cycles lead to significant errors. Such cycles are common in real operating conditions like wind turbine converters. Their finding contrasts with models that properly account for these sub-cycles. In the paper [11], authors refine the CIPS08 and SKiM63 empirical lifetime models using experimental power cycling test data. Their work demonstrates that breaking down complex thermal loads into sub-cycles for analysis is essential. Their recalibrated models show that neglecting realistic, non-uniform cycling can lead to significant overestimation of IGBT lifetime. This approach is achieved through the rainflow counting method and the concept of linear damage accumulation [12].

The rainflow algorithm is an important cycle counting method from material fatigue analysis that extracts and parameterizes temperature cycles from irregular load patterns to estimate reliability and lifetimes of power electronic modules [13]. This directly aligns with findings in reference [14]. An analysis of a hybrid vehicle's load profile demonstrated that accurate cycle extraction requires the rainflow algorithm. Passive temperature cycles significantly contribute to module aging. Therefore, they must be properly parameterized alongside cycle amplitude, absolute temperature, and heating time. Authors in the reference [15] directly apply this concept by using the rainflow algorithm to decompose

an irregular junction temperature profile of a grid-side inverter into elementary cycles characterized by amplitude. This decomposition is essential for linking field-operation thermal loading to the device's power cycling data, enabling the estimation of the inverter's overall lifetime.

For real-time lifetime estimation under variable loads, an online rainflow counting method provides an efficient alternative compared to traditional offline algorithms by processing cycles as they occur, requiring less memory and computational resources. This requirement is addressed explicitly by the authors of the research [16]. They present an online, stack-based rainflow algorithm that processes extremal values as they occur. This enables an estimation of real-time life consumption without requiring the entire load history. The authors demonstrate that this online method reduces memory storage and computational demands compared to traditional offline implementations. It also preserves full cycle information, which ensures greater accuracy in applications like power electronic modules. The paper [17] directly implements the concept of real-time lifetime estimation. It applies an online rainflow counting algorithm to process junction temperature cycles in real time for a three-level traction converter. Their method uses two variable stacks to store and process extreme values as they occur. This enables continuous lifetime consumption calculation with the Lesit model. The approach requires significantly less memory than traditional offline methods.

Palmgren–Miner's Law is commonly used in fatigue damage accumulation. The usage of Miner's rule for calculating relative damage accumulation in IGBT modules under variable loading is experimentally supported. Studies involving power cycling tests with mixed stress cycles have validated that the rule's predictions of cumulative damage correspond reliably with the observed degradation trends [18].

In the proposed reliability-oriented design procedure [19], defining the mission profile is one of the first tasks. A mission profile describes the real operating conditions that a power converter is expected to experience over its lifetime, such as load levels, environmental conditions, and usage patterns. The paper [19] directly supports this statement by proposing a systematic reliability-oriented design procedure where mission profile analysis is identified as a fundamental first step in the concept phase. The authors demonstrate this through a case study on a 2.3 MW wind power converter, where wind speed data are used as the mission profile to perform electrical and thermal stress analysis for lifetime prediction of IGBT modules. The paper [20] aligns with this concept by identifying mission profile analysis as a fundamental first step in the proposed reliability-oriented design procedure for power converters. The authors emphasize that understanding real operating conditions—such as wind speed distributions for a 2.3 MW wind power converter—is essential for performing accurate electrical and thermal stress analysis, which directly feeds into the physics-of-failure-based lifetime prediction of critical components like IGBTs.

The paper [21] presents a method for predicting and validating wear-out reliability metrics in power semiconductor devices using mission profiles for motor drive applications. It proposes the Cumulative Distribution Function (CDF) as a more advanced and informative metric compared to traditional approaches like MTTF. The work details a four-step prediction flow involving stress translation, strength testing, CDF mapping, and metric deduction, with experimental validation demonstrating the method's accuracy.

In paper [22], the authors present a holistic technique for wind power converters, combining comprehensive environmental mission profiles with a dynamic Copula model to address submodule lifespan correlations. Their findings indicate that actual, fluctuating loads, particularly under significant stress, considerably accelerate the degradation of components. This study confirms the essential role of mission profiles in evaluating fatigue life and highlights the systemic consequences of failure dependencies among components.

For lifetime estimation in wind power converters, mission profiles are translated into multi-timescale thermal load profiles, and the results are aggregated using Miner's rule to enhance accuracy [23].

In this paper [24], with a focus on realistic mission profiles with variable stresses, methods for predicting the lifetime of complex power conversion devices and systems are improved.

Objectives of This Study

The primary objective of this study is to perform a comparative damage analysis of these critical sub-profiles. Using a controlled thermal environment to isolate stress effects, the analysis applies rainflow counting and a physics-generic-based lifetime model [25] to a 24-h mission profile. The goal is to quantify and rank the relative damage contribution of each identified sub-profile.

In this paper, the Palmgren–Miner linear damage accumulation rule was applied not for absolute lifetime estimation, but as a relative damage analysis tool. Its purpose was to quantify and rank the contribution of individual load sub-profiles to the total accumulated damage over a defined 24 h mission profile.

This paper is structured as follows. Section 2 presents the case study of an electric drive system for a belt conveyor station. Section 3 defines the concept of the random mission profile used for analysis. Section 4 explains how to use this profile by breaking down a 24 h operational cycle into three separate load sub-profiles. Section 5 reviews relevant lifetime models, including a generic model and the Infineon-specific model. It outlines the assumptions for the comparative damage assessment. Section 6 describes the overall methodology for reliability analysis. Sections 7 and 8 present and discuss the results, respectively. Finally, Section 9 provides the conclusions drawn from the study.

2. Case Study on an Electric Drive of a Belt Conveyor Station

The case study, which focuses on the electric drive system of a belt conveyor station, is conducted to demonstrate the proposed comparative damage analysis. Driving station induction motors (IMs) are powered by frequency converters (FCs) where DC link circuits are galvanically isolated. From an electrical standpoint, this corresponds to the definition of single-motor drives (SMDs).

The configuration of the analyzed belt conveyor system is shown in Figure 1. The system consists of three independent drives, each comprising a frequency converter and an induction motor. The temperature monitoring points $T_{j_IGBT_1}$, $T_{j_IGBT_2}$, and $T_{j_IGBT_3}$ indicate the locations where IGBT module junction temperatures are measured for each respective drive. Figure 1 illustrates the schematic of the three-drive belt conveyor system analyzed in this study. This configuration enables individual thermal stress assessment of each power converter under identical operating conditions.

The induction motors driving the conveyor drums, over which the rubber belt is wound, are elastically coupled to each other with variable coupling parameters via reducers, drums, and the rubber belt. From a mechanical standpoint, the electromechanical drives are multi-motor drives, as they share a common, variable mechanical load (Figure 1).

The frequency converters are housed in cabinets mounted within a shared container, which is additionally cooled by an external cooling system. The heat generated during the operation of the frequency converters is released inside the container and dissipated via the container's external cooling system. From a thermal perspective, the frequency converters are mutually coupled through the common external cooling system, constituting a multi-motor drive (MMD).

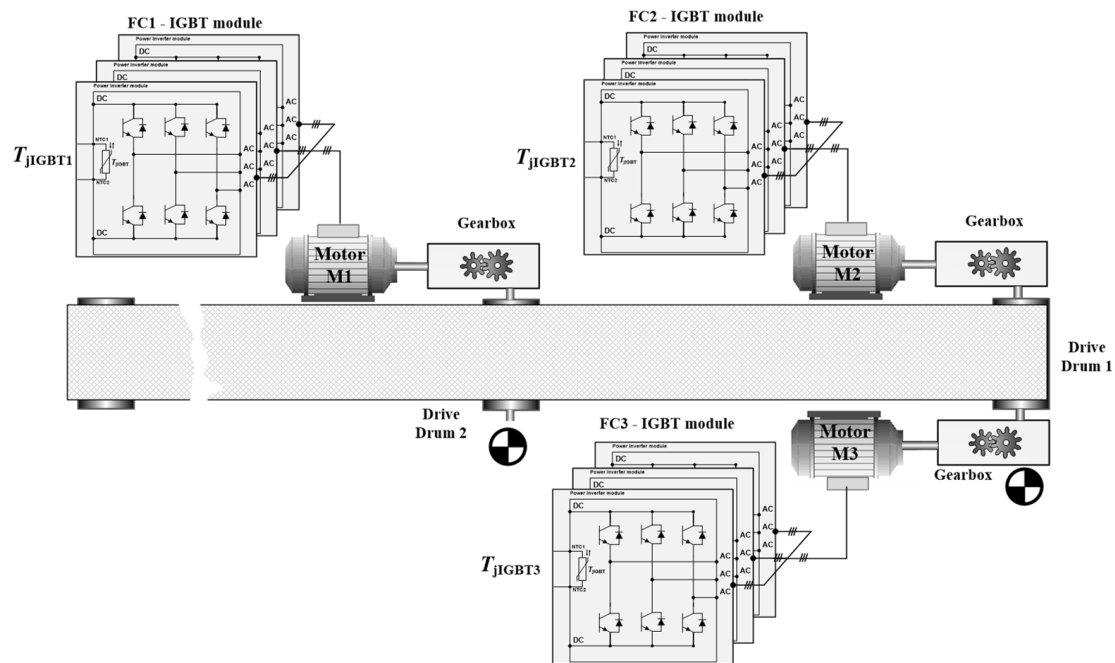


Figure 1. Schematic of the three-drive conveyor system with individual IGBT module temperature monitoring points ($T_{j_IGBT_1}$, $T_{j_IGBT_2}$, $T_{j_IGBT_3}$).

Drive temperature monitoring is based on the power semiconductor (IGBT) temperature measurement, which is compared with a fixed maximum IGBT temperature limit [26]. The measured temperature signals of the IGBT modules from all frequency converters (Figure 1) are transmitted to the superior control system, which is implemented in the PLC of the conveyor drive station. The temperature monitoring system for each IGBT module is implemented as shown in Figure 2. The signal flow begins with the built-in NTC temperature sensors [27] within each IGBT module. The analog signals from the NTCs are converted to a digital format through A/D conversion, processed by the microcontroller unit (MCU) integrated in the drive controller, and then transmitted via the PROFIBUS slave module. The PROFIBUS master module in the PLC collects temperature data from all three drives, enabling centralized thermal monitoring and data acquisition for further reliability analysis.

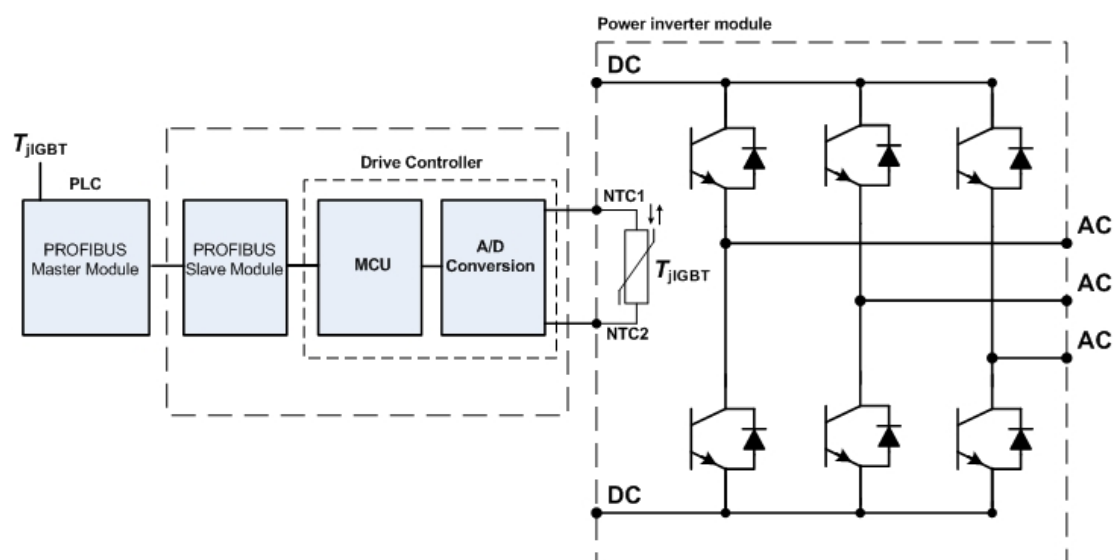


Figure 2. Signal flow diagram for IGBT module temperature monitoring via NTC and PROFIBUS interface.

Table 1 summarizes the key parameters of the frequency converter and induction motor used in the analyzed drive system. The frequency converter specifications include output current ratings for different load profiles (normal, light-overload, and heavy-duty use), as well as corresponding output power levels. The induction motor data provides rated power, voltage, current, speed, power factor, and energy efficiency, which are essential for thermal and reliability modeling of the drive system.

Table 1. Frequency Converter (FC) parameters [28] and Induction Motor (IM) data.

Frequency Converter (FC)	
Output Current, Normal Use (I_n):	1414 A
Output Current, Light-Overload Use (I_{LD}):	1357 A
Output Current, Heavy-Duty Use (I_{HD}):	1058 A
Output Power, Normal Use (P_n):	1400 kW
Output Power, Light-Overload Use (P_{LD}):	1400 kW
Output Power, Heavy-Duty Use (P_{HD}):	1000 kW
Induction Motor (IM)	
Rated power (P_n)	1300 kW
Nominal voltage (U_n)	690 V
Rated Current (I_n)	1307 A
Number of poles ($2p$)	6
Rated speed (n_n)	994 min ^{−1}
Rated Power factor ($\cos\varphi_n$)	0.86
Rated Energy efficiency (η_n)	0.967

3. Random Mission Profile

Based on Figure 3a, we can conclude that the volumetric material flow is time-variable and of a stochastic nature. Comparing the temporal change of the material flow with the temporal change of the motor torque, Figure 3b reveals a linear dependence of the motor torque on the volumetric material flow. In other words, the motor torque is a temporally scaled function of the material flow. This linearity does not hold only during the period when the conveyor runs idle; that is, when there is no material on the belt. During this period, both the speed and the motor torque are constant. The motor load in this period creates the friction of the rotating parts along the belt moving at a constant speed (Figure 3c).

According to the diagram in Figure 3d, which shows the active electrical power of the auxiliary supply system, the external cooling unit operates under a separate, intermittent control logic that is decoupled from the instantaneous mechanical load. One compressor runs continuously, providing the base cooling capacity, while the other is periodically switched on and off. The external cooling system operates in an intermittent mode in which one compressor is constantly on, while the other is alternately switched on and off. It does not respond to the instantaneous motor torque changes but to the cumulative thermal load within the container with the frequency converter cubicles.

The junction temperature profile of the IGBT module is a complex function that depends on the combined effect of the variable motor torque, the constant no-load torque, and the operation of the intermittent cooling system. The waveform of the IGBT module's temperature profile is predominantly influenced by the variable material flow; i.e., the variable load torque. Consequently, the external cooling system, operating intermittently and independent of the drive load variation, also exerts a significant influence. During no-load periods, the IGBT module's temperature profile tends to equalize with the air temperature inside the container.

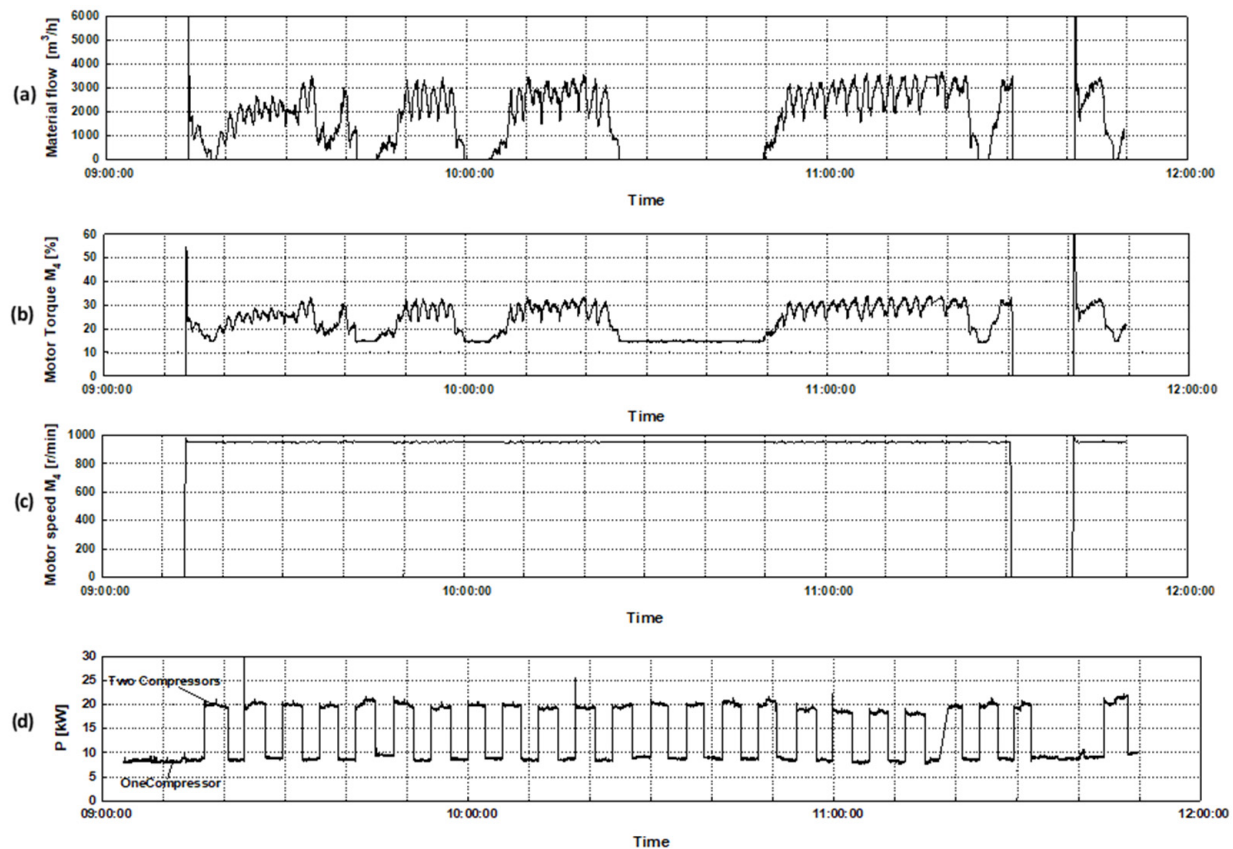


Figure 3. Torque dependence from volume flow material at constant speed: (a) Volume material flow in m^3/h ; (b) Motor Torque %; (c) Motor speed in r/min ; (d) Active power of auxiliary supply system.

4. Electric Drive with Random Load 24 h Mission Profile

A supervisory control system implemented in a PLC regulates the average speed of all motors and maintains an even torque distribution among them. The rated characteristics of the motors and the frequency converters are identical, which, under balanced torque load distribution, results in approximately the same power losses in the IGBT modules of the converters. Due to the symmetry of the rated parameters, control methods of the power converters, and uniform load distribution, the junction temperature profile $T_j(t)$ of the IGBT modules in all frequency converters across different drives is almost equable.

Figure 4 depicts the measured temperatures of the IGBT modules from the three frequency converters at the conveyor drive station. The temperature plot shows that the variations in temperatures $T_{j_IGBT_1}$, $T_{j_IGBT_2}$, and $T_{j_IGBT_3}$ are mostly identical. The exception is the temperature graph for $T_{j_IGBT_1}$, which deviates slightly and is positioned above the graphs for $T_{j_IGBT_2}$ and $T_{j_IGBT_3}$.

Uniform load distribution results in an equalized thermal profile distribution of the IGBT modules and prevents excessive overheating of individual IGBT modules. In this way, the multi-motor drive control system facilitates an increase in the lifetime of the IGBT modules, as it does not allow a rise in the mean temperature of any individual IGBT module powering an overloaded drive over an extended period.

In our case study, a uniform load distribution has been achieved among the frequency converters of individual drives in a belt conveyor system. This approach falls under active thermal stress control at the multi-motor drive level and can be viewed as a specific form of system-level active thermal control [29,30] applied to a multi-motor drive. The method ensures balanced power sharing among converters in drives that are mechanically and thermally coupled. Consequently, the thermal profiles of the IGBT modules are equalized,

which prevents localized overheating. This contributes to improved reliability and lifetime of the power electronic system.

Figure 4 shows the recorded data for a multi-motor belt conveyor drive during a 24 h period. The measured variables throughout operation were the temperatures of the junctions of the IGBT modules from three frequency converters ($T_{J_IGBT_1,2,3}$), the temperature of the air within the container (T_{air_in}), the temperature of the air outside the container ($T_{air_outdoor}$), and the load torque (Torque).

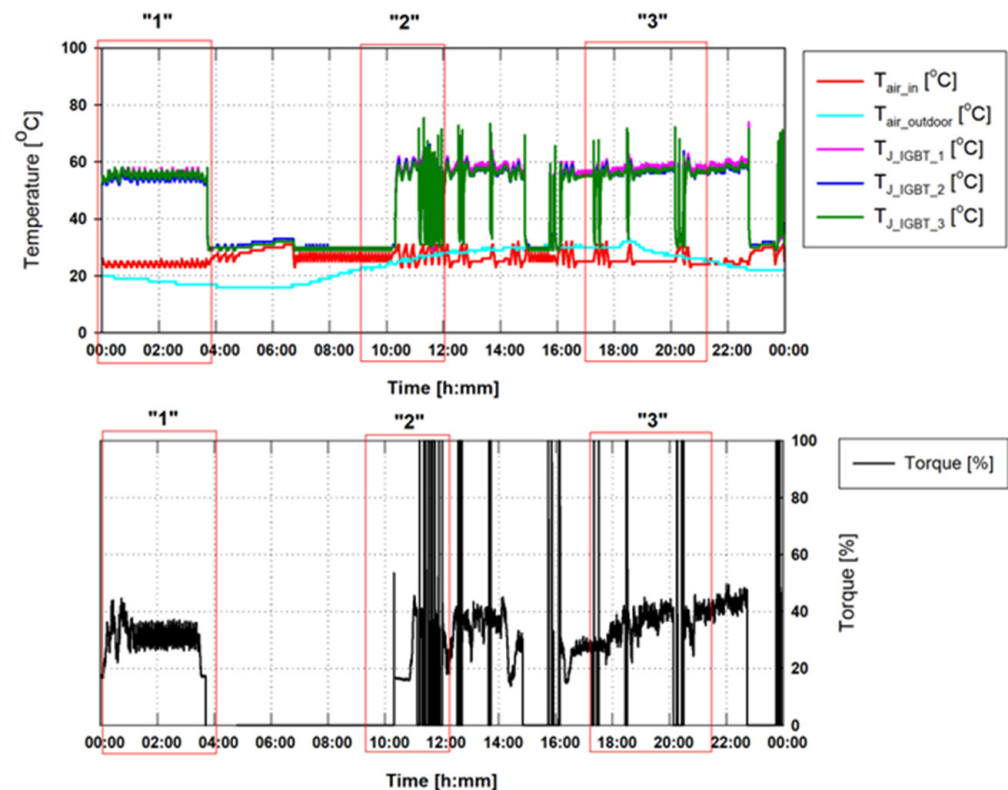


Figure 4. Daily Operational Diagram of a Belt Conveyor Drive Station: (Torque) Load torque as a percentage of motor rated torque; (T_{air_in}) Internal temperature of the container housing the frequency converters; ($T_{air_outdoor}$) Ambient temperature external to the container; $T_{J_IGBT_1}$, $T_{J_IGBT_2}$, $T_{J_IGBT_3}$, junction temperatures of IGBT modules in frequency converters FC_1 , FC_2 , and FC_3 .

The considerable, simultaneous increases in T_{air_in} and all three T_{J_IGBT} curves are direct thermal reactions to periods when the conveyor drive system is under a lot of mechanical stress. When the temperature stays low for a long time, the conveyor drive system is either off or not being used. There is a steady temperature difference between the IGBT junctions (T_{J_IGBT}) and the air temperature inside the container (T_{air_in}). This gradient, which stays very continuous across cycles, shows the path of thermal resistance from the IGBT chips to the internal air through their modules and heatsinks. Because the air within it is always moving, it stays stable, which means it can release heat consistently. The T_{air_in} trace reacts more slowly and with less energy than the T_{J_IGBT} traces, which rise more quickly. Furthermore, T_{air_in} keeps going down after each load event, even while the outside temperature ($T_{air_outdoor}$) rises throughout the day, which shows that the exterior cooling system is actively removing heat.

4.1. Sub-Profile 1

The first analyzed load sub-profile, representing a period of reduced operational activity, is shown in Figure 5. The duration of sub-profile 1 (3 h, 38 min) is determined from Figure 4 by the actual timestamps of the first (00:00) and last data (03:38) points in

its sequence. In Figure 5, load torque oscillations around the mean value of 25% can be observed. The junction temperatures ($T_{j_IGBT_1}$, $T_{j_IGBT_2}$, $T_{j_IGBT_3}$) of the IGBT modules in frequency converters FC_1 , FC_2 , and FC_3 oscillate with a small variation between the maximum and minimum temperatures. This sub-profile captures a four-hour interval during which the load torque is maintained at approximately 40% of the motor rated torque. The figure presents the measured junction temperatures of all three IGBT modules ($T_{j_IGBT_1}$, $T_{j_IGBT_2}$, $T_{j_IGBT_3}$), together with the internal container temperature (T_{air_in}) and the outdoor ambient temperature ($T_{air_outdoor}$). These thermal responses correspond to the applied load torque conditions and provide the basis for damage contribution analysis of this specific operational regime.

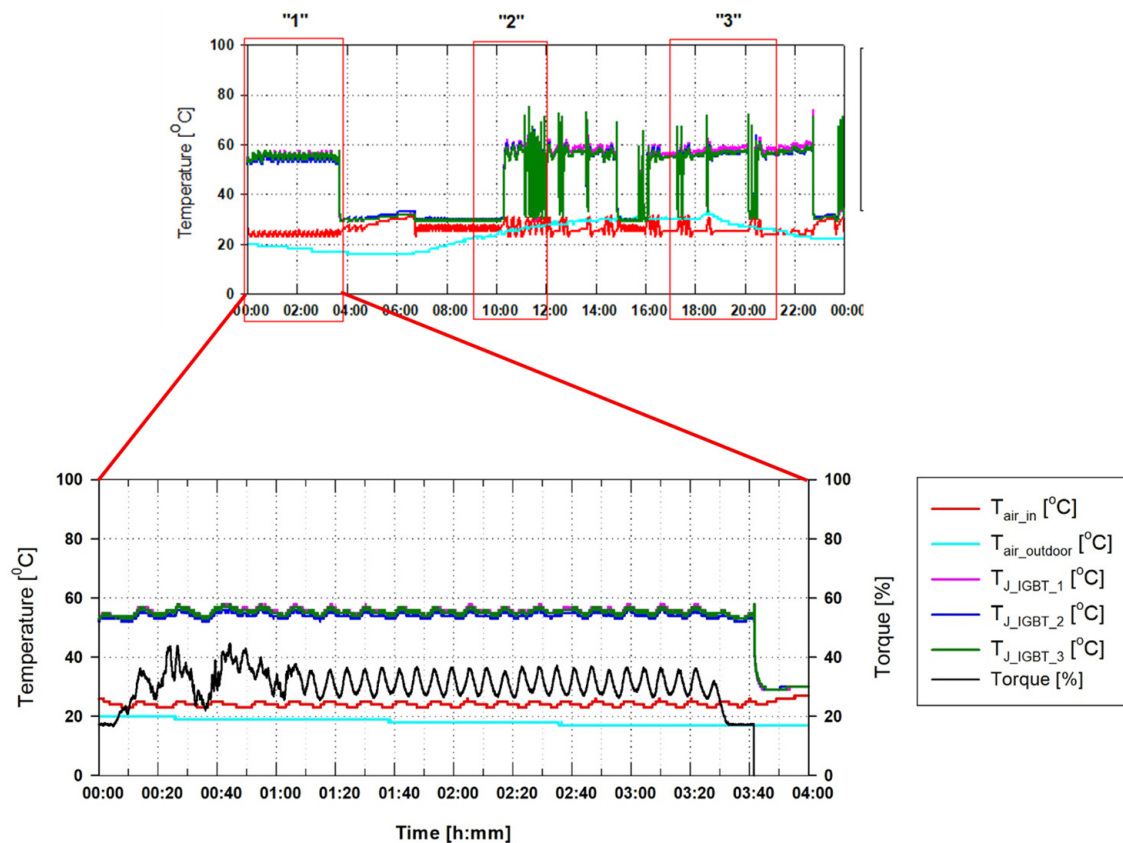


Figure 5. Sub-profile 1: (Torque) Load torque as a percentage of motor rated torque; (T_{air_in}) Internal temperature of the container housing the frequency converters; ($T_{air_outdoor}$) Ambient temperature external to the container; $T_{j_IGBT_1}$, $T_{j_IGBT_2}$, $T_{j_IGBT_3}$, junction temperatures of IGBT modules in frequency converters FC_1 , FC_2 , and FC_3 .

It is characteristic that a quasi-steady state is established in which the curves of all three temperatures are approximately equalized. At the end of the sub-profile, the load drops to zero (torque), while the IGBT module junction temperatures approach the internal container air temperature in value.

4.2. Sub-Profile 2

Figure 6 indicates that sub-profile 2 endures for 2.40 h. This interval captures a period of increased operational activity, with the load torque rising from approximately 40% to 80% of the motor rated torque. Figure 6 displays the corresponding thermal responses, including the junction temperatures of all three IGBT modules ($T_{j_IGBT_1}$, $T_{j_IGBT_2}$, $T_{j_IGBT_3}$), the internal container temperature (T_{air_in}), and the outdoor ambient temperature ($T_{air_outdoor}$). The progressive increase in load torque during this sub-profile results in distinct tempera-

ture elevation patterns across all monitored points, providing essential data for assessing damage accumulation under varying thermal stress conditions. At its onset, the conveyor drive station is idle, with the load torque at zero and the IGBT module temperatures stable. The exterior cooling system works on and off with just one compressor, which can be seen from the trend of the recorded air temperature in the container, $T_{\text{air_in}}$.

The initial transient process occurs when the drive turns on without any load, and then the torque stays at a constant amount. After that, a second transient starts the load increase phase, during which the torque begins to grow in an uneven wave. After this, the drive stop event occurs, which is shown by a negative motor torque value, and then there is an immediate restart, which is shown by a positive motor torque. During both transients, the IGBT junction temperatures reach different maxima, and both occurrences cause the temperature increase. A total of seven such start-stop cycles of different lengths had been accomplished by the ending of the observed sub-profile.

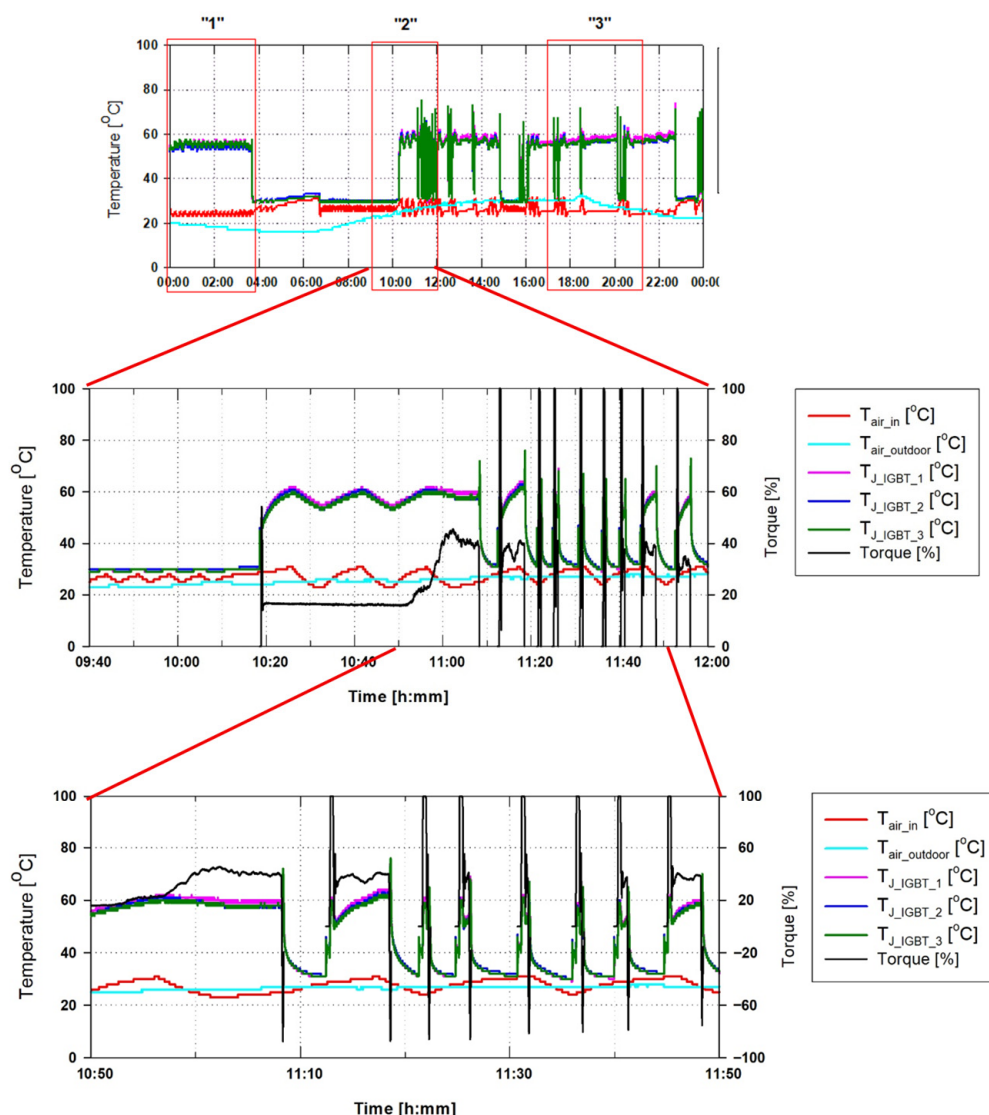


Figure 6. Sub-profile 2: (Torque) Load torque as a percentage of motor rated torque; ($T_{\text{air_in}}$) Internal temperature of the container housing the frequency converters; ($T_{\text{air_outdoor}}$) Ambient temperature external to the container; $T_{j_IGBT_1}$, $T_{j_IGBT_2}$, $T_{j_IGBT_3}$, junction temperatures of IGBT modules in frequency converters FC_1 , FC_2 , and FC_3 .

4.3. Sub-Profile 3

According to Figure 7, the initial timestamp data point of sub-profile 3 is 16:47:00. Its completion is at 21:36:00. The total duration of sub-profile 3 is 4.82 h. During this sub-profile 3, three cycles of consecutive starts and stops were recorded. It can be observed that during stopping, the braking torque reaches approximately 70% of the motor's nominal torque value. The IGBT junction temperature rise is greatest during the stopping transient. This temperature rise in the IGBT module is even higher than the temperature rise during drive start-up.

This phenomenon occurs due to the high inertia of the rotating masses on the motor shaft. The same inertia also acts during start-up. The main reason is that the stopping transient lasts much shorter compared to the start-up transient. The same amount of kinetic energy gained during the starting process is dissipated during the stopping process in a shorter time.

Therefore, the electrical power supplied to the IGBT modules is higher during the stopping process. Higher electrical power means higher current through the IGBT modules. This results in greater power losses, which are converted into heat.

During this sub-profile, a trend of increasing load torque can be observed. Its mean value rises approximately from 30% to 40%. Simultaneously, the IGBT module temperatures also show a slight increase in the mean value by several degrees.

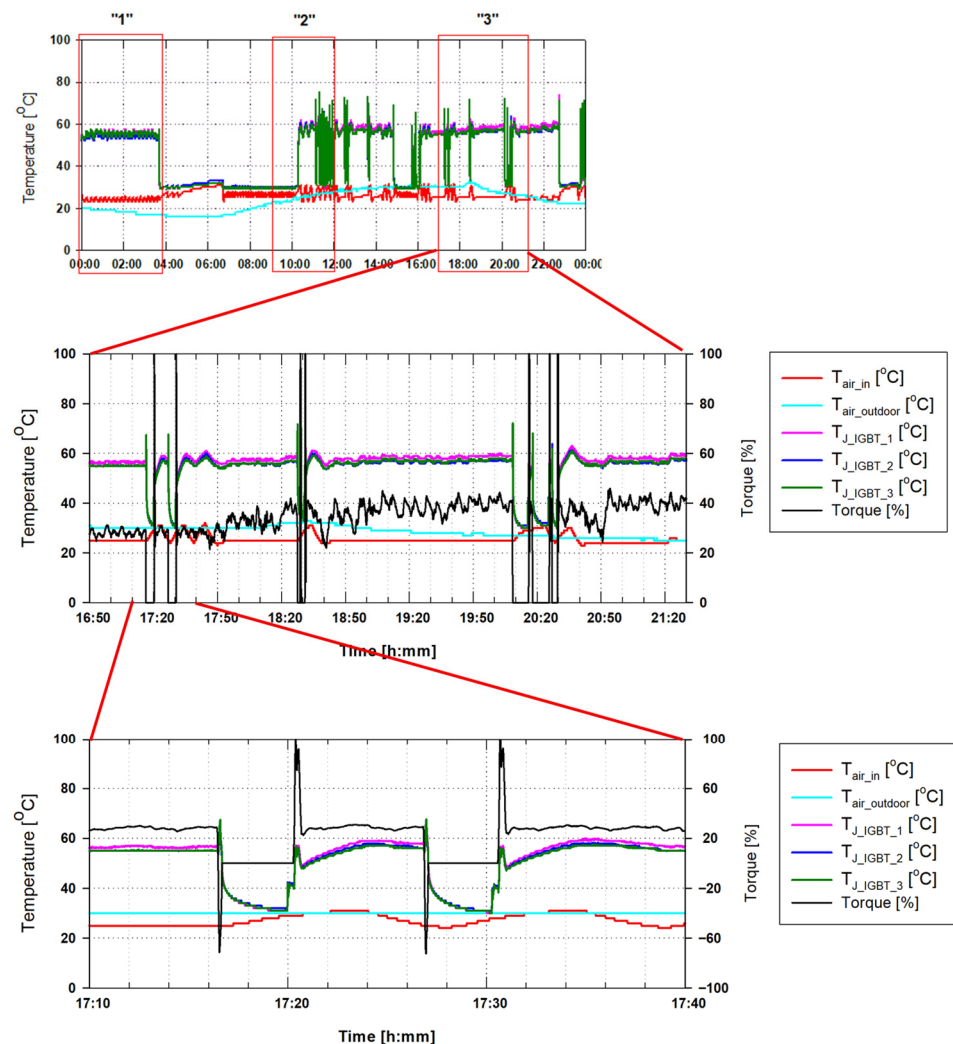


Figure 7. Sub-profile 3: (Torque) Load torque as a percentage of motor rated torque; ($T_{\text{air_in}}$) Internal temperature of the container housing the frequency converters; ($T_{\text{air_outdoor}}$) Ambient temperature external to the container; $T_{j_IGBT_1}$, $T_{j_IGBT_2}$, $T_{j_IGBT_3}$, junction temperatures of IGBT modules in frequency converters FC_1 , FC_2 , and FC_3 .

The total duration of these three dominant sub-profiles is approximately 10.87 h, which accounts for the primary thermal stress events within the 24 h cycle. The remaining ~13.13 h consist of very low-damage or idle periods not analyzed in detail.

The three sub-profiles have a combined duration of 10.87 h. This represents the active or defined operational periods within the full 24 h cycle. The difference between the total mission profile (24 h) and the sum of sub-profiles (10.87 h) is 13.13 h. This time represents periods where the system was likely idle, off, or operating outside the defined, measured sub-profiles.

Figure 4 shows the daily operational diagram of a belt conveyor drive station. Characteristic sub-periods 1, 2, and 3 are marked in it. Their corresponding durations are provided in Table 2, in accordance with the designated values.

Table 2 summarizes the temporal distribution of the complete 24 h mission profile and its three constituent load sub-profiles analyzed in this study. For each sub-profile, the start and end times are specified along with the corresponding duration, expressed in both hh:mm:ss format and decimal hours. The first sub-profile begins at midnight and lasts approximately 3.65 h, the second sub-profile occurs during late morning with a duration of 2.40 h, and the third sub-profile extends from late afternoon to evening, lasting about 4.82 h. Together, these three sub-profiles cover a total of 10.87 h of operational time within the complete daily cycle.

Table 2. Duration of mission profile and its sub-profiles.

Sub-Profile	Start Time	End Time	Duration	Duration
			hh:mm	Hours
1	00:00:00	03:38:52	3 h 39 min	~3.65 h
2	09:36:00	12:00:00	2 h 24 min	~2.40 h
3	16:47:00	21:36:00	4 h 49 min	~4.82 h
			Sum	10.87 h
Mission profile	00:00:00	23:59:58	23:59:58	~24 h

5. Lifetime Models

5.1. Generic Lifetime Model

The research results published by the authors in their article [25] indicate that a major challenge in lifetime prediction arises from the lack of corresponding models for various new chip or packaging technologies.

In their analysis of lifetime models based on power cycling, the authors [25] developed a generic model by aggregating and analyzing more than 200 test results from existing literature. Their model, which covers technologies including Si, SiC, Al/Cu bond wires, soldering, and sintering, is noted by the authors as the first of its kind to integrate such a wide range of data. They state that, considering the limited availability of certain parameters in practical applications (e.g., bond-wire diameter and quantity are often undocumented), they formulated the model using a simplified version of the CIPS08 model [31,32]. As presented in [25], the obtained lifetime models and their corresponding parameters are shown in Equation (1) and in Table 3, respectively.

$$N_f = A \cdot \Delta T_j^{-n} \cdot \exp\left(\frac{\beta_1}{T_{j,\max} + 273}\right) \cdot t_{on}^{\beta_2} \quad (1)$$

The authors in [25] assert that, to their knowledge, this represents the first model in the literature to integrate such diverse data, thereby providing a valuable reference for reliability assessment in the absence of specific lifetime models. In their conclusion, the

obtained generic lifetime model can serve as a useful reference for reliability evaluation when more accurate models are unavailable.

Table 3. Parameters for Generic Lifetime Model (GLM) [25], (CC BY 4.0).

	A	n	β_1	β_2	Packaging Materials
GLM01	1.88×10^{15}	6.88	4641	−0.32	Cu bond wire + Ag sintered die attach
GLM02	1.14×10^9	3.12	2402	−0.39	Al bond wire + Ag sintered die attach
GLM03	9.01×10^{11}	4.31	1191	−0.16	Al bond wire + soft soldering
GLM04	1.86×10^8	3.42	2993	−0.54	SiC MOSFET: Al bond wire + soft soldering

The values in Table 3 for GLM01–GLM03 are a specific generic lifespan model for silicon IGBT modules. It is a logical choice to exclude the GLM04 version of the generic model from the IGBT module lifetime analysis, as this model is designed for estimating the lifetime of silicon carbide (SiC) MOSFET modules, which have different failure mechanisms.

The three GLM01–GLM03 levels cover the full range of modern IGBT technology, from the cutting-edge, high-reliability frontier (GLM01) to the cost-optimized hybrid (GLM02) to the standard baseline (GLM03).

The junction temperature profile (Figure 4) of the IGBT module directly impacts its thermo-mechanical fatigue. The symmetry and uniformity of the temperature profiles across all three converters mean that their lifetime consumption, according to models such as GLM01 or GLM02, will be statistically identical. A controlled maximum junction temperature (maintained in the range of approximately 70–75 °C in each profile) and the absence of excessive heating of individual modules are of significant importance. This operating mode prevents the acceleration of failure mechanisms such as bond wire fatigue or solder creep. By avoiding prolonged periods during which the temperature change is with increased amplitude, the external cooling system and the control strategy of the multi-motor drive directly contribute to minimizing the damage accumulation that depends on the high values of the exponent “ n ” in the GLM models, thereby extending the useful life of the IGBT module.

5.2. Infineon Model

The Infineon aging model [33,34] uses two piecewise Equations (2) and (3), based on the junction temperature swing, ΔT_j . The number of cycles to failure, N_f , is calculated as follows:

$$N_f = \begin{cases} a_1 \cdot \left(\frac{\Delta T_j}{1K}\right)^{-b_1} \cdot \exp\left(\frac{E_{a1}}{k_b \cdot T_{j,max}}\right) \cdot f(t_{on}) & \text{if } \Delta T_j \leq 45K. \\ a_2 \cdot \left(\frac{\Delta T_j}{1K}\right)^{-b_2} \cdot \exp\left(\frac{E_{a2}}{k_b \cdot T_{j,max}}\right) \cdot f(t_{on}) & \text{if } \Delta T_j > 45K. \end{cases} \quad (2)$$

The effect of the power-on time (heating time during a cycle) is accounted for by:

$$f(t_{on}) = \begin{cases} 2.25 & \text{if } t_{on} < 0.1 \text{ s.} \\ \left(\frac{t_{on}}{1.5s}\right)^{-0.3} & \text{if } 0.1 \text{ s} \leq t_{on} \leq 60 \text{ s.} \\ 0.33 & \text{if } t_{on} > 60 \text{ s.} \end{cases} \quad (3)$$

The Infineon aging model and the generic lifetime model (GLM) are both built on the well-known CIPS (Cycling Insulated Power Semiconductor) product family. The Generic Lifetime Model (GLM) is a simplified version of the CIPS08 model. The Infineon model is an enhanced version of the CIPS2008 model.

The parameters for the Infineon lifetime model, which define the coefficients in the piecewise lifetime equations presented above, are summarized in Table 4.

Table 4. Parameters for Infineon lifetime model.

a_1	a_2	b_1	b_2	E_{a1} [eV]	E_{a2} [eV]	k_b [$\mu\text{eV/K}$]
5.4×10^{14}	2×10^9	7	3.7	0.215	0.215	86

The Infineon aging model, Equations (2) and (3) with parameters in Table 4, shares the same CIPS08/2008 foundation as the generic lifetime models. However, several factors led to the decision not to incorporate it as a primary model in this study. The Infineon model requires detailed knowledge of the specific module construction and materials to determine which parameter regime applies, and manufacturer-specific documentation for the analyzed frequency converters was not available. Additionally, the dual-regime structure of the Infineon model introduces a discontinuity at $\Delta T_j = 45$ K, and many thermal cycles in the analyzed profile occur in the range around this threshold, which could introduce unnecessary sensitivity. Notably, the high- ΔT_j regime of the Infineon model uses parameters $a_2 = 2.0 \times 10^9$ and $b_2 = 3.7$, which are remarkably similar to GLM02 with its scale factor of 1.14×10^9 and exponent of 3.12. Since the most damaging cycles in the analyzed profile are precisely those with high ΔT_j values occurring in sub-profiles 2 and 3, the GLM02 model effectively captures the same physical behavior as the Infineon model in the regime that matters most for lifetime consumption.

As demonstrated by the authors [25] in relevant research (e.g., in works extending the CIPS framework), generic models, although simplified, preserve the fundamental physical relationship between thermal cycles and damage. They explicitly express the dependence of lifetime (N_f) on temperature swing (ΔT_j), maximum junction temperature ($T_{j,\text{max}}$), and cycle duration, which is the common foundation of even more advanced, manufacturer-specific variants.

5.3. Assumption for the Comparative Damage Assessment Applying a Generic Lifetime Model

The primary goal of this analysis is to conduct a comparative assessment. This assessment focuses on the relative damage contribution of different operational phases (sub-profiles) within a defined mission profile. It does not aim to predict the absolute lifetime of the IGBT modules. Predicting absolute lifetime would require precise model parameters calibrated by the manufacturer. Since we do not possess manufacturer parameters calibrated for the specific module, a direct and absolute lifetime estimation would be uncertain. Therefore, the GLM parameters as published in [25] and reproduced in Table 3 are applied as published, without additional calibration.

The selection of the appropriate parameter set among the available GLM models requires careful consideration. Among GLM01, GLM02, and GLM03, which cover the full range of modern IGBT technologies, GLM02 was selected as the most suitable for this comparative analysis. This choice can be justified by examining two key parameters: the exponent n and the coefficient A . The exponent n directly determines the sensitivity of the model to temperature swings ΔT_j , with GLM01 exhibiting an extremely high value of 6.88, GLM02 a moderate value of 3.12, and GLM03 a relatively high value of 4.31. The moderate n value of GLM02 makes it the most appropriate choice for the analyzed frequency converters, as a lower value would underestimate the damaging effects of temperature swings while a higher value would overestimate them, potentially leading to misleading conclusions about the relative severity of different operational sub-profiles.

The coefficient A , which serves as the scale factor in the lifetime model, provides further justification for the selection of GLM02. With a value of 1.14×10^9 , GLM02 represents the most balanced and conservative basis for comparative damage assessment among the three IGBT-specific models. In contrast, GLM01 has an A value of 1.88×10^{15} —approximately 1.65 million times larger than GLM02—which would yield unrealistically optimistic lifetime

predictions for standard industrial applications. GLM03, with an A value of 9.01×10^{11} , is nearly 790 times larger than GLM02.

The moderate scaling factor of GLM02 ensures balanced results. Relative differences between operational sub-profiles are neither amplified nor diminished, making GLM02 a prudent, reasonable choice. It avoids the extreme optimism found in GLM01 and also steers clear of the overly conservative scaling that would result from even smaller A values. GLM04 was excluded from consideration because it is designed for SiC MOSFETs rather than silicon IGBTs, and SiC devices have fundamentally different failure mechanisms.

It is important to acknowledge the limitations inherent in this approach. The generic lifetime model does not account for module-specific geometric features such as chip layout, bond wire diameter, or the number of bond wires, which can influence absolute lifetime but are often unavailable in practical applications. The model assumes that failure mechanisms are consistent across all modules, whereas, in reality, different packaging technologies may exhibit different dominant failure modes. Additionally, the Arrhenius term and power-law exponents are derived from aggregated experimental data and may not perfectly represent the exact materials used in the analyzed modules. Despite these limitations, the approach remains valid for comparative assessment, as the relative ranking of sub-profiles is robust to these uncertainties. Any systematic errors introduced by the model assumptions affect all sub-profiles equally and therefore cancel out in the relative comparison, ensuring that the identification of critical operational phases remains reliable.

The assumption that applying the GLM for relative comparison yields valid results is based on several considerations. For the purpose of ranking sub-profiles by their damage contribution, it is sufficient that the model correctly captures the relative severity of different thermal cycles; even if absolute damage values are subject to uncertainty, the proportional relationship between cycles is preserved. Furthermore, the same model with identical parameters is applied to all sub-profiles, meaning that any systematic error affects all sub-profiles equally and cancels out in the relative comparison.

As recommended in [25], the generic lifetime model can serve as a useful reference for reliability evaluation when more accurate, module-specific models are unavailable, providing a baseline for comparative assessments, particularly when manufacturer-calibrated parameters are not accessible.

6. Methodology

In the reliability analysis of power electronic modules, it is often necessary to evaluate the relative damage contribution of a specific operating interval (sub-profile) within a longer mission profile, such as a 24-h daily cycle [21,23]. This allows engineers to identify critical operational phases that dominate fatigue accumulation and to optimize maintenance schedules or operating strategies. A systematic method for quantifying the damage share of a sub-profile is presented in Figure 8, utilizing rainflow cycle counting [13–15], a generic lifetime model [25], and linear damage accumulation [18].

To clarify the terminology used in this study, two key terms are specifically defined: sub-profile and thermal cycle (or hysteresis).

Term “sub-profile” refers to three specific, extended operational periods (sub-profile 1, 2, and 3), each exceeding two or more hours in duration. These multi-hour segments form the fundamental structural components of the analyzed 24-h mission cycle. The analysis focuses on evaluating the cumulative damage generated specifically during the runtime of each of these macroscopic sub-profiles.

The second term is “thermal cycle” (or hysteresis). The junction temperature undergoes repeated fluctuations throughout the duration of each multi-hour sub-profile. The rainflow counting algorithm is applied to identify and extract these individual thermal

cycles—complete heating and cooling hysteresis loops—defined by their temperature swing (ΔT_j) and mean temperature ($T_{j,\text{mean}}$).

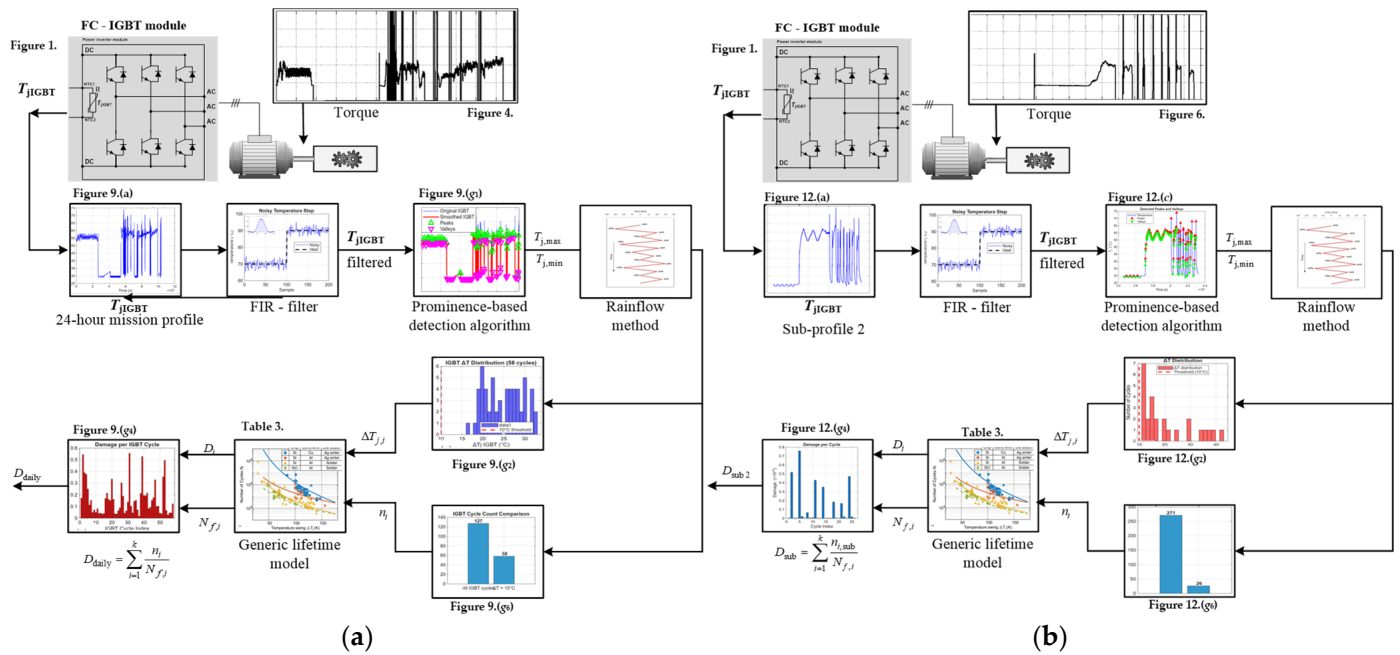


Figure 8. Block diagram of systematic method for quantifying the damage share of a sub-profile: (a) Total daily damage D_{daily} for 24 h mission profile. (b) Total damage D_{sub2} accumulated during that specific sub-profile 2.

The primary input to the analyses was the junction temperature profile, $T_j(t)$, obtained from IGBT modules operating under real-world conditions within an industrial drive system, plot (a) in Figures 9–13. (a). This ensured that the captured thermal dynamics corresponded to actual electrical loading and environmental factors.

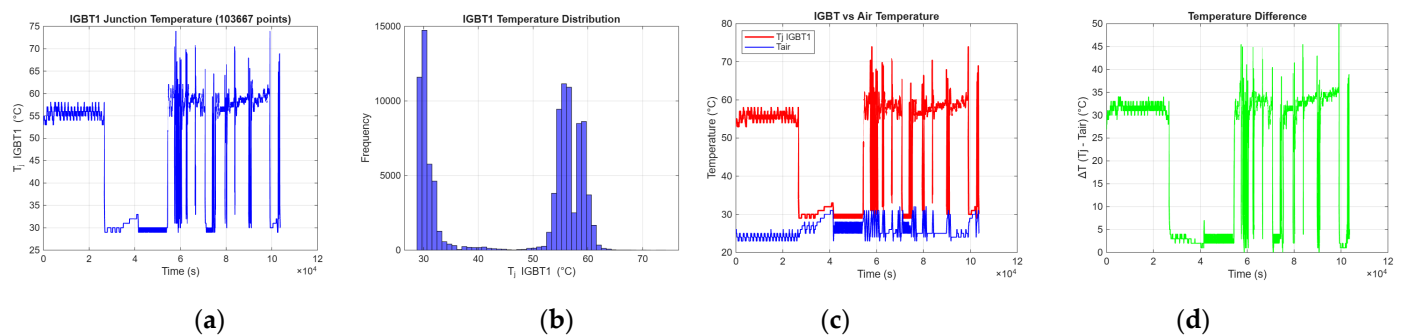


Figure 9. Cont.

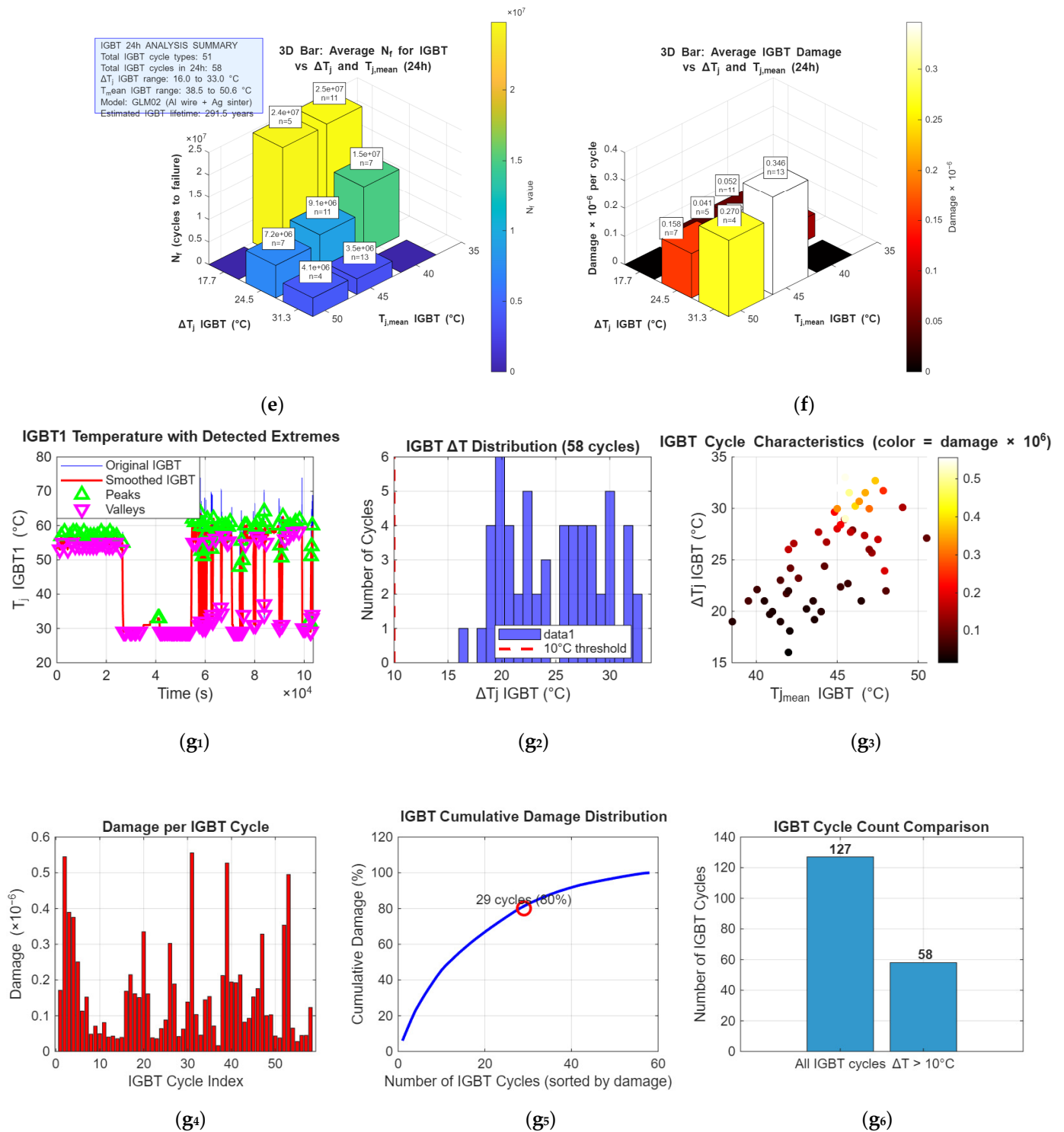


Figure 9. Resulting fatigue damage based on the application of the generic lifetime model (GLF02) to a 24 h mission profile: (a) IGBT junction temperature time diagram, $T_j(t)$. (b) Histogram of $T_j(t)$. (c) IGBT junction temperature $T_j(t)$ and ambient air temperature time diagram $T_{air,in}(t)$. (d) Temperature difference time diagram: $T_j(t) - T_{air,in}(t)$. (e) 3D bar graph of average number of cycles to failure (N_f) = $f(\Delta T_j, T_{j,mean})$. (f) 3D bar graph of average damage per cycle. (g1) Junction temperature profile of an IGBT over time with detected extremes. (g2) Distribution of junction temperature swings (ΔT_j). (g3) A scatter plot of the extracted IGBT thermal cycles. (g4) Damage per IGBT cycle. (g5) Cumulative damage distribution graph. (g6) IGBT cycle count comparison.

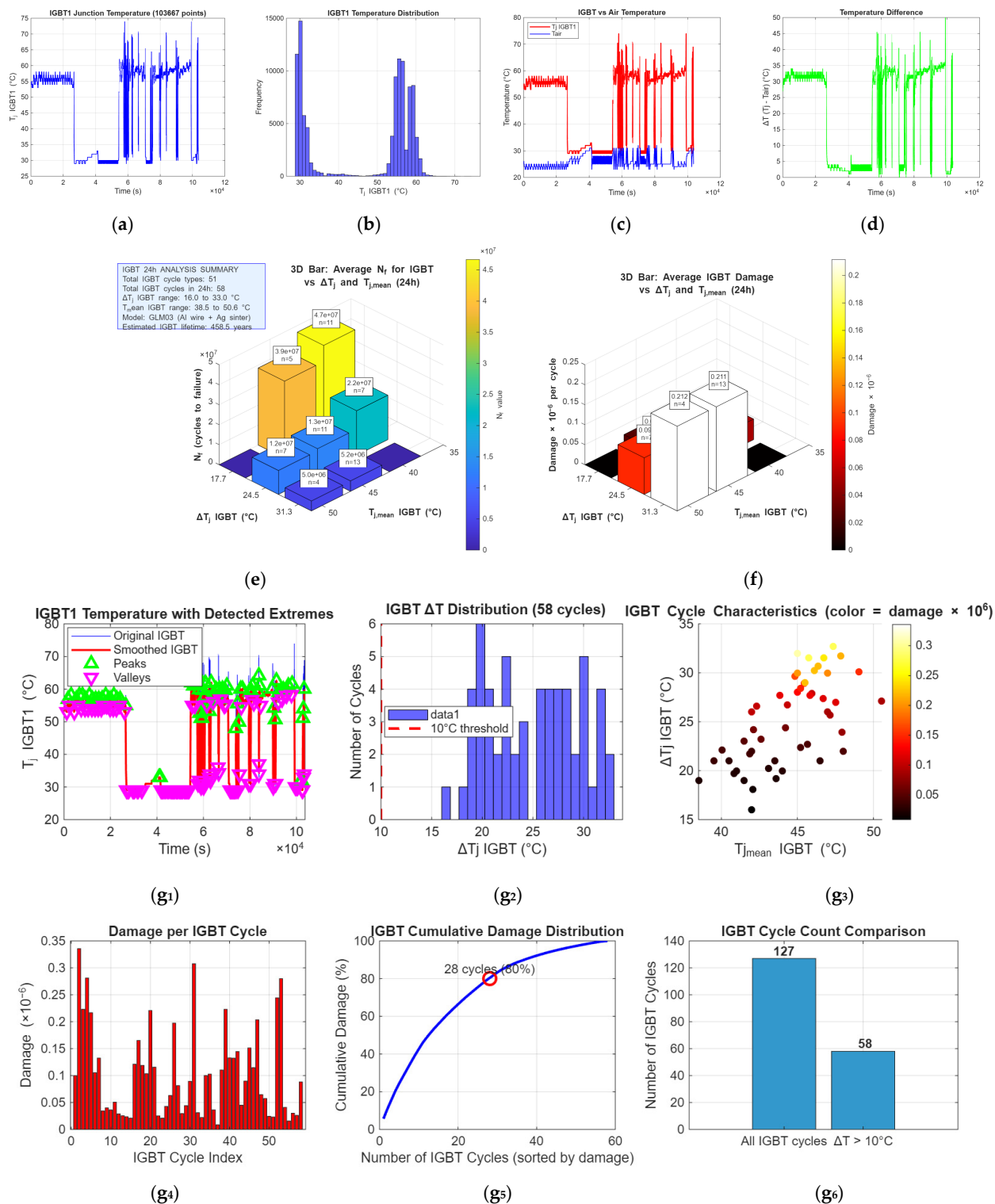


Figure 10. Resulting fatigue damage based on the application of the generic lifetime model (GLF03) to a 24 h mission profile. **(a)** IGBT junction temperature time diagram, $T_j(t)$. **(b)** Histogram of $T_j(t)$. **(c)** IGBT junction temperature $T_j(t)$ and ambient air temperature time diagram $T_{air,in}(t)$. **(d)** Temperature difference time diagram: $T_j(t) - T_{air,in}(t)$. **(e)** 3D bar graph of average number of cycles to failure (N_f) = $f(\Delta T_j, T_{j,mean})$. **(f)** 3D bar graph of average damage per cycle. **(g1)** Junction temperature profile of an IGBT over time with detected extremes. **(g2)** Distribution of junction temperature swings (ΔT_j). **(g3)** A scatter plot of the extracted IGBT thermal cycles. **(g4)** Damage per IGBT cycle. **(g5)** Cumulative damage distribution graph. **(g6)** IGBT cycle count comparison.

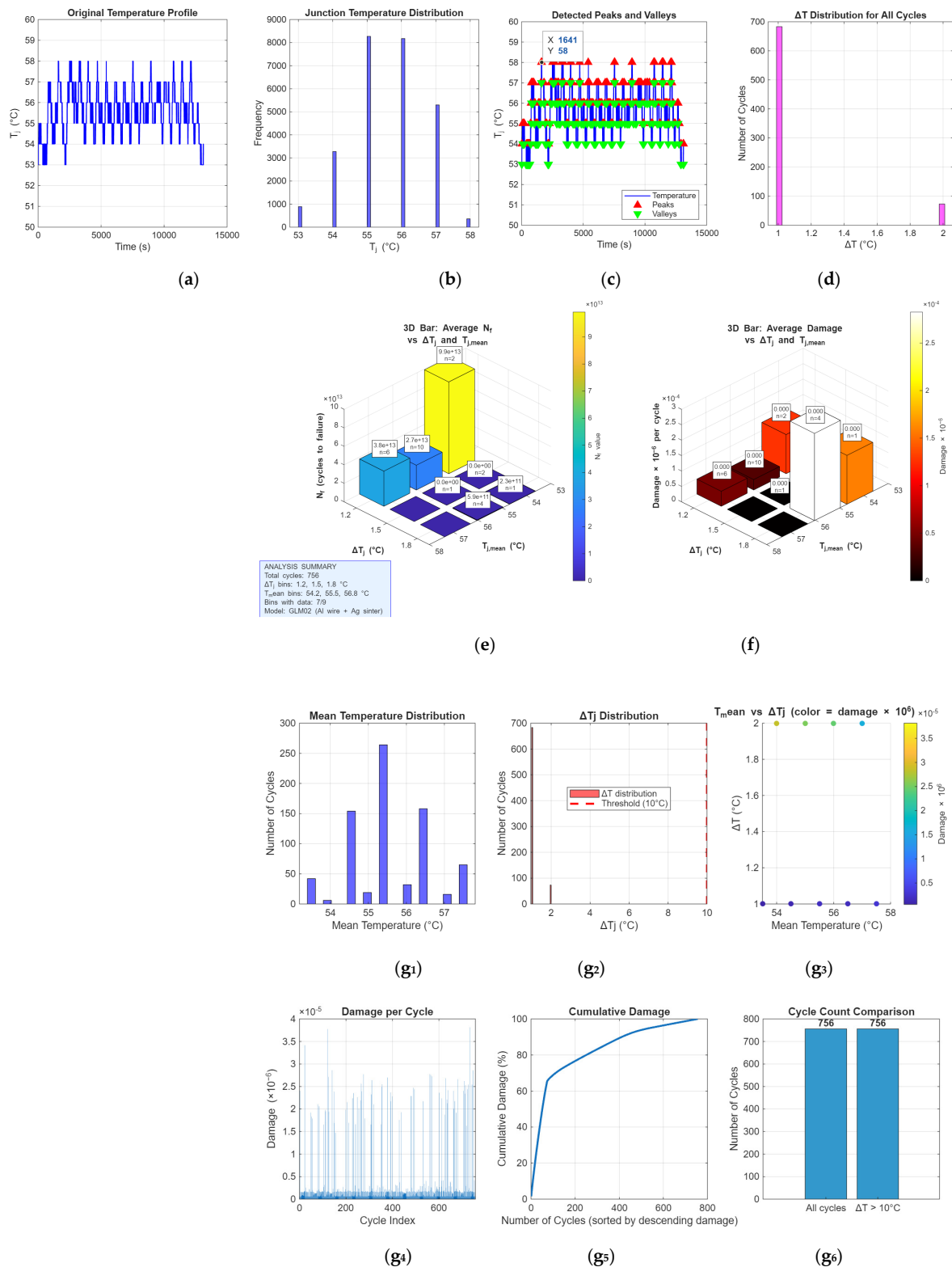


Figure 11. Resulting fatigue damage based on the application of the generic lifetime model (GLF02) to a sub-profile 1: (a) IGBT junction temperature time diagram, $T_j(t)$. (b) Histogram of $T_j(t)$. (c) Junction temperature profile of an IGBT over time with detected extremes $T_j(t)$. (d) ΔT_j distribution for all cycles. (e) 3D bar graph of average number of cycles to failure (N_f) = $f(\Delta T_j, T_{j,mean})$. (f) 3D bar graph of average damage per cycle. (g1) Mean temperature distribution (g2) Distribution of junction temperature swings (ΔT_j). (g3) A scatter plot of extracted thermal cycles. (g4) Damage per cycle. (g5) Cumulative damage distribution graph. (g6) Cycle count comparison.

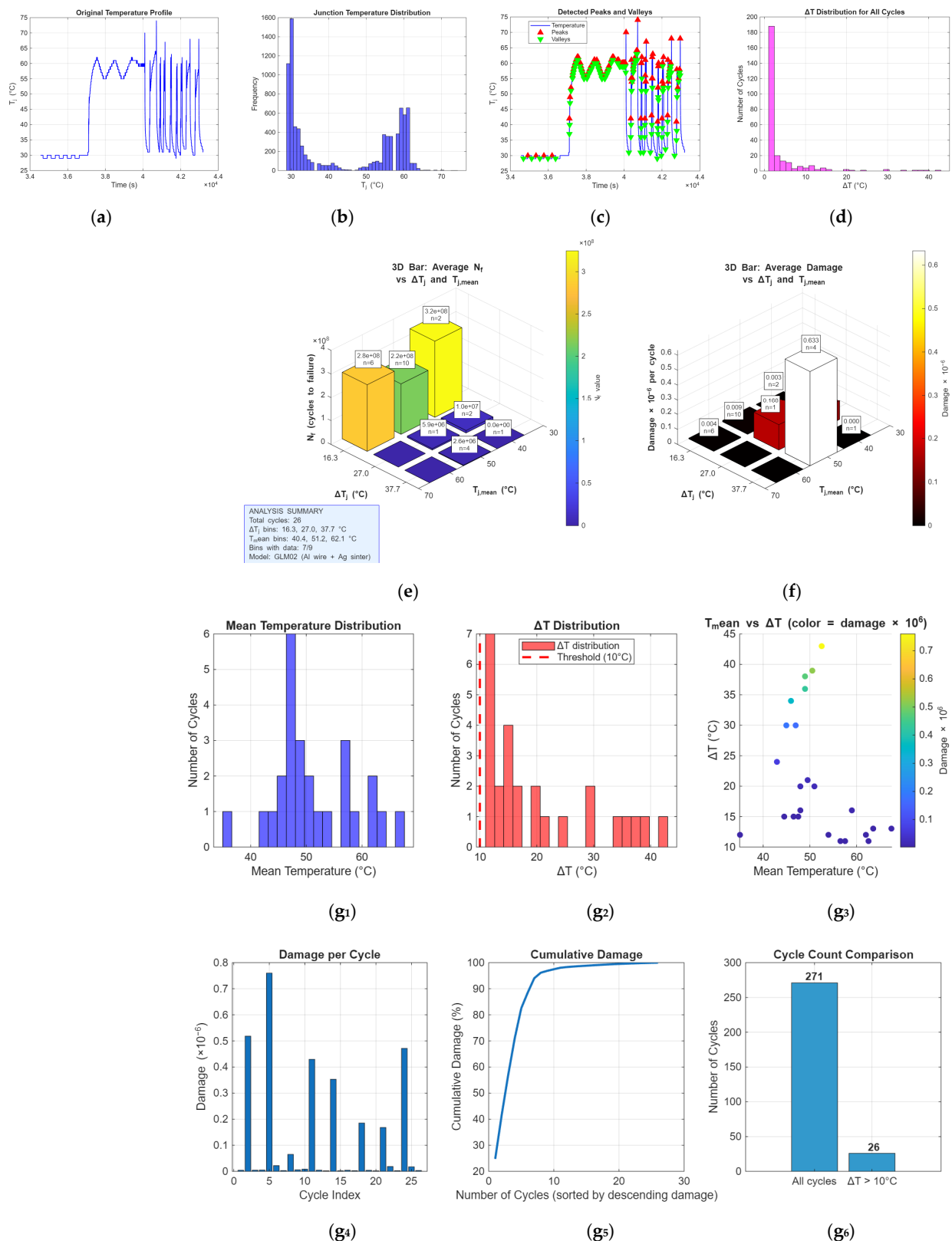


Figure 12. Resulting fatigue damage based on the application of the generic lifetime model (GLF02) to a sub-profile 2: (a) IGBT junction temperature time diagram, $T_j(t)$. (b) Histogram of $T_j(t)$. (c) Junction temperature profile of an IGBT over time with detected extremes $T_j(t)$. (d) ΔT_j distribution for all cycles. (e) 3D bar graph of average number of cycles to failure (N_f) = $f(\Delta T_j, T_{j,mean})$. (f) 3D bar graph of average damage per cycle. (g₁) Mean temperature distribution (g₂). Distribution of junction temperature swings (ΔT_j). (g₃) A scatter plot of extracted thermal cycles. (g₄) Damage per cycle. (g₅) Cumulative damage distribution graph. (g₆) Cycle count comparison.

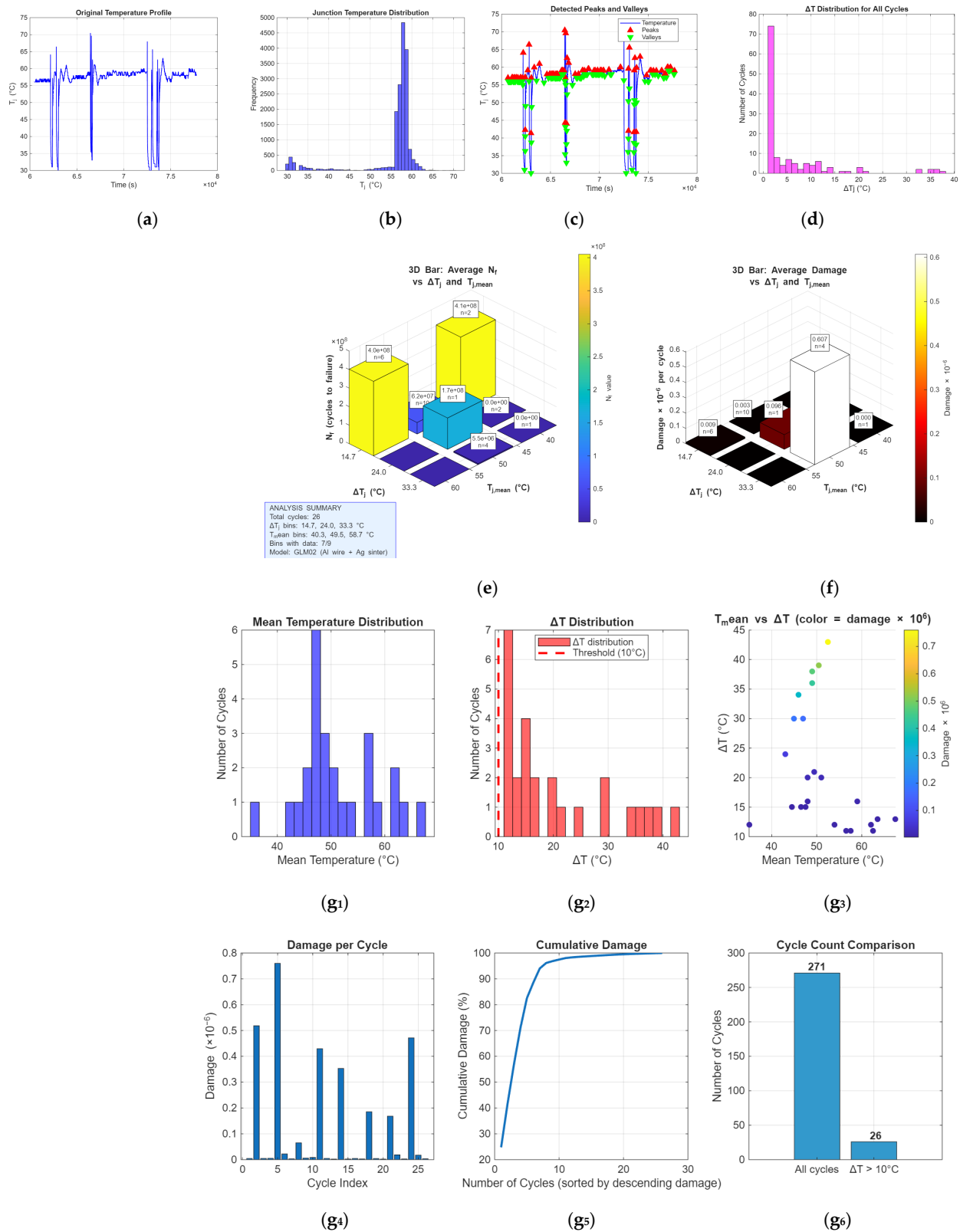


Figure 13. Resulting fatigue damage based on the application of the generic lifetime model (GLF02) to a sub-profile 3: (a) IGBT junction temperature time diagram, $T_j(t)$. (b) Histogram of $T_j(t)$. (c) Junction temperature profile of an IGBT over time with detected extremes $T_j(t)$. (d) ΔT_j distribution for all cycles. (e) 3D bar graph of average number of cycles to failure (N_f) = $f(\Delta T_j, T_{j,mean})$. (f) 3D bar graph of average damage per cycle. (g1) Mean temperature distribution (g2). Distribution of junction temperature swings (ΔT_j). (g3) A scatter plot of extracted thermal cycles. (g4) Damage per cycle. (g5) Cumulative damage distribution graph. (g6) Cycle count comparison.

To mitigate the influence of electrical and sensor noise inherent in field measurements, the raw $T_j(t)$ signal first underwent digital smoothing. A low-pass finite impulse response (FIR) filter (Figure 8) was applied to attenuate high-frequency components above 2 Hz, preserving the essential low-frequency thermal trends necessary for reliable cycle identification [35–38].

Subsequent identification of the characteristic local maxima and local minima within the smoothed temperature profile was performed using a prominence-based detection algorithm. This approach offers critical advantages for analyzing dynamic signals like temperature. It detects local maxima and local minima based on their vertical distance from the surrounding contour lines, not their absolute amplitude. This makes the algorithm insensitive to slow baseline drift or offset errors common in sensors, as it focuses on localized changes rather than global signal levels.

The initial output from this detection phase was a list of candidate extremes. This list was then subjected to a post-processing rule that enforced a strict physical alteration between local maxima and local minima. This correction step resolved any sequences containing consecutive local maxima or local minima, resulting in a validated, time-ordered series of proper temperature turning points.

The core of the stress quantification relied on an enhanced rainflow counting algorithm. This method processes the validated series of extremes to deconstruct the irregular, variable-amplitude $T_j(t)$ history into a set of discrete, full thermal cycles. Each identified cycle i is characterized by its temperature swing amplitude, $\Delta T_{j,i}$, and its mean temperature, $T_{j,\text{mean},i}$. Finally, the damage contribution of each extracted thermal cycle $N_{f,i}$ was evaluated using a generic lifetime model.

Based on the thermal cycles to be extracted from the 24-h operational profile, a damage accumulation analysis will be performed using the Palmgren–Miner linear damage summation rule. The total daily damage D_{daily} will be calculated as the sum of the damage contributions from all n unique cycle types identified, expressed as:

$$D_{\text{daily}} = \sum_{i=1}^k \frac{n_i}{N_{f,i}} \quad (4)$$

where n_i is the number of occurrences of cycle type i within the 24 h period, and $N_{f,i}$ is the number of cycles to failure for that specific cycle type as predicted by the generic lifetime model. For a defined sub-profile, the Palmgren–Miner linear damage summation rule will be applied in an identical manner:

$$D_{\text{sub}} = \sum_{i=1}^k \frac{n_{i,\text{sub}}}{N_{f,i}} \quad (5)$$

where:

- total damage D_{sub} is that accumulated during that specific sub-profile,
- $n_{i,\text{sub}}$ is the number of occurrences of cycle type i within the sub-profile,
- cycles-to-failure $N_{f,i}$ for cycle type i (from the same lifetime model),
- k is the number of unique cycle types within the sub-profile.

The applied linear Miner’s rule provides a deterministic estimate of accumulated damage. Its use is justified for this comparative analysis.

It is important to acknowledge that while rainflow counting effectively extracts individual thermal cycles from a complex temperature profile, the subsequent application of Miner’s linear damage rule does not account for sequence effects. In reality, the order in which thermal cycles occur can influence the progression of damage—for example, a large temperature swing followed by smaller swings may produce different crack propagation

behavior than the reverse sequence. This phenomenon, known as sequence effects, is not captured by linear summation. Miner's rule treats all cycles as independent and additive, regardless of their chronological order.

However, for the purpose of this study—comparative assessment of relative damage contributions—this limitation is partially mitigated by the fact that the analyzed temperature profiles are derived from real-world in situ measurements. The sequence of cycles is inherently preserved in the measured data, and Rainflow counting captures the actual thermal history. While linear accumulation remains an approximation, it is applied consistently across all sub-profiles, ensuring that the relative comparison remains valid even if the absolute damage values are subject to uncertainty. The primary goal of this analysis is to identify which operational phases dominate fatigue accumulation, not to predict absolute lifetime with high precision. In the analyzed mission profile, damage is dominated by a relatively small number of high-amplitude thermal cycles, particularly in sub-profiles 2 and 3. Under such conditions, where a few cycles account for the majority of damage, the influence of sequence effects on the overall damage ranking is expected to be less pronounced.

7. Results

This analysis examines thermal data from the IGBT module. The rainflow counting method and the GLF02 lifetime model were used to process the data. The resulting plots show the device's operational stress and its reliability.

Figure 9a shows the junction temperature history for IGBT1. It covers a long operational period. Over 100,000 data points were recorded, and the thermal signature is not stationary. Temperature variations range from an initial level of around 27 °C to local maxima nearing 68 °C. These repeated swings are generated by power cycling, which is a key feature of inverters under varying loads. This causes cyclic thermo-mechanical stress at the material boundaries, which is the leading cause of wear-out failures.

The histogram in Figure 9b gives a statistical summary of this thermal activity. The distribution is obviously multimodal, which opposes a simple Gaussian or uniform spread. This multimodality shows that the device does not operate in a consistent temperature range with equal probability. Instead, it works mainly within a few separate thermal bands. These bands correspond to the system's primary operating states, such as no-load conditions, nominal torque, and peak load.

Figure 9c shows the IGBT junction temperature has large dynamic swings. Pronounced thermal cycles are present, with local maxima near 65 °C. In contrast, the ambient air temperature in Figure 9d is nearly stable. It varies only slightly around an average of 25 °C. This visual difference in Figure 9d illustrates that the thermal dynamics of the IGBT are primarily caused by self-heating due to internal power losses, rather than by changes in the external cooling conditions. The two temperature traces are largely independent. This fact confirms the cooling system works effectively.

Figure 9e,f shows a dual 3D bar graph analysis. It summarizes damage accumulation and lifetime from thermal cycles over 24 h. Both plots offer different views of the same underlying data.

Figure 9e presents the average number of cycles to failure, N_f . This value is plotted against the mean junction temperature ($T_{j,mean}$) and the temperature swing (ΔT_j). Data points are grouped into a 3×3 matrix. This matrix uses bins for each parameter. The ΔT_j bins are set at 17.7, 24.5, and 31.3 °C. The $T_{j,mean}$ bins are 40, 45, and 50 °C. An inverse relationship is clearly visible. As both ΔT_j and $T_{j,mean}$ rise, the N_f value drops substantially. The bin with the most severe conditions has the lowest N_f . This value is approximately 4.1×10^6 cycles. Conversely, the mildest bin shows an N_f of about 2.4×10^7 cycles. Labels on the bars, such as ' $n = 5$ ' or ' $n = 11$ ', show the cycle count per bin. Most cycles, with

$n = 11$, are found in the moderate stress region. This leads to a mid-range N_f value of approximately 9.1×10^6 cycles.

The plot in Figure 9f shows the average damage per cycle. This graph visualizes the average damage per cycle ($\times 10^6$ actual damage), which is the mathematical inverse of N_f (Damage = $1/N_f$). The 3D representation emphasizes how sensitive damage is to thermal stress. Damage rises very sharply when both ΔT_j and $T_{j,\text{mean}}$ are high, reaching approximately $0.34\text{--}0.36$ ($\times 10^{-6}$ actual damage). On the other hand, bins with lower thermal stress show much less damage (near 0.1×10^{-6}).

The data underpinning these graphs originates from 58 IGBT cycles, grouped into 51 unique thermal cycle types extracted from the 24 h profile. The analysis shows that while the operational profile generates a wide range of cycles, the most damaging ones are relatively infrequent. Applying Miner's rule to the aggregated daily damage (9.39×10^{-6}) yields an estimated IGBT lifetime of 291.5 years for this specific load profile. This exceptionally long lifetime is a direct consequence of the profile's characteristics: the most severe thermal cycles (ΔT_j up to 33°C , $T_{j,\text{mean}}$ up to 50.6°C), although highly damaging individually, occur too infrequently within a single day to cause rapid accumulation of fatigue.

Figure 9(g₁) displays the junction temperature profile of an IGBT over time. The x -axis shows time in seconds. The y -axis represents temperature. Four data series are shown. First is a faint line plotting the noisy, raw temperature measurements. Then, a bold line showing the filtered data, which clarifies the main thermal trend. Upward-pointing markers highlight local temperature maxima on the smooth curve. Downward-pointing markers highlight local temperature minima. The chart illustrates the standard process of filtering raw thermal data and then identifying key turning points (local maxima and local minima). The extreme points are necessary for further stress and fatigue analysis in reliability evaluations. The visual comparison facilitates the assessment of smoothing and detecting techniques.

The distribution of junction temperature swings (ΔT_j) for the extracted 58 IGBT thermal cycles is shown in Figure 9(g₂). The most frequent discrete ΔT_j value is 20°C , which occurs 6 times. Multiple occurrences are seen for ΔT_j values of 23°C , 26°C , 27°C , 28°C , and 30°C . A dashed vertical line indicates the 10°C threshold. The limitation is applied to disregard cycles that cause slight fatigue damage.

Figure 9(g₃) shows a scatter plot of the IGBT thermal cycles. It plots the mean junction temperature ($T_{j,\text{mean}}$) against the temperature swing (ΔT_j). Each data point is color-coded. The color intensity shows the calculated damage per cycle. A scaling factor of 10^6 is used for clearer visualization. The data points form two clear groups. The main group contains many cycles, which have moderate mean temperatures roughly between 40 and 47°C . Their temperature swings are also moderate, ranging from 15 to 25°C . The markers here are a lighter blue, indicating relatively low damage values. A second, more significant group of data point cycles is present, occurring at higher mean temperatures (45 to 50°C) and with considerably greater temperature swings (25 to 33°C). In this region, the marker colors shift from yellow to a dark red. This color change shows a rapid, non-linear increase in the damage per cycle.

This visual pattern directly illustrates the exponential relationship inherent in the employed lifetime model, where damage is disproportionately sensitive to increases in both ΔT_j and $T_{j,\text{max}}$ (closely related to $T_{j,\text{mean}}$). The graphic obviously illustrates that not all heat cycles are equally damaging. The overall damage accumulation in the IGBT is dominated by a limited subset of high-stress cycles occurring at elevated temperatures and large thermal swings.

The graph in Figure 9(g₄) shows the cumulative damage distribution. It was created by following several analytical steps. First, all significant thermal cycles were identified. Their individual damage contribution was then calculated using a physics-based lifetime model. Next, these damage values were sorted according to the index of the identified

thermal cycle. The cumulative sum in Figure 9(g₅) was then normalized. It was divided by the total damage and expressed as a percentage. The result is a curve where the x -axis is the index of the identified thermal cycle and the y -axis represents the cumulative percentage of total damage. The shape of this curve shows that a small portion of the most damaging cycles is responsible for most of the total accumulated damage.

The same comprehensive analysis presented for Figure 9 is now applied using the alternative GLF03 lifetime model, with the corresponding results shown in Figure 10. While Figure 10 follows an identical structure and presents the same types of graphical representations as Figure 9, the application of the GLF03 model yields quantitatively different damage assessments, allowing for a direct comparison between the two lifetime models under identical thermal loading conditions.

A comparative analysis was performed using two generic lifetime models, GLM02 and GLM03, as presented in Figures 9 and 10. The damage calculation coefficients in these models are substantially different. Generic model GLM02 has a stronger exponential connection with mean temperature via its Arrhenius term and a greater power-law coefficient for ΔT_j , leading to more rapid damage development. Generic model GLM03 employs far more conservative damage weighting for each cycle. As a consequence, given the same mission profile, GLM03 predicts significantly slower growth in cumulative damage and a much longer projected lifespan than GLM02. The GLM02 model was selected as the reference for assessing how each operational sub-profile influences the 24 h mission because it is more sensitive to both junction temperature swing and mean junction temperature. This sensitivity makes the differences in predicted damage contributions between different operating circumstances clearer. While the absolute lifetime prediction from GLM02 is very long—approximately 291 years—this indicates that the daily profile represents a relatively safe operating regime. However, the relative damage distribution it creates is a useful and stable diagnostic tool. The model adequately makes the differences between low-stress and high-stress sub-profiles more pronounced, establishing a clear and useful hierarchy of operational severity.

The damage contribution analysis of sub-profile 1 within the complete 24 h mission profile is presented in Figure 11. This sub-profile represents a period of extremely low thermal stress, and the quantitative results obtained from the rainflow counting algorithm offer comprehensive information regarding its negligible impact on the overall IGBT lifetime consumption. The corresponding analysis of the results from Figure 11 is presented in Section 8.2.

Figure 12 shows the damage contribution analysis of sub-profile 2 within the 24 h mission profile. Figure 12 illustrates junction temperature variations, cycle distributions, and resulting damage metrics, which together demonstrate why this brief period is responsible for approximately 32.68% of total daily fatigue damage, establishing transient overloads as the primary drivers of thermo-mechanical stress in IGBT modules. The results presented in Figure 12 are analyzed in detail within Section 8.3.

The thermal response and damage accumulation for sub-profile 3, representing the demanding operational segment of the daily cycle, are presented in Figure 13. The application of the rainflow counting algorithm and GLF02 lifetime model yields the quantitative results shown in Figure 13, which together illustrate why this sub-profile, despite constituting only 20% of the daily operational time, accounts for approximately 27.90% of the total accumulated fatigue damage. The analysis in Section 8.4 provides a detailed interpretation of these findings.

Figure 14 provides a comparative overview of the damage analysis results. It presents data from four analyzed datasets: the complete 24 h mission profile (Figure 9) and three sub-profiles (Figures 11–13). For each dataset, three key graphical representations are shown side by side. The first is a scatter plot of the extracted thermal cycles, where colors indicate the damage per cycle. The second shows the damage contributed by each individual cycle. The third displays the cumulative damage distribution.

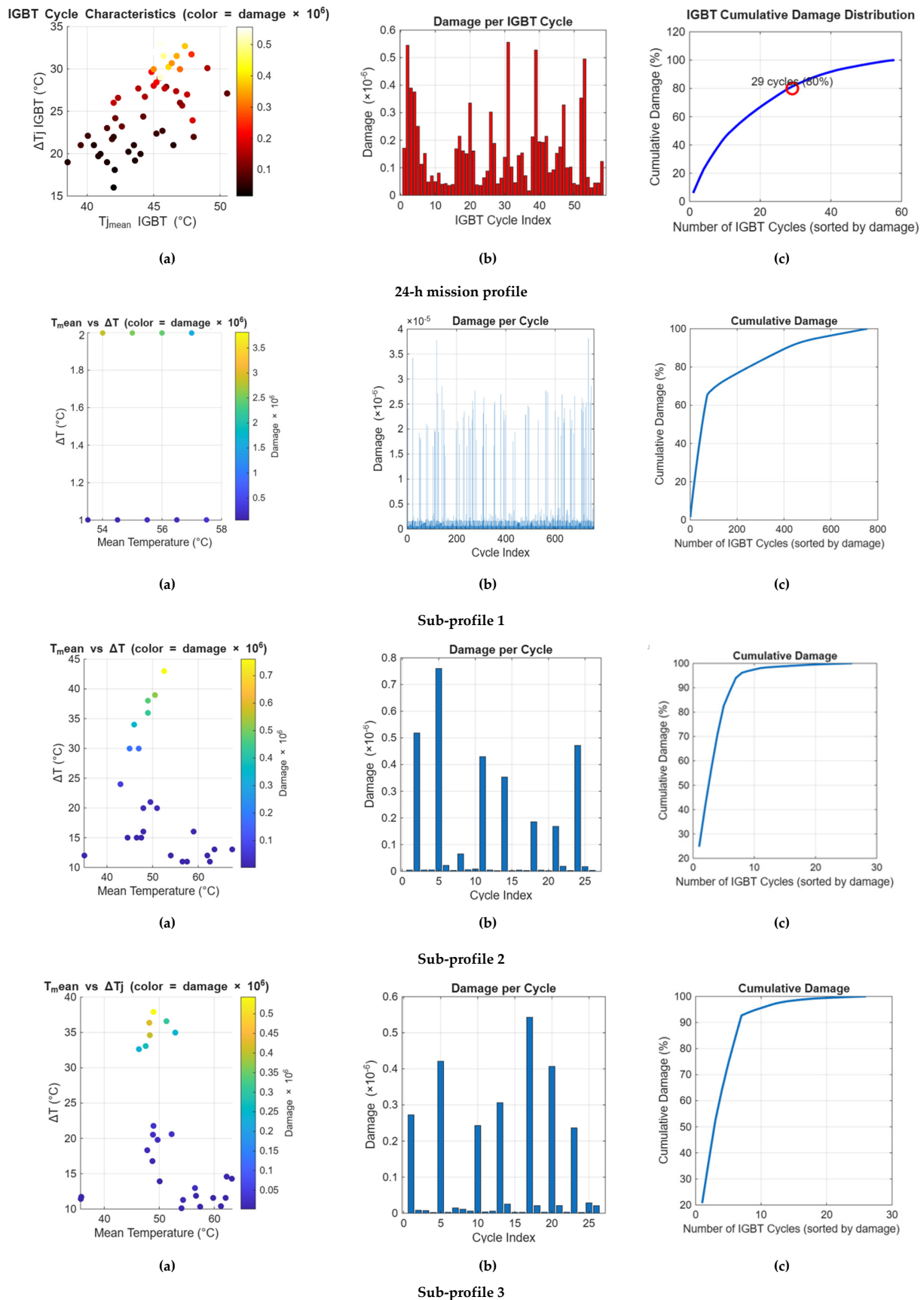


Figure 14. Graphical comparisons of resulting fatigue damage based on the application of the generic lifetime model (GLF02): (a) A scatter plot of the extracted thermal cycles. (b) Damage per cycle. (c) Cumulative damage distribution graph.

This combined presentation enables direct visual comparison across different operational periods. It clearly illustrates why transient overload events in sub-profile 2 and sustained high-intensity operation in sub-profile 3 dominate the total fatigue damage. It also confirms that sub-profile 1 contributes negligibly, despite its significant duration.

8. Discussion

The validity of this comparative approach is qualitatively supported by the obtained numerical results and their alignment with physical expectations derived from the mission profile analysis.

For sub-profile 1 (e.g., a steady-state, low-load operation with minimal ΔT_j fluctuations), the calculated relative damage contribution to the overall 24 h damage was negligible ($\sim 0.03\%$). This aligns with the physical expectation that periods of stable thermal conditions induce minimal thermo-mechanical stress.

In contrast, for sub-profiles 2 and 3 (characterized by frequent and high-intensity load changes, resulting in larger and more numerous ΔT_j cycles), the analysis calculated significantly higher relative damage contributions. This directly corresponds to the operational phases where the highest mechanical and thermal stresses on the module's interconnections (bond wires, solder joints) are expected.

8.1. Damage Analysis of a 24 h Mission Profile

To determine the thermal fatigue experienced by an IGBT module under real operating conditions, a full 24 h mission profile was analyzed. The evaluation begins with a raw data file containing a continuous temperature log from midnight to just before the following midnight (00:00:00 to 23:59:58), shown in Figure 4. This file holds 103,667 individual temperature readings. With 86,400 s in a day, the data density translates to an average sampling rate of about 1.2 Hz. This resolution adequately captures the module's thermal inertia, which changes over seconds, not milliseconds.

The next step involved processing this temperature history to isolate the repetitive heating and cooling events that cause material stress. Applying the rainflow counting algorithm to the 24 h signal extracted 127 complete thermal cycles, shown in Figure 9(g₆). Not all cycles contribute equally to long-term wear. To focus on the most damaging events, a practical filter was applied: only cycles with a temperature swing (ΔT_j) greater than 10 °C were considered significant for fatigue. This filter narrowed the set down to 58 critical cycles (Figure 9(g₆)), which became the primary topics for damage modeling.

For the final calculation, these 58 cycles were not treated as a simple list. They were statistically sorted into 51 distinct groups, or "cycle types," where each type shares a specific ΔT_j and mean junction temperature $T_{j,mean}$. This grouping creates a condensed, manageable model of the daily thermal load. Using this model with Miner's rule for linear damage accumulation allows for the calculation of a total daily damage value. The ultimate output is a clear, ranked profile showing which specific operating conditions—which combinations of temperature swing and heat level—are responsible for the greatest share of the module's accumulated fatigue over time.

The GLF_02 lifetime model was applied to this derived 24 h profile. The Generic model, parameterized for a module with aluminum bond wires and a sintered silver die attached, calculated a total daily damage accumulation of 9.39×10^{-6} .

Applying Miner's rule of linear damage accumulation, the inverse of this daily damage yields a predicted lifetime of approximately 106,500 days, or 291 years, to reach the theoretical failure threshold.

This extremely long lifetime arises because the analyzed 24 h profile contains mostly very-low-amplitude temperature swings. The damaging IGBT cycles, while present, are too infrequent in this daily profile to cause significant accumulated fatigue.

A key breakdown objective of this methodology is to calculate the individual damage contribution (D) for each unique sub-profile within the overall daily cycle. This breakdown creates a relative relationship, clearly showing the proportional impact of each specific temperature and load sub-profile on the total cumulative damage. This relative contribution of individual stress events is far more reliable and valuable than the absolute lifetime estimates in years. It provides an accurate map of which operational modes are the primary drivers of wear, information that is critical for maintenance planning and operational optimization, regardless of the final calendar-life projection.

The application of two distinct lifetime models, GLF02 and GLF03, to the recorded IGBT thermal cycles yields significantly different prognostic outcomes. A comparison of the results from applying the generic lifetime models GLF02 and GLF03 to a 24 h mission profile shows that the expected damage progression for the IGBT module varies under the same thermal cycling conditions. This discrepancy originates from fundamental differences in the models' parametric construction.

The damage calculation coefficients in the generic lifetime models GLF02 and GLF03 are substantially different. Generic model GLF02 (results in Figure 9) has a stronger exponential connection with mean temperature (via an Arrhenius term) and/or a greater power-law coefficient for ΔT , leading to rapid damage development. Generic model GLF03 (results in Figure 10) employs far more conservative damage weighing each cycle. As a consequence, given the similar mission profile, GLF03 predicts a significantly slower growth in cumulative damage and a much longer projected lifespan for the IGBT module than GLF02.

The GLF_02 model is used as a reference for assessing how each operational sub-profile influences the 24 h mission based on what was discussed above. This choice is practical since it is more sensitive to both junction temperature swing (ΔT_j) and mean junction temperature ($T_{j,mean}$), which makes the differences in predicted damage contributions between different operating circumstances clearer. The resulting absolute lifetime prediction is very long, which is a clear sign that the daily profile being looked at represents a relatively safe operating regime. However, the relative damage distribution it creates is a useful and stable diagnostic tool. The model does an adequate task creating the differences between low-stress and high-stress sub-profiles more pronounced, which makes a clear and useful hierarchy of operational severity. This established hierarchy, which links each sub-profile's unique thermal signature to its percentage of the overall daily damage, provides the basis for the next thorough breakdown.

8.2. Damage Contribution Analysis of a Sub-Profile 1 Within a 24 h Mission Profile

The application of the rainflow counting algorithm to sub-profile 1 provides quantitative insights into its role within the complete 24-h mission profile, shown in Figure 11. Sub-profile 1 can definitely be characterized as a period of extremely low thermal stress. The rainflow analysis identified a high number of cycles (756), as presented in Figure 11(g₃), but with a remarkably low average temperature swing ($\Delta T_j \approx 1.1^\circ\text{C}$), shown in Figure 11(g₆). This pattern indicates a stable operational state—such as idling, light load, or steady-state operation—where the power losses in the IGBT are minimal and consistently managed by the cooling system.

The primary outcome of the analysis is the quantification of its negligible impact on total lifetime consumption. The cumulative damage for the entire 3.65 h segment is 2.56×10^{-9} . When compared to the total daily damage of the full 24 h profile (9.39×10^{-6}), sub-profile 1 contributes less than 0.03% of the daily fatigue load. Consequently, this sub-profile has no

meaningful influence on the estimated module lifetime. The lifetime-limiting damage occurs almost entirely during other sub-profiles involving significant thermal cycling.

In summary, the rainflow analysis conclusively positions sub-profile 1 as a thermally non-critical segment of the daily mission profile. While it constitutes a significant portion of the operational time (~15%), its contribution to thermo-mechanical fatigue is insignificant. Therefore, the critical drivers of the IGBT's lifetime consumption reside exclusively within the other, more dynamic sub-profiles of the 24-h cycle.

8.3. Damage Contribution Analysis of a Sub-Profile 2 Within a 24 h Mission Profile

Sub-profile 2, a high-intensity operational phase, occurred from 09:36 to 12:00, lasting 2.4 h, as shown in Figure 6. The rainflow analysis of sub-profile 2 reveals a highly damaging operational segment characterized by severe thermal cycling. This sub-profile, with a total duration of approximately 2 h, contains 26 distinct thermal cycles, each with a junction temperature swing (ΔT_j) exceeding 10 °C, as shown in Figure 12(g₆).

The total cumulative damage for sub-profile 2, calculated from all 26 cycles, is 3.07×10^{-6} . The total damage from the 58 cycles of the entire day is 9.39×10^{-6} . Therefore, sub-profile 2 alone—representing only about 8% of the day's time—is responsible for approximately 33% (one-third) of the total daily damage accumulation.

This establishes sub-profile 2 as the primary driver of thermo-mechanical fatigue in the IGBT module under this mission profile. The extreme ΔT_j values and elevated mean temperatures during this period create the most critical stress conditions for solder joints and bond wires.

8.4. Damage Contribution Analysis of Sub-Profile 3 Within a 24 h Mission Profile

The rainflow analysis of sub-profile 3, a prolonged operational period lasting 4 h and 49 min (16:47 to 21:36), identifies it as a phase of sustained but intermittent high thermal stress, as shown in Figure 7. From this nearly 5 h segment, 26 significant thermal cycles ($\Delta T > 10$ °C) were extracted, shown in Figure 13(g₆).

There were several extreme cycles with very high ΔT_j (32 °C to 38 °C) at elevated mean temperatures (46 °C to 52 °C), as shown in Figure 13(g₁,g₃). These isolated events, such as the cycle with $\Delta T_j = 37.9$ °C (damage: 5.43×10^{-7}), are among the most damaging in the entire 24 h profile.

Many cycles with smaller ΔT_j (10 °C to 20 °C) occur at consistently high mean temperatures (54 °C to 63 °C). This indicates periods of sustained high-power operation with minor fluctuations, contributing to a background level of damage.

Despite the lower cycle count compared to the full-day analysis, the severity of the high-intensity bursts results in substantial total damage. The total cumulative damage for this 4.8 h sub-profile is 2.62×10^{-6} .

Sub-profile 3 contributes 27.9% of the total daily damage. However, it does so over a much longer period (4.8 h) compared to sub-profile 2, which caused 32.68 % of the damage in just 2.4 h. This indicates that sub-profile 3's damage is more distributed over time.

While both sub-profiles SP_2 and SP_3 are critical, their temporal signatures differ. Sub-profile 2 represents a short, intense, high-power phase. Sub-profile 3 represents a long, evening period with a mix of extreme transient events and sustained high-temperature operation.

8.5. Summary Damage Analysis

The summary damage analysis consolidates the quantitative findings from the three examined sub-profiles and provides a comprehensive assessment of their individual contributions to the total fatigue damage accumulated over the complete 24 h mission profile. By comparing the temporal duration of each operational segment with its corresponding

damage contribution, this analysis establishes a clear hierarchy of thermal stress severity and identifies the most critical periods for IGBT module lifetime consumption.

Table 5 summarizes the durations of the three analyzed sub-profiles and their respective shares within the complete 24 h mission profile. Sub-profile 1 lasts 3.65 h (15.21% of the day), sub-profile 2 lasts 2.40 h (10.00%), and sub-profile 3 lasts 4.82 h (20.08%). Together, these three segments cover approximately 45% of the daily operational cycle, providing the temporal framework for the subsequent damage contribution analysis of each sub-profile.

Table 5. Durations of sub-profiles and mission profile.

SP ₁ [h]	SP ₂ [h]	SP ₃ [h]	Day [h]	SP ₁ /24 [%]	SP ₂ /24 [%]	SP ₃ /24 [%]
3.65	2.4	4.82	24	15.21	10.00	20.08

To provide a more quantitative assessment of damage distribution, the relative contribution of each operational sub-profile to the total daily damage was calculated. As presented in Table 6, the analysis confirms that transient overloads—despite constituting only a small fraction of the total operating time—account for the majority of the accumulated fatigue damage. Sub-profile 2, representing transient overload conditions, contributes approximately 32.68% of the total daily damage despite lasting only 2.4 h, which represents just 10% of the daily operational time. Sub-profile 3, characterized by prolonged high-intensity operation with mixed transient events, contributes 27.90% of the total damage over a 4.8 h period. In contrast, sub-profile 1, which represents stable low-load steady-state operation, contributes less than 0.03% of the daily fatigue load despite constituting approximately 15% of the operational time.

Table 6. Daily and sub-profile damage summary with contribution ratios.

	D ₁	D ₂	D ₃	D ₂₄	D ₁ /D ₂₄ [%]	D ₂ /D ₂₄ [%]	D ₃ /D ₂₄ [%]	Σ(D _i /D ₂₄) [%]
GLM02	2.56×10^{-9}	3.07×10^{-6}	2.62×10^{-6}	9.39×10^{-6}	0.03	32.68	27.90	60.61

These quantitative results, summarized in Table 7, which shows the damage contribution ratios of individual sub-profiles to the cumulative damage of all three sub-profiles, clearly demonstrate that transient overload events are the primary drivers of thermo-mechanical fatigue in IGBT modules, with a disproportionately high damage contribution relative to their duration.

Table 7. Damage contribution ratios of individual sub-profiles to the cumulative damage.

	D ₁	D ₂	D ₃	ΣD ₁₂₃	D ₁ /D ₁₂₃ [%]	D ₂ /D ₁₂₃ [%]	D ₃ /D ₁₂₃ [%]	Σ(D _i /D ₁₂₃) [%]
GLM02	2.56×10^{-9}	3.07×10^{-6}	2.62×10^{-6}	5.69×10^{-6}	0.04	53.92	46.04	100

8.6. Discuss Implications for Control Strategies

To mitigate damage accumulation and extend IGBT module lifetime, several practical measures are recommended based on the quantitative hierarchy established in this study. Limiting transient overloads can be achieved by implementing current limiting or slew-rate control during high-demand periods, directly targeting sub-profile 2, which contributes 32.68% of daily damage despite lasting only 2.4 h. Optimizing the cooling system response ensures rapid heat dissipation during and immediately after transient events, reducing both

the magnitude of temperature swings and the duration of exposure to elevated junction temperatures. This is particularly important for sub-profile 3, where cycles with ΔT_j values between 32 °C and 38 °C occur at elevated mean temperatures between 46 °C and 63 °C. Adaptive control strategies that dynamically adjust switching frequency or load sharing based on real-time junction temperature monitoring can actively prevent operation in the most damaging regimes. Furthermore, predictive maintenance scheduling should be focused on periods following intensive transient activity, particularly after the high-intensity phase represented by sub-profile 2, rather than relying solely on calendar-based intervals. This condition-based approach allows maintenance resources to be directed where they are most needed, improving operational efficiency and reducing unplanned downtime. Incorporating such strategies into the drive control logic could significantly extend the operational lifetime of IGBT modules in industrial applications, particularly in systems with frequent load variations such as belt conveyor stations.

9. Conclusions

The generic lifetime model (GLF02) is adopted for the final comparative analysis, as it yields a more realistic lifetime prediction. This choice is based on the premise that its parameters better represent the thermo-mechanical response of the specific IGBT module studied here. The following conclusions will therefore be drawn from the results obtained using the GLF02 model.

This study employed rainflow cycle counting and a generic lifetime model to perform damage contribution analysis of a 24 h mission profile for an electric drive power converter. By decomposing the profile into three distinct sub-profiles, the analysis successfully quantified the disproportionate impact of specific operational phases on cumulative thermo-mechanical fatigue.

This qualitative agreement between the computed damage distribution and the independently observable stress characteristics of the mission profile provides an appropriate validation of the methodological framework. It confirms that the combined rainflow counting and generic model approach successfully quantifies the differential impact of distinct mission profile segments, achieving its primary goal of identifying the most damaging operational phases for further optimization or reliability enhancement.

The time diagram for sub-profile 1, which lasts 3.65 h, illustrates a quasi-stationary operation mode. A load with no sudden changes distinguishes this mode. As a result, the thermal stress of the IGBT module has a minimal range of change, demonstrating thermal stability. The computed relative damage impact of sub-profile 1, which is 0.03% of the total daily damage, shows that this profile has a minor effect on the IGBT module's lifetime.

Based on the obtained results, sub-profile 2 is the primary source of thermal stress during the analyzed 24 h mission profile. According to the generic GLF 02 model, the relative daily damage impact of sub-profile 2 is 32.68%. Although it has the shortest duration among all sub-profiles (2.4 h, or 10% of 24 h), it causes the greatest cumulative damage. This result demonstrates that the thermal stress in sub-profile 2 significantly influences the lifetime of the IGBT module.

Sub-profile 3 has a duration of 4.82 h, or 20.08% of 24 h. The calculated relative daily damage impact of sub-profile 3 is 27.9%. The thermal stress in sub-profile 3 has a significant influence on the lifetime of the IGBT module, but it is smaller compared to sub-profile 2. The lower frequency of abrupt changes in sub-profile 3 compared to sub-profile 2 explains this relationship. Additionally, the duration of sub-profile 3 (4.82 h) is longer than that of sub-profile 2 (2.4 h).

The quantitative analysis of the damage contribution indicates that the system's lifetime is mostly utilized during two critical time intervals, in a shortened timeframe (sub-profile 2) and an extended operating period (sub-profile 3).

The most effective way to extend the lifetime of the IGBT module is to reduce the frequency and intensity of thermal stresses during the 24 h mission profile. Starting and stopping the conveyor belt drive are the operational modes that cause the greatest thermal stress on the module. The frequency of these operational modes at the drive station depends on unpredictable events from other parts of the technological process. The control system of the conveyor drive station cannot influence the frequency of this event, but it can reduce its negative impact on the thermal stress of the IGBT module. One way to extend the lifetime of the IGBT module, achievable by changing the parameters of the control system, is to extend the stopping time of the drive. Such an action would reduce the braking power and the thermal stress on the module.

Future research on this issue will focus on identifying the critical mission profile that causes the IGBT module's junction temperature increase to the maximum permissible temperature of 150 °C. For this reason, it is necessary to identify the thermal model that includes the frequency converter's IGBT module and the external cooling system of the container.

To enhance accuracy, future research should explore nonlinear damage models, such as damage curve methods or energy-based approaches, especially if the objective transitions from damage comparison to more accurate lifespan prediction. Furthermore, validation via empirical power cycling experiments under normal mission profiles would provide important insights into actual damage mechanisms and support in the calibration of more advanced models.

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Abbreviations

The following abbreviations are used in this manuscript:

A/D	Analog-to-Digital
AC	Alternating Current
Ag	Silver
Al/Cu	Aluminum (Al) and Copper (Cu)
CDF	Cumulative Distribution Function
CIPS08	Cycling Insulated Power Semiconductor—2008
Cu	Copper
DC	Direct Current
FC	Frequency Converter
FIR	Finite Impulse Response (FIR filter)

FIT	Failure In Time (FIT rate)
GLM	Generic Lifetime Model
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Motor
MCU	Microcontroller Unit
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
MTBF	Mean Time Between Failures
MMD	Multi-Motor Drive
NTC	Negative Temperature Coefficient
PLC	Programmable Logic Controller
PROFIBUS	Process Field Bus
Si	Silicon
SiC	Silicon Carbide
SMD	Single-Motor Drive

References

1. Vernica, I.; Wang, H.; Blaabjerg, F. *Design for Reliability and Robustness Tool Platform for Power Electronic Systems—Study Case on Motor Drive Applications*; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2018; pp. 2470–6647. [\[CrossRef\]](#)
2. Macken, K.J.P.; Wallace, I.T.; Bollen, M.H.J. Reliability Assessment of Motor Drives. In *2006 37th IEEE Power Electronics Specialists Conference*; IEEE: New York, NY, USA, 2006; pp. 1–7. [\[CrossRef\]](#)
3. MIL-HDBK-217F, Military Handbook: Reliability Prediction of Electronic Equipment. 1990. Available online: <https://www.quanterion.com/wp-content/uploads/2014/09/MIL-HDBK-217F.pdf> (accessed on 5 December 2025).
4. Application Note, Eupec GMB, Infineon Technologies Company, Fit Rates for IGBT Modules. Available online: http://www.igbt.cn/UserFiles/Support_IGBT/file_086.pdf (accessed on 5 December 2025).
5. Štatkić, S.; Jeftenić, I.B.; Bebić, M.Z.; Milkić, Ž.; Jović, S. Reliability Assessment of the Single Motor Drive of the Belt Conveyor on Drmno Open-Pit Mine. *Int. J. Electr. Power Energy Syst.* **2019**, *113*, 393–402. [\[CrossRef\]](#)
6. Wikstrom, P.; Terens, L.A.; Kobi, H. Reliability, Availability, and Maintainability of High-Power Variable-Speed Drive Systems. *IEEE Trans. Ind. Appl.* **2000**, *36*, 231–241. [\[CrossRef\]](#)
7. Pieters, P.; Riikonen, J. Reliability of Adjustable Speed Drives. *IEEE Ind. Appl. Mag.* **2010**, *16*, 47–55. [\[CrossRef\]](#)
8. Rahimpour, S.; Tarzamni, H.; Kurdkandi, N.V.; Husev, O.; Vinnikov, D.; Tahami, F. An Overview of Lifetime Management of Power Electronic Converters. *IEEE Access* **2022**, *10*, 109688–109711. [\[CrossRef\]](#)
9. Hanif, A.; Yu, Y.; DeVoto, D.; Khan, F. A Comprehensive Review Toward the State-of-the-Art in Failure and Lifetime Predictions of Power Electronic Devices. *IEEE Trans. Power Electron.* **2018**, *34*, 4729–4746. [\[CrossRef\]](#)
10. Deng, Z.; Chen, M.; Lai, W.; Ding, X.; Xia, H. A Comparative Study on Lifetime Models in IGBT Power Modules. In *2019 4th International Conference on Intelligent Green Building and Smart Grid (IGBSG)*; IEEE: New York, NY, USA, 2019; pp. 241–245. [\[CrossRef\]](#)
11. Alavi, O.; De Ceuninck, W.; Daenen, M. Optimizing Insulated-Gate Bipolar Transistors' Lifetime Estimation: A Critical Evaluation of Lifetime Model Adjustments Based on Power Cycling Tests. *Energies* **2024**, *17*, 2616. [\[CrossRef\]](#)
12. van der Broeck, C.H. Methodology for Thermal Modeling, Monitoring and Control of Power Electronic Modules. Ph.D. Thesis, RWTH Aachen University, Aachen, Germany, 2018.
13. Bryant, A.T.; Mawby, P.A.; Palmer, P.R.; Santi, E.; Hudgins, J.L. Exploration of Power Device Reliability Using Compact Device Models and Fast Electrothermal Simulation. *IEEE Trans. Ind. Appl.* **2008**, *44*, 894–903. [\[CrossRef\]](#)
14. Denk, M.; Bakran, M.-M. Comparison of Counting Algorithms and Empiric Lifetime Models to Analyze the Load-Profile of an IGBT Power Module in a Hybrid Car. In *2013 3rd International Electric Drives Production Conference (EDPC)*; IEEE: New York, NY, USA, 2013; pp. 1–6. [\[CrossRef\]](#)
15. Huang, H.; Mawby, P.A. A Lifetime Estimation Technique for Voltage Source Inverters. *IEEE Trans. Power Electron.* **2013**, *28*, 4113–4119. [\[CrossRef\]](#)
16. Musallam, M.; Johnson, C.M. An Efficient Implementation of the Rainflow Counting Algorithm for Life Consumption Estimation. *IEEE Trans. Reliab.* **2012**, *61*, 978–986. [\[CrossRef\]](#)
17. Chen, Z.; Gao, F.; Yang, C.; Peng, T.; Zhou, L.; Yang, C. Converter Lifetime Modeling Based on Online Rainflow Counting Algorithm. In *2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*; IEEE: New York, NY, USA, 2019; pp. 1743–1748.
18. Hernes, M.; D'Arco, S.; Spro, O.C.; Pefitsis, D. Experimental validation of linear damage superposition for IGBT power modules under high and low temperature stress cycles. In *PCIM Europe Digital Days 2021; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*; IEEE: New York, NY, USA, 2021; pp. 1–6. Available online: <https://ieeexplore.ieee.org/document/9472389> (accessed on 25 December 2025).

19. Wang, H.; Zhou, D.; Blaabjerg, F. A reliability-oriented design method for power electronic converters. In *2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*; IEEE: New York, NY, USA, 2013; pp. 2291–2298. [CrossRef]
20. Wang, H.; Ma, K.; Blaabjerg, F. Design for reliability of power electronic systems. In *Proceedings of the IECON 2012—38th Annual Conference on IEEE Industrial Electronics Society*, Montreal, QC, Canada, 25–28 October 2012; pp. 33–44. [CrossRef]
21. Ma, K.; Choi, U.-M.; Blaabjerg, F. Prediction and Validation of Wear-Out Reliability Metrics for Power Semiconductor Devices with Mission Profiles in Motor Drive Application. *IEEE Trans. Power Electron.* **2017**, *33*, 9843–9853. [CrossRef]
22. Qi, J.; Li, J.; Feng, H.; Shi, J.; Fan, M.; Jia, C.; Zhen, D. Reliability Assessment of Wind Power Converter Systems Based on Mission Profiles and Sub Module Life Correlations. *IEEE Access* **2024**, *12*, 166162–166175. [CrossRef]
23. Ma, K.; Liserre, M.; Blaabjerg, F.; Kerekes, T. Thermal Loading and Lifetime Estimation for Power Device Considering Mission Profiles in Wind Power Converter. *IEEE Trans. Power Electron.* **2015**, *30*, 590–602. [CrossRef]
24. Ciappa, M. Lifetime Prediction on the Base of Mission Profiles. *Microelectron. Reliab.* **2005**, *45*, 1293–1298. [CrossRef]
25. Zhang, Y.; Heimler, P.; Abuogo, J.O.; Zhang, X.; Zhang, Y.; Xie, D.; Zhang, Y.; Zhang, K.; Li, X.; Luo, H.; et al. Power Cycling Testing for Power Semiconductor Switches: Methods, Standards, Limitations, and Outlooks. *IEEE Trans. Power Electron.* **2025**, *41*, 849–869. [CrossRef]
26. ABB Oy. ACS800 Firmware Manual, 3AFE64527592 REV L. ACS800 Standard Control Program 7.x. 2011. Available online: https://library.e.abb.com/public/6f96ed70e1b467a9c12578f80034ed25/EN_ACS800_Standard_FW_L.pdf (accessed on 15 December 2025).
27. Ma, M.; Yan, X.; Guo, W.; Yang, S.; Cai, G.; Chen, W. Online Junction Temperature Estimation Using Integrated NTC Thermistor in IGBT Modules for PMSM Drives. *Microelectron. Reliab.* **2020**, *114*, 113836. [CrossRef]
28. ABB Industrial Drives, ACS800 Multidrives, Catalog, 3AFE68248531 REV F EN 20.2. 2009. Available online: https://library.e.abb.com/public/5191911f18a8d00cc1257944002e8828/ACS800multidrivescatalogREVI_EN.pdf (accessed on 10 January 2026).
29. Ibrahim, A.; Salem, M.; Kamarol, M.; Delgado, M.T.; Desa, M.K.M. Review of Active Thermal Control for Power Electronics: Potentials, Limitations, and Future Trends. *IEEE Open J. Power Electron.* **2024**, *5*, 414–435. [CrossRef]
30. Rahman, S.M.I.; Moghassemi, A.; Arsalan, A.; Timilsina, L.; Chamarithi, P.K.; Papari, B.; Ozkan, G.; Edrington, C.S. Emerging Trends and Challenges in Thermal Management of Power Electronic Converters: A State of the Art Review. *IEEE Access* **2024**, *12*, 50633–50672. [CrossRef]
31. Hosseiniabadi, F.; Chakraborty, S.; Bhoi, S.K.; Prochart, G.; Hrvanovic, D.; Hegazy, O. A Comprehensive Overview of Reliability Assessment Strategies and Testing of Power Electronics Converters. *IEEE Open J. Power Electron.* **2024**, *5*, 473–512. [CrossRef]
32. Bayerer, R.; Herrmann, T.; Licht, T.; Lutz, J.; Feller, M. Model for Power Cycling lifetime of IGBT Modules—Various factors influencing lifetime. In *Proceedings of the 5th International Conference on Integrated Power Electronics Systems*, Nuremberg, Germany, 11–13 March 2008; pp. 1–6.
33. Lu, Y.; Xiang, E.; Zhu, L.; Gao, H.; Yang, H.; Zhao, R. Mission Profile-Based Lifetime Estimation and Its System-Controlled Improvement Method of IGBT Modules for Electric Vehicle Converters. *CPSS Trans. Power Electron. Appl.* **2023**, *8*, 246–256. [CrossRef]
34. Thoben, M. Infineon Technologies. Reliability and Lifetime of Power Modules. In *EPE'16 ECCE Europe*. Available online: https://www.researchgate.net/publication/312155578_Reliability_and_Lifetime_of_Power_Modules_Tutorial_Industry_Best_Practices_in_Reliability_Prediction_and_Assurance_for_Power_Electronics (accessed on 12 January 2026).
35. Sousa, R.O.D.; Barros, R.C.D.; Amorim, W.C.S.; Cupertino, A.F.; Pereira, H.A. Modified Rainflow Algorithm for Lifetime Estimation of Semiconductors Devices. In *2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP)*; IEEE: New York, NY, USA, 2023; pp. 1–8. [CrossRef]
36. Sousa, R.O.D.; Barros, R.C.D.; Amorim, W.C.S.; Cupertino, A.F.; Pereira, H.A.; Morais, L.M.F. Modified Rainflow Algorithm for Temperature-Time-Dependent Counting in Lifetime Estimation of Power Devices. *Eletrônica Potência* **2025**, *30*, e202532. [CrossRef]
37. Letz, S.A.; Zhao, D.; Leib, J.; Eckardt, B.; Maerz, M. Modified Approach for the Rainflow Counting Analysis of Temperature Load Signals in Power Electronics Modules. In *CIPS 2024; 13th International Conference on Integrated Power Electronics Systems*; VDE: Düsseldorf, Germany, 2024.
38. Rainflow Counting and Lifetime Prediction. In PLECS. Available online: https://www.plexim.com/sites/default/files/demo_models_categorized/plecs/rainflow_counting.pdf (accessed on 15 January 2026).

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