Lifetime Assessment of PV Inverters Using Marco-Starkey Theory and Nonlinear Damage Accumulation

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Abstract

The lifespan of a photovoltaic system is typically estimated at 25 years, with photovoltaic panel manufacturers guaranteeing at least 80% of the initial power output over this period. However, system performance can be compromised by failures and irregular operation of other components, such as inverters, which require frequent maintenance and remain prone to malfunctions. As the large-scale photovoltaic systems expand, accurate lifetime assessment of inverters becomes crucial to ensuring availability, optimizing maintenance schedules, and maintaining a competitive Levelized Cost of Energy. This study contributes to reliability analysis by incorporating Marco-Starkey Theory into the damage accumulation rule. We analyze the impact of the variation in the damage accumulation exponent on lifespan in three Brazilian cities. The proposed approach could enable calibration of the damage-accumulation exponent using historical failure data; however, this paper focuses on a sensitivity analysis and does not demonstrate such calibration with field failure records. We show that a seemingly small change of +10% in the exponent may increase the expected lifetime by approximately 300%, whereas a −10% variation can reduce it by about 75%, highlighting the sensitivity of lifetime predictions to this parameter.

Keywords: reliability, lifetime assessment, photovoltaic inverters, Marco-Starkey theory, damage accumulation

1. Introduction

By the end of 2024, the cumulative installed photovoltaic (PV) capacity reached 1,858.7 GW globally, including 37.9 GW in Brazil. A decade earlier, capacity was substantially lower: 220.9 GW worldwide and approximately 49 MW in Brazil (IRENA, 2025). According to the *Renewable Energy and Jobs: Annual Review,* by IRENA and International Labour Organization (2024), this expansion has positioned the PV sector as a major global employer, generating about 7.1 million jobs worldwide. This rapid growth underscores the importance of ensuring long-term system reliability to sustain energy production and economic returns.

Reliability is the ability of a system to perform its intended functions successfully throughout its expected useful life. In PV systems, reliability is closely tied to economic performance, since component failures lead to maintenance expenses and energy production losses (Abdulla et al., 2024; Hacke et al., 2018). This relationship can be expressed through the levelized cost of energy (LCOE), which measures lifetime costs relative to total energy produced. As reliability directly affects the amount of energy a power plant can deliver, higher reliability results in a lower LCOE (Abdulla et al., 2024). Recent projections indicate that improvements in operation and maintenance (O&M) services could further decrease the PV plants LCOE by about 0.8% to 1.4% between 2015 and 2030 (Emblemsvåg, 2021).

Many factors govern the expected lifetime of PV inverters, thereby influencing their operation and maintenance practices. The mission profile, defined by irradiance and ambient temperature (Fogsgaard et al., 2022; Lenz et al., 2017), influences component thermal loading. Operating conditions, including reactive power compensation (Anurag et al., 2015; Brito et al., 2023; Zhang & Gao, 2023), and converter design parameters such as component sizing, fan failure occurrence and derating strategies (Chen et al., 2023; Ribeiro et al., 2025; De León-Aldaco et al., 2013; De Lima et al., 2023) also affect internal temperatures. Together, these factors define the thermal stress on power switches and capacitors, ultimately determining their lifetime.

Although several reliability assessment pipelines have been established for power electronic systems (Peyghami et al., 2019; Singh et al., 2023), the treatment of cumulative damage remains underdeveloped. Most studies continue to rely on Miner's Rule, leaving the influence of alternative damage-accumulation exponents

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underexplored in PV inverter lifetime prediction (Zeng et al., 2019). Furthermore, there are few methods to calibrate model parameters, such as the accumulation exponent, with historical failure data, reducing the accuracy of current reliability models.

This work addresses this gap by analyzing nonlinear damage accumulation through a sensitivity-based approach. Section 2 covers the fundamentals of reliability assessment in PV inverters, from mission profile analysis to Monte Carlo simulation. Section 3 presents the general methodology, including system description, the reliability assessment pipeline used, and the tested range of high-to-low and low-to-high variants. Section 4 presents and discusses the main results, highlighting the sensitivity of lifetime metrics to the accumulation exponent. Conclusions and future work are provided in Section 5.

2. Basics of reliability assessment in photovoltaic inverters

Reliability assessment follows a structured pipeline that begins with mission profile data and progresses toward lifespan prediction. Thermal models use these inputs to estimate the junction temperatures of semiconductor devices, while empirical lifetime models and damage-accumulation rules quantify the consumed life fraction. Finally, uncertainty propagation is performed through Monte Carlo simulation to obtain probabilistic lifetime estimations.

2.1. Mission profile

The mission profile, composed of irradiance and ambient temperature**,** characterizes the environmental and operational conditions that a product will encounter over its lifespan. This study evaluates PV inverter reliability in three representative Brazilian locations - Campos do Jordão, Campinas, and Teresina – also adopted in Ribeiro et al. (2024).

2.2. Thermal models

The semiconductor junction temperature (T_j) can be estimated from its power losses (P_{Loss}) through a thermal impedance network, as illustrated in Figure 1. For a single fundamental grid cycle, the junction temperature fluctuation (ΔT_j) can be calculated using the following equation (Ma, K. & Blaabjerg, F., 2012):

$$\Delta T_j = P_{Loss} \cdot Z_{th}\left(\frac{1}{8f_0}\right) + 2P_{Loss} \cdot Z_{th}\left(\frac{1}{4f_0}\right), \quad \text{(eq. 1)}$$

where f_0 denotes the grid frequency and Z_{th} represents the thermal impedance between junction and case.

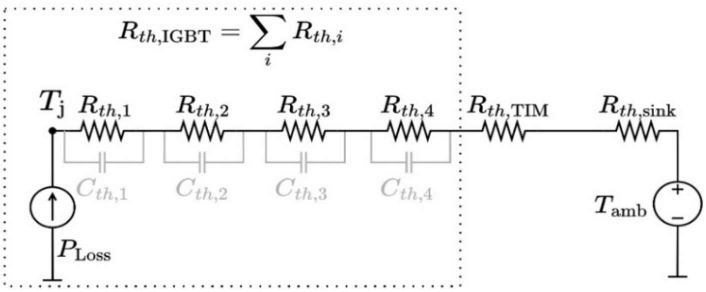

Figure 1: A generic thermal network including IGBT and heat sink thermal resistances.

2.3. Lifetime models

The thermal cycling induced by junction temperature fluctuations accelerates degradation mechanisms such as bond-wire lift-off and solder fatigue. To quantify this effect, several models are employed to estimate the number of thermal cycles to failure (Hosseinabadi et al., 2024). In this work, the Bayerer model is adopted (Bayerer et at., 2008):

$$N_f = A \cdot \left(\Delta T_j\right)^{\beta_1} \cdot e^{\frac{\beta_2}{T_{jm}}} \cdot {t_{on}}^{\beta_3} \cdot I^{\beta_4} \cdot V^{\beta_5} \cdot D^{\beta_6}, \quad \text{(eq. 2)}$$

where N_f is the number of cycles to failure, A is a technology factor, β_1 to β_6 are curve fitting parameters listed in Table 1, ΔT_j [K or ºC] is the junction temperature oscillation, T_{jm} [K] is the mean junction temperature,

t_{on} [s] is the heating time, I [A] is the current per bond foot, V [V] is the blocking voltage divided by 100, and D [μm] is the bond wire diameter.

Table 1: Curve fitting parameters and experimental conditions (Bayerer et al., 2008).

Parameter	Value	Experimental Condition
A	9.34E14	–
β_1	-4.416	$45\,K \le \Delta T_j \le 150\,K$
β_2	1285	$20\,°C \le T_{jm} \le 120\,°C$
β_3	-0.463	$1\,s \le t_{on} \le 15\,s$
β_4	-0.716	$3\,A \le I \le 23\,A$
β_5	-0.761	$6\,V \le V/100 \le 33\,V$
β_6	-0.5	$75\,\mu m \le D \le 500\,\mu m$

2.4. Damage accumulation rules

Power semiconductor devices are subjected to a wide range of thermal loadings during operation, each contributing partially to the overall fatigue damage. For a given operating condition i, the lifetime consumption LC_i is defined as

$$LC_i = \frac{n_i}{N_{f,i}}, \qquad \text{(eq. 3)}$$

where n_i is the number of thermal cycles in condition i obtained via counting algorithms or mission profile sampling. Since a mission profile comprises multiple operating conditions, aggregating the lifetime consumption across different thermal load phases is challenging (Simões & Busarello, 2024). To address this, the most common approach is the linear damage accumulation rule, known as Miner's rule.

2.4.1. Miner's Rule

The foundational model for fatigue failure phenomenon is the linear damage rule (LDR), a concept introduced by Palmgren (1924) and later expressed in a mathematical form by Miner (1945):

$$D = \sum LC_i = \sum_{i=1}^{k} \frac{n_i}{N_{f,i}}. \qquad \text{(eq. 4)}$$

Failure is deemed to occur when $\sum LC_i = 1$. The damage-ratio curve, or D-r curve, for Miner's Rule is simply a diagonal straight line.

Although widely adopted, the validity of linear accumulation has been debated in the literature (Fatemi & Yang, 1998). Studies show that Miner's Rule tends to be conservative, meaning it underestimates the lifespan of components in real-world conditions (Wang et al., 2019; Zeng et al., 2019).

2.4.2. Marco-Starkey Theory

The main shortcomings of Miner's Rule are that it does not account for load-level or load-sequence (Fatemi & Yang, 1998). Experimental evidence under completely reversed loading conditions indicates that for a low-to-high (L-H) sequence, a system can endure more cycles than predicted ($\sum LC_i > 1$). Contrariwise, starting with high loads and then decreasing to low ones (H-L), the system fails sooner ($\sum LC_i < 1$).

To remedy these deficiencies, Richart and Newmark (1948) suggested that D-r curves should differ depending on the sequence of stress levels. Examples of D-r curves are shown in Figure 2. Nine years after Miner's Rule was released, Marco and Starkey (1954) proposed the first nonlinear load- dependent damage theory, represented by the power relationship $D = \sum LC_i^{x_i}$, where x_i is the accumulated damage exponent related to the i-th load level. Miner's Rule is a special case of the above equation with $x_i = 1$. Based on Marco-Starkey Theory, $x_i > 1$ when there is a low-high sequence, and $x_i < 1$ for a high-low sequence.

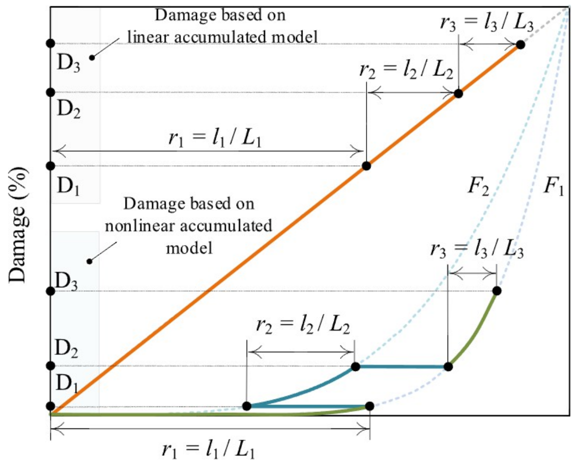

Figure 2: D-r curves: Comparison of linear and nonlinear accumulated damage models (Wang et al., 2019).

2.5. Monte Carlo simulation

Monte Carlo (MC) is a statistical method based on repeated random sampling to estimate the behavior of complex systems under uncertainty. In the context of PV inverter reliability, MC enables the evaluation of how variations in environmental and operational conditions influence the expected lifetime (He et al., 2021; Novak et al., 2021). In the simulation, probability distributions are assigned to parameters in the thermal loading and/or in the lifetime model (Kardan et al., 2025), providing a statistical framework for propagating parameter uncertainty through the reliability assessment chain and deriving lifetime indicators such as B_{10}, defined as the time at which 10% of the simulated samples have failed. Among the existing variants, the static Monte Carlo method remains the most widely employed due to its computational simplicity and efficiency (Morocho et al., 2025).

3. Methodology

This section outlines the methodology developed to investigate a previously unexamined factor in PV inverter reliability: the impact of damage accumulation exponent variation on the B_{10} lifespan. The analysis is structured in two fundamental stages. First, Section 3.1 details the system configuration. Subsequently, Section 3.2 elaborates on the reliability assessment pipeline, which is designed to quantify the sensitivity of lifetime predictions to this specific exponent. Within a PV inverter, electrolytic capacitors and power switches are among the components most susceptible to failure. This study, however focuses exclusively on power switches to streamline the analysis.

3.1. System description

This work employs the system depicted in Figure 3. The key converter parameters and the IGBT's thermal characteristics are listed in Tables 2 and 3, respectively.

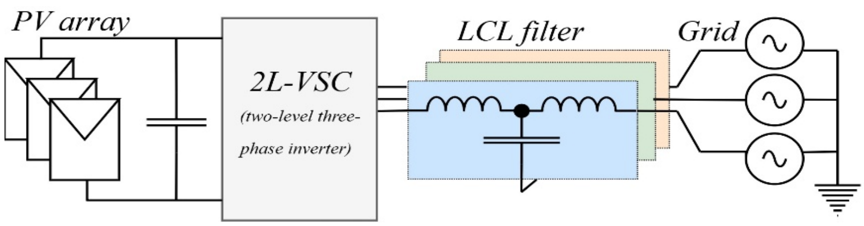

Figure 3: Photovoltaic system: PV array, DC link, IGBT bridge, filters and grid connection.

Table 2: PV converter main parameters (Ribeiro et al., 2024).

Parameter	Symbol	Value
Nominal power	P_n	40 kW
Switching frequency	f_{sw}	15 kHz
PV array maximum power	P_{mpp}	38 kW
PV open circuit voltage	V_{oc}	850 V
DC-link voltage reference	V_{dc}	680 V
Line-to-line grid voltage	$V_{g,l-l}$	220 Vrms
Grid frequency	f_g	60 Hz
DC-link capacitance	C_{dc}	2.35 mF
AC Filter inductance	L_f	4 mH

Table 3: Electrothermal description for the power module — part number: IFS150B12N3E-B31 (Ribeiro et al., 2024).

Parameter	Symbol	Value
Collector-emitter voltage	V_{ce}	1200 V
Nominal collector current	$I_{c,nom}$	150 A
Operating junction temperature	$T_{j,op}$	150°C
Maximum junction temperature	$T_{j,max}$	175°C
Total power dissipation	P_{tot}	750 W
IGBT J-C thermal resistance*	$R_{qth\ j-c}$	0.2 K/W
IGBT C-H thermal resistance*	$R_{qth\ c-h}$	0.083 K/W
Diode J-C thermal resistance*	$R_{dth\ j-c}$	0.375 K/W
Diode C-H thermal resistance*	$R_{dth\ c-h}$	0.155 K/W

*Per IGBT and diode

3.2. Reliability assessment pipeline

Figure 4 presents the reliability assessment pipeline (RAP) employed. The RAP begins by processing annual mission profiles, which comprise 5-minute samples of irradiance and ambient temperature data, into thermal loading profiles (T_j and ΔT_j) using power loss look-up tables and thermal models with datasheet information. T_j and ΔT_j are then analyzed to evaluate the degradation of power switches. The specifications for each stage of the pipeline are detailed in Table 4.

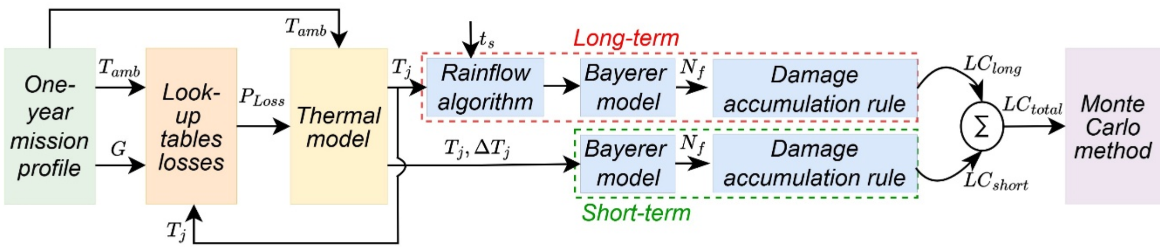

Figure 4: Pipeline for inverter reliability assessment: from mission profile to lifetime distribution.

Table 4: Reliability assessment pipeline: summary description with comments.

Stage	Description	Comment
Mission profiles	SOLCAST: Teresina (2016), Campinas (2019), Campos do Jordão (2020).	Representative years from 2014 to 2023 (Ribeiro et al., 2024). T_{amb} is ambient temperature and G is global horizontal irradiance.
Power losses estimation	Look-up table (LUT) approach. P_{Loss} are total power losses (conduction losses + switching losses).	Three-dimensional LUT with 48 samples combining irradiance $(0, 200, 400, 600, 800, 1000\ W/m^2)$, ambient temperature $(-10, 10, 30, 50\ °C)$ and junction temperature $(25$ and $125\ °C)$ points.
Thermal loadings	Thermal resistances network + analytical method.	Demands an analytical approach to obtain ΔT_j.
Counting cycle method	Rainflow algorithm.	MATLAB's native function *rainflow()*. t_s is the sampling time (300 s).
Lifetime model	Bayerer model.	Complying with Table 1.
Simulation tools	PLECS + MATLAB.	PLECS 4.7.6: converter thermal and electrical analyses (steady-state). MATLAB R2020a: reliability assessment pipeline implementation and data visualization.
Damage accumulation rule	Miner's Rule vs. Marco-Starkey Theory.	Damage accumulation exponent range: $x_i \in [0.90, 1.10]$ step 0.01. LC_{short} and LC_{long} are lifetime consumption in short and long-term, respectively.
Monte Carlo	Static variant.	Unreliability curves with 50,000 samples and $\pm 5\%$ normal deviation from nominal input parameters $(T_j, \Delta T_j$ and $A)$.
System-level reliability	Series reliability block diagram.	All IGBTs are considered in series in terms of reliability, meaning the failure of one IGBT results in a converter failure.

4. Results and discussion

The climatic differences among Teresina, Campinas, and Campos do Jordão (Figure 5) play a crucial role in shaping the inverter's thermal loading (Figure 6) and, consequently, its reliability. Teresina presents the highest average ambient temperatures and solar irradiance levels, leading to a harsher thermal condition. Campinas shows intermediate behavior, while Campos do Jordão exhibits lower temperatures and reduced irradiance.

After obtaining the system's unreliability, the next step is to examine it with a reliability metric, with the B_x being the most commonly used. The metric B_x represents the time by which $x\%$ of the PV inverter population will fail. In particular, B_{10} is frequently employed in the industry as a reliability benchmark. Tables 5-7 present the reliability assessment for each accumulation damage exponent scenario.

It is important to emphasize that lifetime is highly sensitive to the accumulation damage exponent. Since the exponent appears at the end of the pipeline, it is an interesting variable to explore, especially when no justified parameter variations are available (e.g., from datasheet) for Monte Carlo. However, caution is required. Accordingly, the very large B10 values observed for the L–H variants should be interpreted primarily as evidence of strong model sensitivity to the damage accumulation exponent, rather than as realistic inverter service lifetimes. The lifetimes are therefore not representative of field operation and should not be taken as practical expectations. A seemingly small change of $+10\%$ in the exponent increase the prediction by approximately 300%, whereas a -10% variation may reduce it by about 75%.

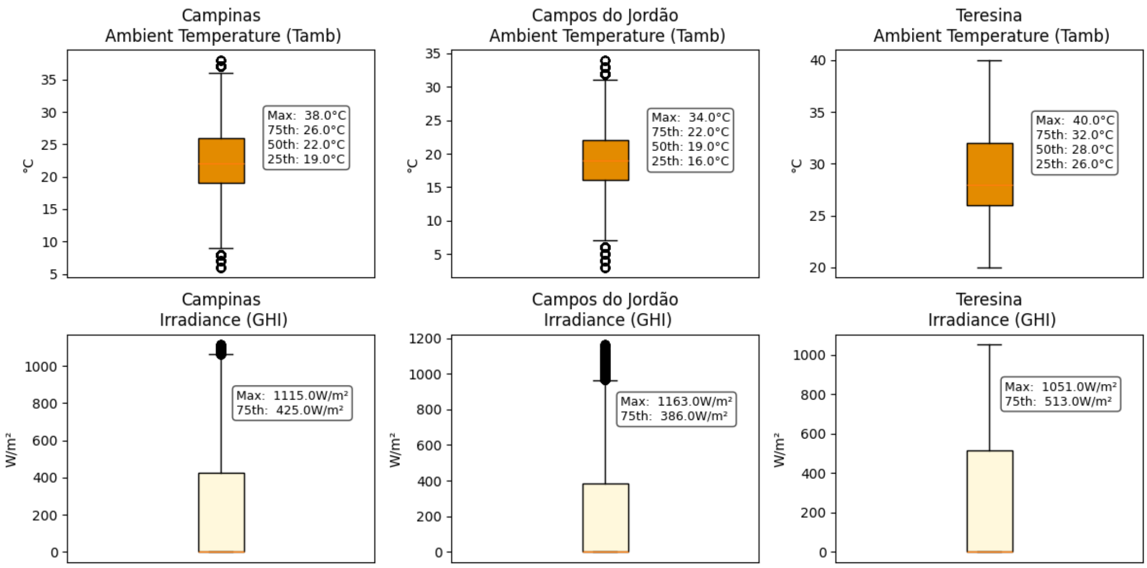

Figure 5: Boxplots considering the mission profile in Campinas (2019), Campos do Jordão (2020) and Teresina (2016).

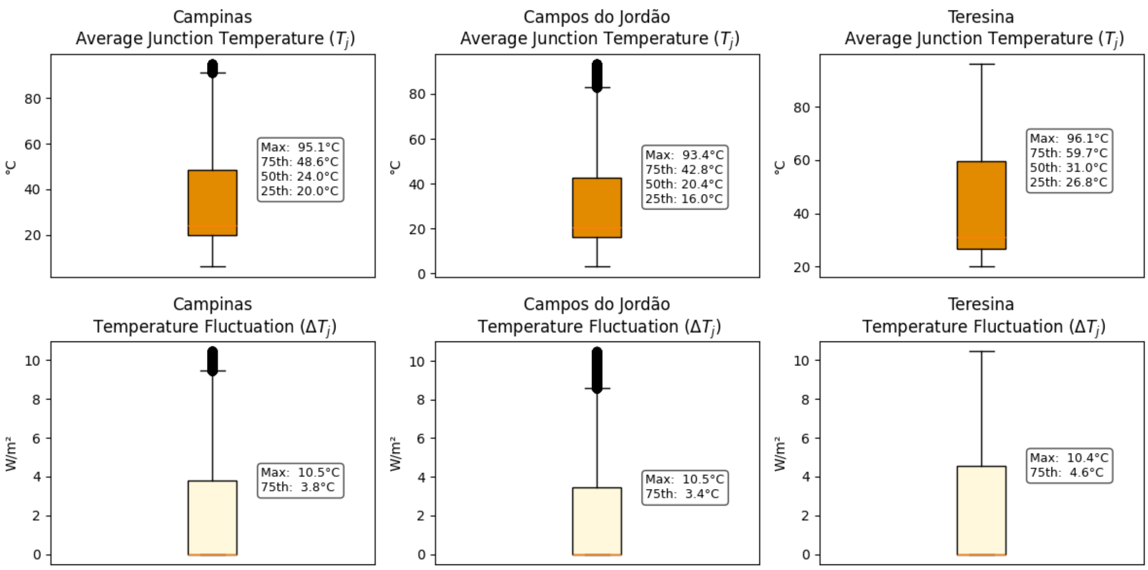

Figure 6: Boxplots considering the thermal loading in Campinas (2019), Campos do Jordão (2020) and Teresina (2016).

Table 5: Static lifetime and Monte Carlo results in years for IGBT and PV inverter in Teresina.

Scenario	IGBT (static lifetime)	IGBT (B_{10})	PV inverter (B_{10})
$x_i = 0.90$	15.06 (−75.2%)	13.20 (−75.3%)	11.60 (−75.0%)
$x_i = 0.95$	30.29 (−50.1%)	26.40 (−50.6%)	23.00 (−50.4%)
$x_i = 0.99$	52.86 (−13.0%)	46.20 (−13.5%)	40.20 (−13.4%)
$x_i = 1.00$	60.74	53.40	46.40
$x_i = 1.01$	69.80 (+14.9%)	61.40 (+15.0%)	53.00 (+14.2%)
$x_i = 1.05$	121.54 (+100.1%)	107.20 (+100.7%)	92.20 (+98.7%)
$x_i = 1.10$	242.62 (+299.5%)	212.00 (+297.0%)	184.60 (+297.8%)

Table 6: Static lifetime and Monte Carlo results in years for IGBT and PV inverter in Campinas.

Scenario	IGBT (static lifetime)	IGBT (B_{10})	PV inverter (B_{10})
$x_i = 0.90$	18.35 (−75.1%)	16.00 (−75.1%)	14.00 (−74.9%)
$x_i = 0.95$	36.69 (−50.2%)	32.20 (−49.8%)	28.00 (−49.8%)
$x_i = 0.99$	63.70 (−13.5%)	56.00 (−12.8%)	48.50 (−13.1%)
$x_i = 1.00$	73.64	64.20	55.80
$x_i = 1.01$	83.86 (+13.9%)	73.00 (+13.7%)	64.00 (+14.7%)
$x_i = 1.05$	145.12 (+97.1%)	127.00 (+97.9%)	111.00 (+99.0%)
$x_i = 1.10$	287.11 (+289.9%)	251.20 (+291.2%)	219.00 (+292.4%)

Table 7: Static lifetime and Monte Carlo results in years for IGBT and PV inverter in Campos do Jordão.

Scenario	IGBT (static lifetime)	IGBT (B_{10})	PV inverter (B_{10})
$x_i = 0.90$	22.15 (−75.2%)	19.20 (−75.4%)	16.80 (−75.3%)
$x_i = 0.95$	44.54 (−50.1%)	39.00 (−50.1%)	34.00 (−50.0%)
$x_i = 0.99$	77.67 (−12.9%)	67.80 (−13.3%)	59.20 (−12.9%)
$x_i = 1.00$	89.22	78.20	68.00
$x_i = 1.01$	102.47 (+14.8%)	89.40 (+14.3%)	78.00 (+14.7%)
$x_i = 1.05$	177.98 (+99.5%)	155.80 (+99.3%)	135.80 (+99.7%)
$x_i = 1.10$	353.58 (+296.4%)	309.00 (+295.2%)	269.10 (+295.7%)

5. Conclusions and future work

PV systems are designed for a 25-year operational lifespan, yet their long-term reliability is often compromised by converter-level failures. A critical example is PV inverters, which frequently experience wear-out failures as early as 5-10 years into operation — a trend reflected in standard industry warranties. While most reliability studies adopt Miner's Rule, this work demonstrates that the predicted lifetime varies when different damage accumulation exponents are applied. The L-H variants predict extended lifetimes, while, the H-L variants anticipate them. Moreover, the consistency of these results across the three locations investigated confirms that this sensitivity is intrinsic to the reliability model itself rather than dependent on the mission profile. These insights indicate a potential methodological capability: in principle, the damage exponent could be calibrated to match historical failure data. This study does not perform or validate such calibration, which is left for future work when field failure records will be available. However, this calibration must be approached with caution: a +10% variation in the damage exponent can increase predicted lifetime by 300%, while a −10% change can reduce it by 75%. Ultimately, by establishing it as a key lever for methodological refinement, this study provides a foundation for more accurate lifetime predictions, paving the way for future work that will integrate dynamic aging factors for even greater model fidelity.

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