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Comparative reliability and performance analysis of PV inverters with bifacial and monofacial panels

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ABSTRACT

In the realm of solar energy systems, the reliability and performance of photovoltaic (PV) inverters play a critical role in ensuring efficient energy conversion and long-term operation. This study delves into a comprehensive reliability-oriented performance assessment of PV inverters, with a particular focus on the comparative analysis between bifacial and monofacial panels. Reliability evaluation is carried out by considering a yearly mission profile with a one-minute sample at Hyderabad, India. A test case of a 3-kW PV system for grid-connected applications is considered. By integrating reliability metrics with performance indicators, we aim to provide a holistic evaluation of PV inverters operating under varying conditions inherent to both panel types. The research methodology involves detailed simulations and field data analysis to capture the nuances of inverter performance influenced by the unique characteristics of bifacial panels, such as their ability to capture light from both sides, compared to the traditional monofacial panels. In this paper, performance parameters such as junction temperature, MCS, and B10 lifetime (system level (SL) and component level (CL)) are evaluated. Key findings highlight the impact of these differences on inverter reliability. The Bi-PV panel exhibits a decreasing trend. In India, CL reliability (B10) is decreased from 34 years to 1.5 years, and SL reliability (B10) is decreased from 24 years to 1 year. In comparison with monofacial panels, the thermal stress on the PV inverter due to the bifacial panel is increased, and reliability is decreased.

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1. INTRODUCTION

The global shift towards renewable energy has highlighted the need to optimize solar photovoltaic (PV) systems, which are central to sustainable energy production. Central to these systems are PV inverters, which convert direct current (DC) generated by solar panels into alternating current (AC) suitable for use in electrical grids and domestic applications. The performance and reliability of these inverters are critical for maximizing energy yield and ensuring the longevity of PV systems. Recent advancements in PV technology have introduced bifacial panels, which can capture solar energy from both their front and rear surfaces, as a potential alternative to the conventional monofacial panels that only utilize the front surface. Bifacial panels promise higher energy output, especially in environments where ground albedo and reflective surfaces can enhance rear-side irradiation. However, the incorporation of bifacial panels introduces new dynamics in the energy conversion process, thereby affecting the performance and reliability of PV inverters. This study aims to provide a thorough reliability-oriented performance assessment of PV inverters, with a comparative analysis of systems utilizing bifacial and monofacial panels. By evaluating the interplay between panel type and inverter performance under diverse operational conditions, we seek to elucidate the potential benefits and challenges associated with bifacial panels. Our approach involves a combination of theoretical modeling, simulation studies, and empirical data analysis to capture the complex interactions affecting inverter reliability and efficiency. Understanding these dynamics is essential for manufacturers, system designers, and stakeholders aiming to optimize PV system performance and enhance the deployment of solar energy solutions. This research contributes to the growing body of knowledge necessary for advancing PV technology and fostering the adoption of more reliable and efficient renewable energy systems.

Many countries have reached grid parity with solar photovoltaic systems, and many plans are proposed to reach 100% utilization of green energy sources by 2050. Furthermore, in the next ten years, the cost of renewables is projected to undercut the cost of fossil fuels [1]. Nevertheless, the PV system is one of the preferred solutions for future energy demand. The factors for the increasing tendency of the PV market are increased energy demand, government policies towards renewable energy sources, concerns related to the environment, rapid development in PV technologies, and an increase in PV installations globally. A recent advancement in PV panel technology concerned with energy yield is the Bi-PV panel. As the name implies, it can harvest energy from both sides, i.e., front and rear sides of the panel, as shown in Figure 1, which leads to increased energy yield. Hence, this technology attracted the PV industry in recent years [2]. According to the IEA PVPS report [3], Bi-PV shares about 20% of the global PV cell market in 2021. By 2030. It is predicted that this will rise to 70%. The market share of Bi-PV modules has been estimated at 12% in 2020 and is expected to grow to 30% by 2030. This indicates that most of the future production of these cells will be utilized in Mo-PV modules. In order to improve the power rating of these components, white back encapsulants and reflective back sheets can be used. Several research facilities are currently conducting studies on the performance and design of Bi-PV modules to improve their efficiency and reduce their cost.

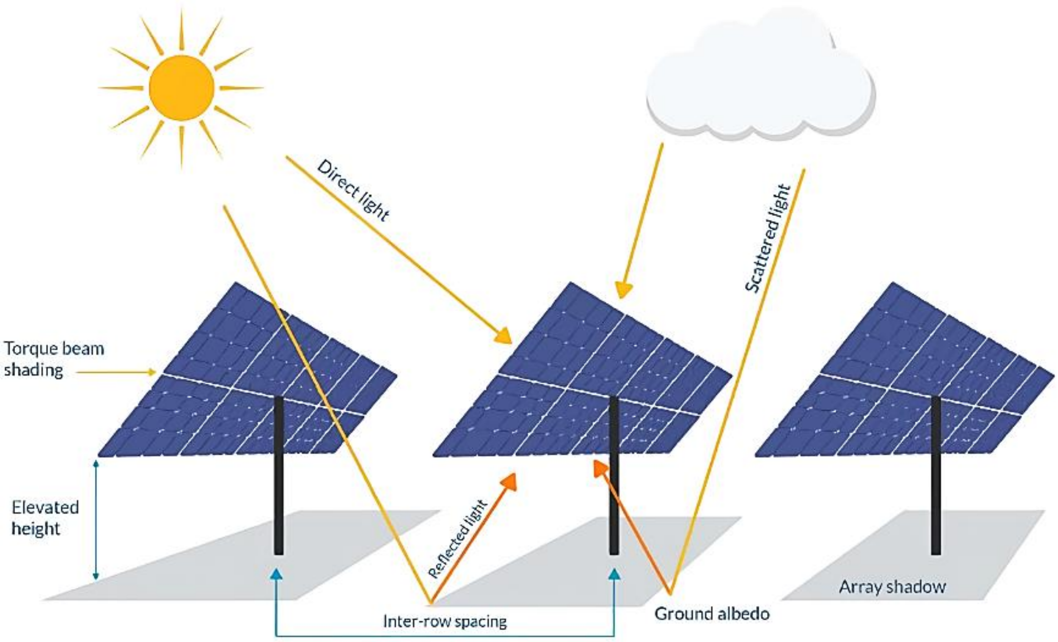

Figure 1. Bi-PV panel

Rodríguez-Gallegos *et al.* [4] analyzed the various design parameters of PV systems to determine which type of module would result in the lowest levelized cost of energy (LCOE). It revealed that the most optimal design for sites is a Bi-PV module on a horizontal single-axis tracker (HSAT). On the other hand, Mo-PV systems were the least efficient at reducing the LCOE of 3.1% of the land area. When compared to Mo-PV systems, Bi-PV modules have the lowest LCOE in areas with high latitudes. This trend is expected to continue for the next decade. Bi-PV manufacturers Trina Solar, LONGi, and LG claim up to 30% more energy yield. About 20 countries had already installed the Bi-PV panels by the end of August 2019. The total installed Bi-PV panel capacity is 8.53 GW, and it is forecasted that about 21 GW to be installed by 2024. The global annual bifacial installed capacity is shown in Figure 2 [5].

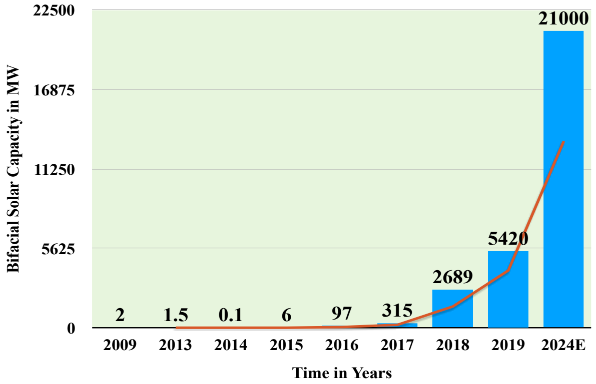

Figure 2. Global annual installed bifacial solar capacity [5]

Figure 3 shows the country-wise Bi-PV installed capacity. China leads with 6282 MW, followed by the USA, Brazil, Egypt, and Australia. About 100 MW is installed in Taiwan, Mexico, Oman, and 1 0–35 MW have been built in European countries. A model to estimate the rear solar irradiance is presented in Pelaez *et al.* and [6]. Zengwei *et al.* [7], the performance analysis of Bi-PV panels, considering horizontal and inclined sun trackers in several locations in China, is compared with Mo-PV panels. Also, a comparative analysis of floating-type panels is performed by Widayat *et al.* [8], and an experimental model for both panels is implemented Ayadi *et al.* [9]. In Ontario, bifacial solar panels were able to gain an 18% annual energy yield when compared to Mo-PV panels. There is a significant increase in power production of about 13 % to 35 % during sunny days and 40% to 70% during cloudy days [10]. In Japan, a 1.2 MW bifacial power plant was able to gain a bifacial gain of almost 20% during the past two years. This project was developed by the local company, the Hokuto Group. The performance of Bi-PV panels has been extensively examined in several studies [11]–[15].

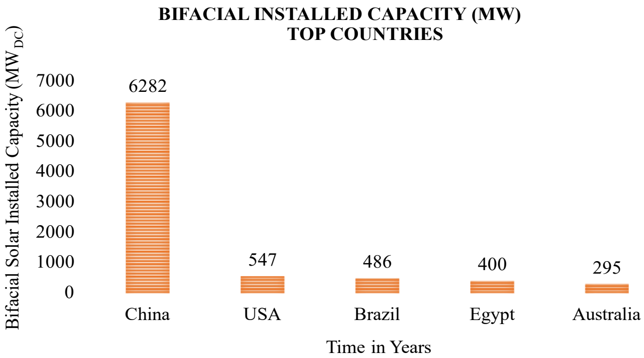

Figure 3. Country-wise Bi-PV installed capacity [5]

Meanwhile, PV manufacturers focused on improving the design for highly reliable power electronics conversion systems. Bi-PV panel inevitably affects the loading performance of PV inverter, as it operates nearly the rated power for a longer duration. This leads to an increase in thermal stress on power electronic components. PV inverter is reported as the most unreliable component. The most critical components of photovoltaic plants are power electronic systems [16]–[18]. The field survey from 2001 to 2006 on unscheduled costs and events of PV plants is presented in Figures 4 and 5, respectively.

A total of 156 events are recorded and categorized as PV inverter, PV panels, junction box, system, AC disconnects, and data acquisition. Among the events, PV inverter shares 37% and the cost associated with it is 59%. Therefore, the PV inverter is the most crucial component and plays a significant role in terms of reliability concerns. Increased reliability concerns may counteract the benefits of Bi-PV panels, i.e., increased energy yield has a negative effect on the system [16]. Hence, a lifetime analysis of a PV inverter is required to ensure its reliability.

Mission profile (MP) in terms of solar irradiance (SI) and ambient temperature (TA) is considered as the factor affecting the performance and reliability of PV inverters. The impact of SI and TA on PV inverter reliability at different locations is presented in [19]. Kshatri *et al.* presented MP MP-oriented reliability assessment. However, in these studies, performance is evaluated considering only the Mo-PV panel, where energy is harvested only from the front side. Reliability-oriented assessment of PV inverter studies is also presented in [21]-[23].

Therefore, in this paper comparative reliability evaluation between bifacial and Mo-PV panels is carried out on a single-phase inverter for a 3-kW PV to explore the challenges. This evaluation is performed with yearly MP data from Hyderabad, India. Lifetime (LT) samples of 10000 are generated using the MCS with 5% variation. LT of PV inverter with a 10% probability of bearing failure (B10) at the system level (SL) and component level (CL) are calculated and compared for both the bifacial and Mo-PV panels.

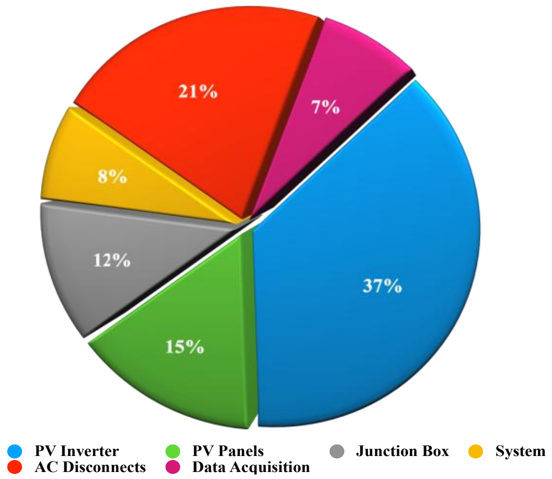

Figure 4. PV plant unscheduled maintenance events [16]

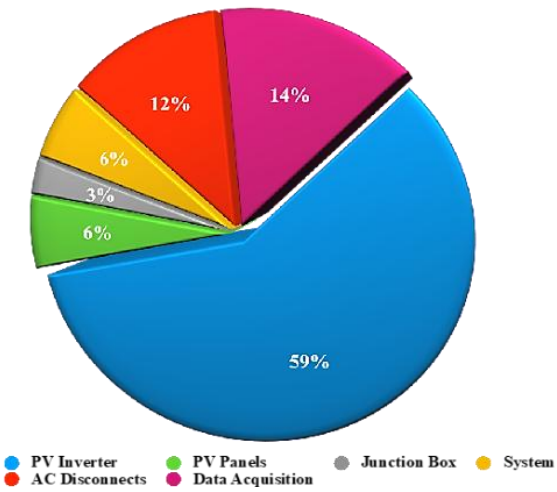

Figure 5. PV plant unscheduled maintenance costs [16]

2. RELIABILITY ANALYSIS OF PV INVERTER

The power electronic switch is reported as the most failed component. The common failures, wear out, and bond wire liftoff, are reported Kshatri *et al.* [20]. Thermal stress is the main reason for the failure. Hence, to obtain the reliability of the PV inverter, the performance of the power electronic switch needs to be evaluated. For this study, an insulated gate bipolar transistor (IGBT) is considered to provide the switching operation. The reliability evaluation of the PV inverter follows several stages as shown in Figure 6.

2.1. Data logging of mission profile

Yearly MP i.e., SI and TA profiles (Sep-2020 to Aug-2021) at the India location are logged by the PV weather station installed at “B V Raju Institute of Technology, Narsapur, Medak, Telangana, India”, where Latitude is 17.7394° N and Longitude is 78.2846° E. CMP11 Pyranometer from Kipp and Zonen manufacturer is used to measure solar irradiance, RTD device from Kipp & Zonen manufacturer is used to measure ambient temperature, CR3000 data logger from Campbell Manufacturer is used to log mission profile. RS485 cable is used as a communication cable and interfaced to the CPU via RS232 cable as shown in Figure 7. The climatic condition in India is relatively hot. Average SI is relatively high overall for the year at the India location. The mission profile is logged as shown in Figure 8 [24].

2.2. Junction temperature calculation

To quantify the failures of IGBT, its junction temperature (Tj) variations need to be assessed. Yearly Tj needs to be calculated from MP. To obtain the Tj, an electro-thermal modeling topology is required. The Foster Electro Thermal (FET) model is commonly used by the manufacturers; hence, it is used in this paper to calculate the Tj. The parameters of FET model are taken from [21].

2.3. Rainflow analysis

To analyze variations of Tj, a counting algorithm is required. In this paper, the variations are analyzed using the rainflow counting algorithm. The parameters that are extracted using the analysis are the number of cycles Ni, mean of junction temperature Tjm, and cycle amplitude ΔTj.

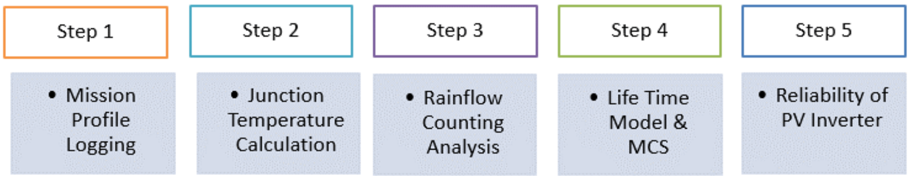

Figure 6. Flowchart for reliability assessment

(a) (b) (c)

Figure 7. Data logging system: (a) CMP11 pyranometer, (b) RTD device, and (c) CR3000 data logger

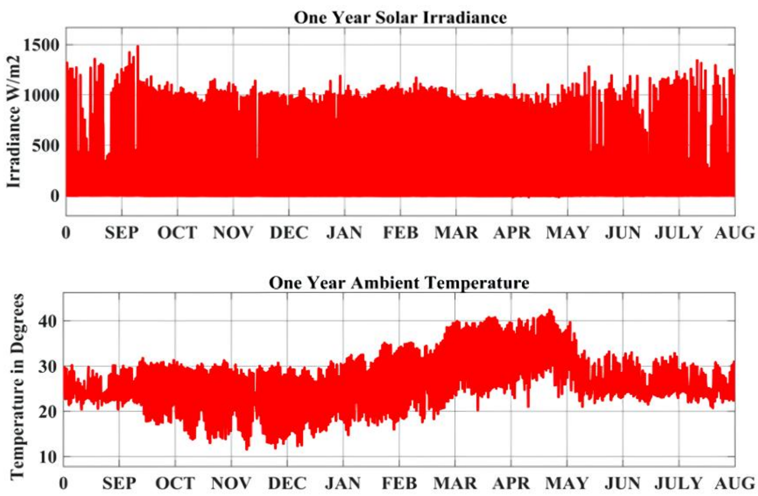

Figure 8. Yearly MP: (a) solar irradiance (Wh/m^2) and (b) ambient temperature (oC)

2.4. Lifetime model

There are several LT models used for power semiconductors. These are categorized into two types, i.e., physical models and analytical models. Based on the thermo-mechanical aspects, LT models are designed considering the failure mechanisms and temperature profiles. The physical model requires the knowledge of stress/strain deformation and failure mechanisms. By conducting the experiments, stress/strain deformation and failure mechanisms can be known. Analytical models are based on the number of cycles to failure (Nfi). Bayerer's lifetime model [25] is implemented in this work. In this model, Nf is calculated using (1).

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

Where: A = technology factor; $\beta 1$ to $\beta 6$ = coefficients; I = current per foot bond; V = voltage class; and D = diameter of the bond wire. The LT is calculated using (2).

$$L_T = \frac{1}{\sum\frac{No.of\ cycles\ (n_i)}{No.of\ cycle\ to\ failure\ (N_{fi})}} \quad (2)$$

2.5. Reliability analysis using MCS

In this paper, LT is calculated at each sample using (2), and LT samples of 10,000 are generated using the MCS with 5% variation. Weibull distribution is used to fit the samples. The reliability function R(t) is calculated at both SL and CL using (3) and (4).

$$R_i(t) = e^{-\left(\frac{t}{\propto}\right)^{\gamma}} \quad (3)$$

Where: $R_i(t)$ = reliability of individual component; $\propto$ = scale parameter; γ = shaper parameter. The total SL reliability is given as (4).

$$R_{total}(t) = \prod_{i=1}^{n} R_i(t) \quad (4)$$

3. RESULTS AND DISCUSSION

To evaluate the performance of bifacial (Bi-PV) panels, a case study involving a 3-kW grid-connected PV system is conducted. The PV system includes BP365 solar panels, a full-bridge inverter, and IGW30N60H3 insulated-gate bipolar transistors (IGBTs) from Infineon, which are selected as switches in the inverter. The case study is modeled and simulated in the PLECS environment, as illustrated in Figure 9, and the detailed system configuration is provided in Table 1. A comprehensive reliability analysis is performed, comparing the performance of monofacial (Mo-PV) and bifacial (Bi-PV) panels under identical operational conditions.

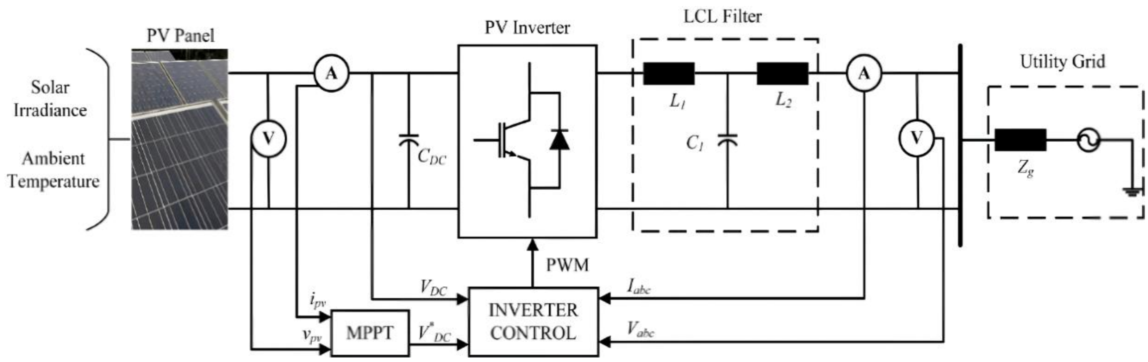

Figure 9. Proposed test case

Table 1. 3-kW test case parameters

Item	Parameter
Panel make number	BP-365
Inverter power (kW)	3-kW
Rated grid voltage	230 Volts
Rated grid frequency	50 Hertz

3.1. PV inverter reliability analysis considering Mo-PV panel

In this case, the Mo-PV panel has been selected as the primary system under evaluation. For performance benchmarking, Maximum Power (MP) data specific to India has been utilized to ensure a realistic representation of local solar conditions. The corresponding dataset captures variations influenced by regional climatic and irradiance factors, making it highly relevant for the study. Figure 7 illustrates the MP data distribution across India, providing a visual reference for the evaluation process.

3.1.1. Calculation of junction temperature

To analyze the thermal cycling behavior of the system, it is essential to calculate the junction temperature (Tj) variations of the IGBT. These variations directly influence the reliability and lifetime of the device, as repeated thermal stresses can lead to material degradation and failure. The Foster electro-thermal model is employed to accurately determine Tj by representing the transient thermal response through an equivalent RC network. Figure 10 illustrates this model, which provides a clear framework for estimating temperature fluctuations under varying operating conditions.

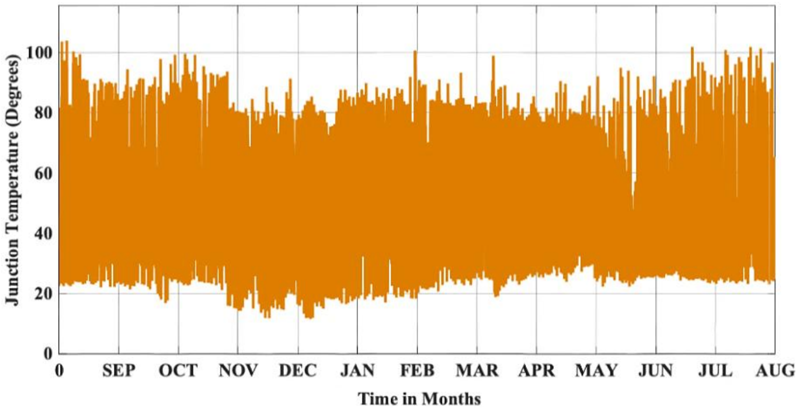

Figure 10. Tj at Hyderabad, India

3.1.2. Rainflow counting analysis

The change in the junction temperature (Tj) is analyzed by using the rainflow counting algorithm, which transforms the complicated junction temperature profile into a series of simple thermal cycles with a binary digital format. Based on this analysis, three major parameters are obtained, which are the number of cycles (Ni), the average junction temperature (Tjm), and the temperature swing (o T). The cycle count Ni represents the frequency of occurrence of a particular thermal load, and Tjm, the average of maximum and minimum temperature on each cycle, signifies the thermal environment causing material degradation. Thermal stress can be seen through its temperature swing, 0 T, which is calculated as the difference between the maximum and minimum temperatures over one cycle. Figure 11 shows these parameters that are needed to evaluate thermal fatigue and determine the lifetime of power electronics components.

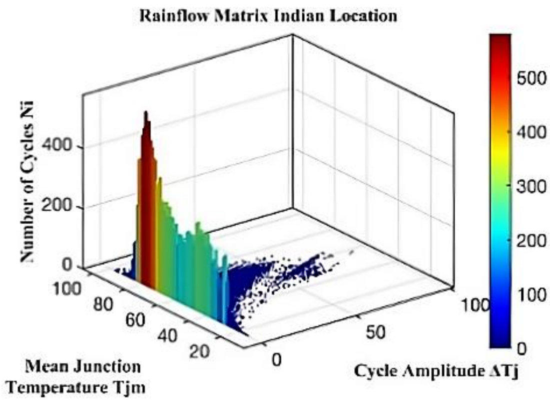

Figure 11. Rainflow matrix in the India location

3.1.3. Lifetime and MCS-based reliability evaluation

The LT for static values represents the constant failure, but practically, it is not feasible. Hence, ten thousand samples with five percent variation are generated using MCS. LT is calculated at each sample using (6) and fitted in a Weibull distribution as shown in Figure 12. The reliability function R(t) is calculated at both SL and CL using (3) and (4) as shown in Figures 13 and 14, respectively.

From the findings mentioned, the B10 line intersecting the reliability curve indicates the time at which 10% of the population is expected to fail. For component-level failures, this point is reached at 34 years, while for system-level failures, it's reached at 24 years. This suggests that while individual components might have a longer lifespan, the system as a whole is more susceptible to failure due to interactions between components or other system-level factors. This highlights the importance of considering both component and system-level reliability in PV system design and maintenance.

3.2. PV inverter reliability analysis considering Bi-PV panel

In this analysis, bifacial PV panels are evaluated under different energy yield scenarios compared to traditional monofacial panels. The scenarios consider Bi-PV panels producing 0%, 30%, and 50% more energy yield. This allows for a comprehensive comparison of the performance and reliability of both panel types under varying conditions, providing insights into the potential benefits and challenges of adopting bifacial technology. The 0% increase scenario serves as a baseline comparison, representing equivalent energy production between bifacial and monofacial panels. The 30% and 50% scenarios explore the impact of increased energy yield on system performance and reliability metrics, helping to quantify the potential advantages of bifacial technology in different environments.

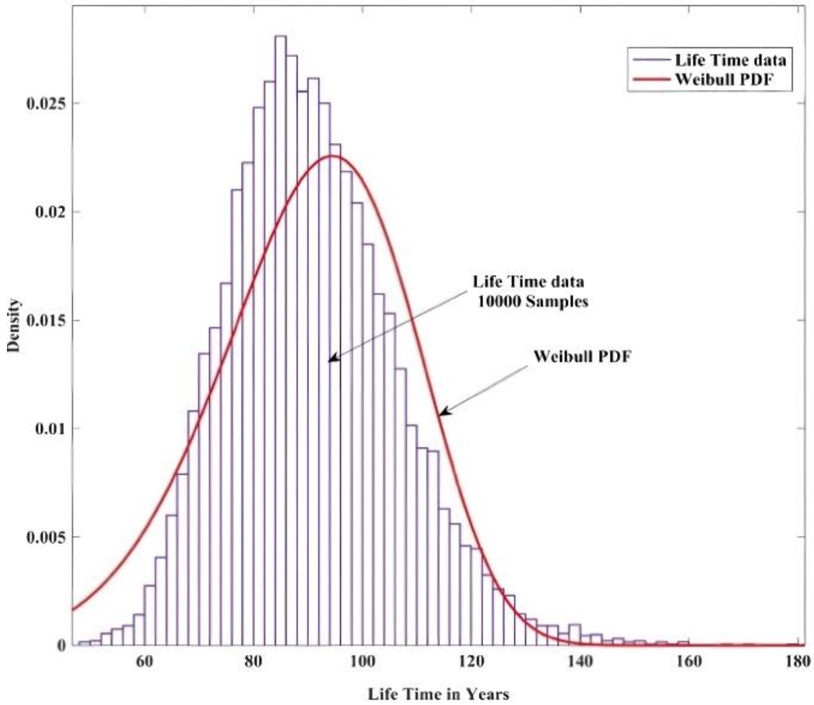

Figure 12. PV inverter lifetime distribution at India location

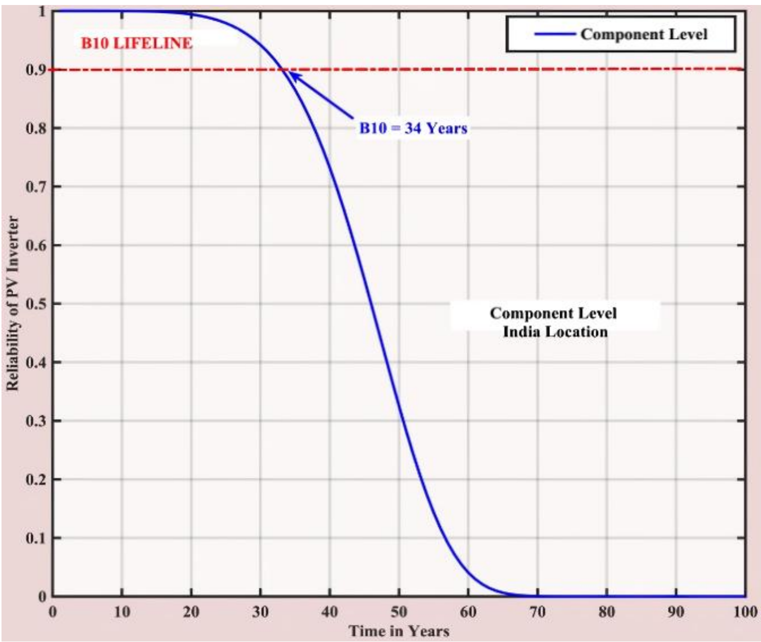

Figure 13. Reliability function R(t) in India (CL)

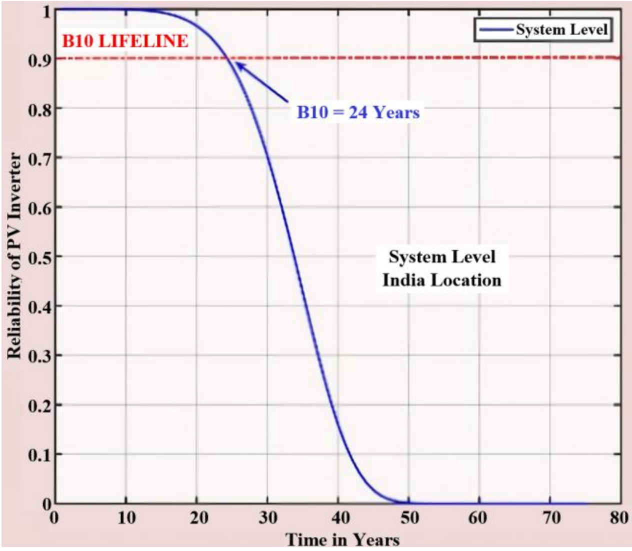

Figure 14. Reliability function R(t) at India (SL)

3.2.1. Junction temperature calculation

To understand the effect of IGBT thermal cycle variations, the junction temperature (Tj) is computed by use of the Foster electro-thermal model, which considers the source of dynamic thermal behavior driven by power losses. Several cases are analyzed regarding a Bi-facial PV system with a 0%, 30%, and 50% higher energy yield related to a higher inverter load and thermal stress. The resulting mean Tj values in these cases are illustrated in Figure 15, which underscores the subject of energy yield and its influence on the IGBT thermals.

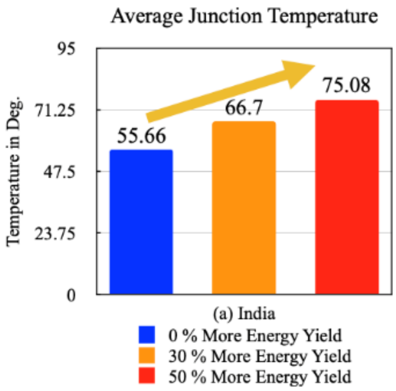

Figure 15. Average Tj at the India location

3.2.2. Rainflow counting analysis

The variations of junction temperature (Tj) are systematically analyzed using the rain flow counting algorithm, which is widely applied for thermal fatigue assessment. This method enables the identification of thermal cycles from fluctuating Tj profiles, allowing for a more accurate evaluation of device stress. Key Tj parameters such as the number of cycles (Ni), mean junction temperature (Tjm), and temperature swing (ΔT) are extracted to quantify the thermal loading conditions. These parameters are evaluated by considering the Bi-PV panel under scenarios of 0%, 30%, and 50% increased energy yield, as illustrated in Figure 16.

3.2.3. Lifetime and MCS-based reliability evaluation

The LT for static values represents the constant failure, but practically it is not feasible. Hence, ten thousand samples with 5% variation are generated using MCS when a Bi-PV panel with 0%, 30%, and 50% energy yield. LT is calculated at each sample using (6) and fitted in a Weibull distribution as shown in Figure 17.

The reliability function R(t) is calculated at both SL and CL using (3) and (4). The CL and SL reliability considering the Bi-PV panel are presented in Figures 18 and 19, respectively. The Bi-PV panel exhibits a decreasing trend. In India, CL reliability (B10) is decreased from 34 years to 1 year, and SL reliability (B10) is decreased from 24 years to 1 year. In comparison with monofacial panels, the thermal stress on the PV inverter due to the bifacial panel is increased, and reliability is decreased.

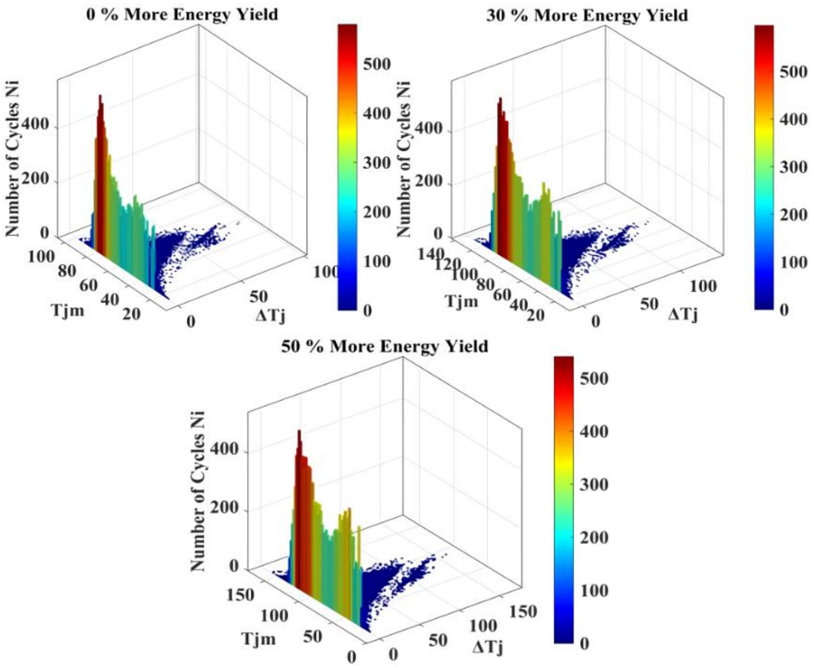

Figure 16. Rainflow matrix in the India location

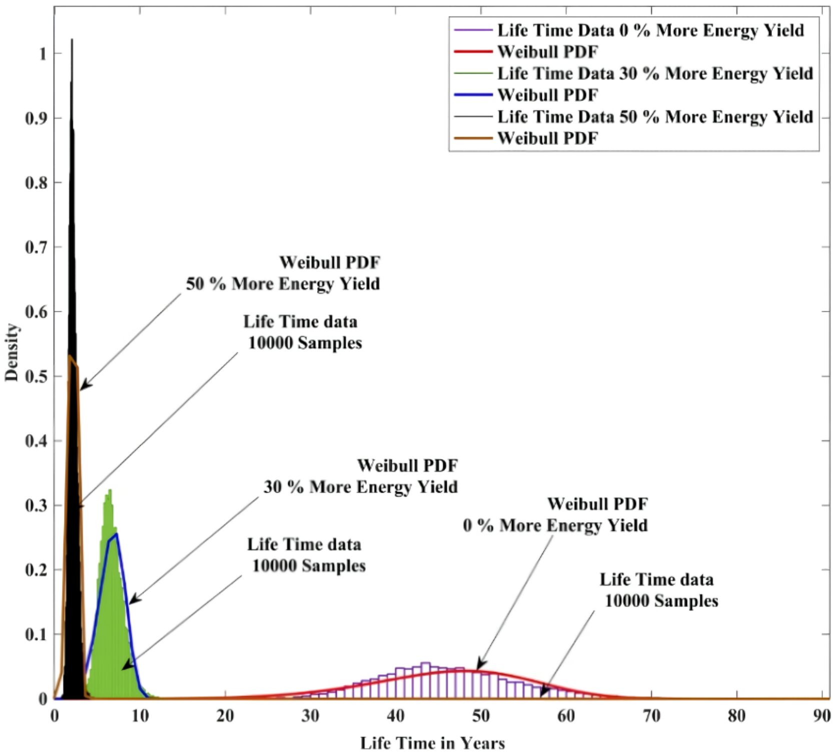

Figure 17. PV inverter lifetime distribution at India location

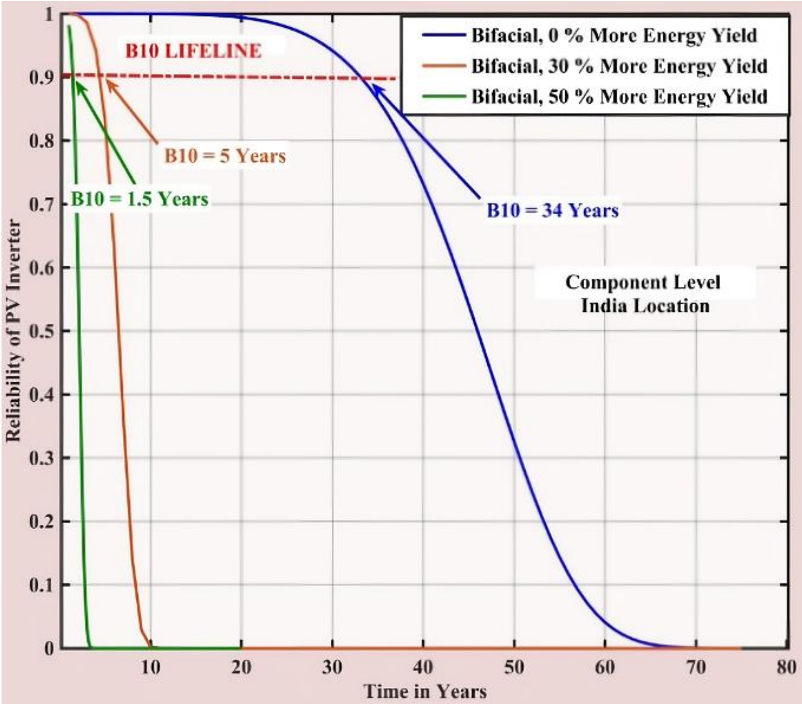

Figure 18. Reliability function R(t) in India (CL)

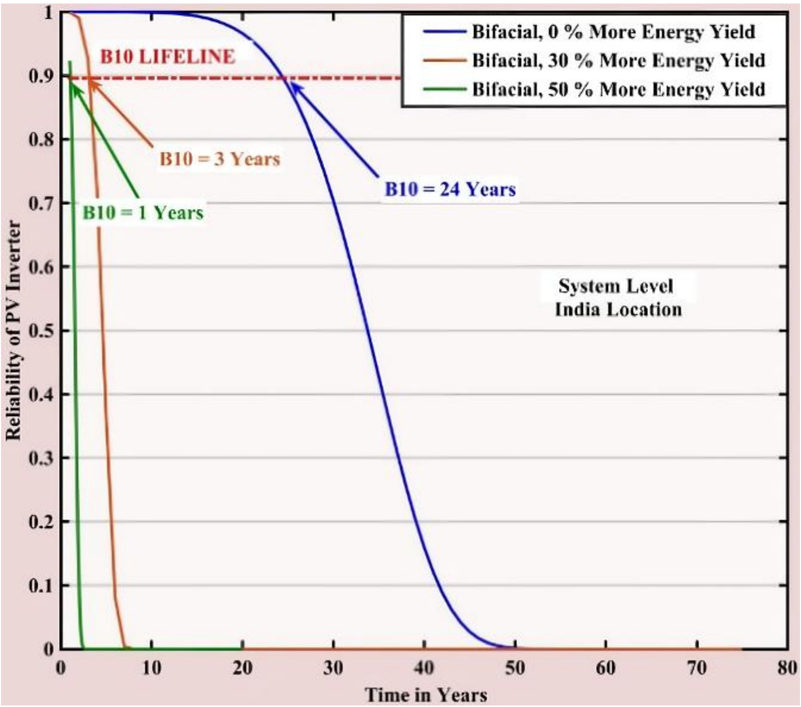

Figure 19. Reliability function R(t) in India (SL)

4. CONCLUSION

In this paper, the reliability analysis is implemented for Mo-PV and Bi-PV panels. This paper considers a test case for a 3-kilowatt PV system. The system comprises BP365 PV panels, a full-bridge inverter, and IGW30N60H3 insulated-gate bipolar transistors (IGBTs) from Infineon, which are used as switches in the inverter. The MP at Hyderabad locations is logged. The Foster electrothermal model is implemented for Tj calculation. Rainflow analysis is performed on Tj and static variables are extracted. LT samples of 10,000 are generated using the MCS with 5% variation and fitted in the Weibull distribution. SL and CL reliability is calculated to determine the B10 lifetime. Comparative reliability analysis is presented between Mo-PV and Bi-PV panels. The comparative reliability analysis shows that the B10 lifetime of Bi-PV panels is significantly reduced compared to Mo-PV panels, primarily due to increased thermal stress on the PV inverter. The Bi-PV panel exhibits a decreasing trend. At the India CL reliability (B10), the lifespan decreases from 34 years to 1.5 years, while at the SL reliability (B10), it declines from 24 years to 1 year. Compared to monofacial panels, the Bi-PV panels increase the thermal stress on the PV inverter, leading to a reduction in its reliability.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Muneeshwar Ramavath	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Rama Krishna Puvvula Venkata						✓	✓	✓	✓	✓	✓	✓		

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

No conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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