International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Journal Européen des Systèmes Automatisés
Vol. 55, No. 1, February, 2022, pp. 119-124
Journal homepage: http://iieta.org/journals/jesa

Impact of Mission Profile on Reliability of Grid-Connected Photovoltaic Inverter

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https://doi.org/10.18280/jesa.550112

Received: 13 October 2021
Accepted: 22 December 2021

Keywords:
mission profile, reliability, PV inverter, IGBT module

ABSTRACT

In recent decades intense demand for energy increases the utilization of Photovoltaic (PV) energy as an alternative to fossil fuels. Today's PV energy shares a significant electricity demand with the advancements in power electronic technologies. Nevertheless, reliability performance of PV system is a major concern. Environmental conditions like mission profile (Solar Irradiance; Ambient Temperature), installation location impacts the performance of PV system. Researchers reported PV inverter as the critical component of PV system. Furthermore, reliability assessment of PV inverter considering environmental conditions is needed for the reliable operation. Therefore, the aim of this paper is evaluating the impact of mission profile on reliability (lifetime) of PV. To accomplish this, a 3-kW single phase grid connected PV system with full bridge PV inverter is considered as test case and modelled in PLECS. A 600V/30A IGBT from leading manufacturer is considered as power electronic switch in PV inverter. Top ten countries of PV market are identified and selected as installation locations, real time mission profile for one year at each installation location is considered. With this mission profile reliability assessment of PV inverter is carried out on test case. The results reveal that mission profile have considerable impact on reliability performance of PV inverter.

1. INTRODUCTION

The PV market broke several records and continued its global expansion, by reaching almost the 500 GW threshold. According to International Energy Agency [1] about 10 countries have reached GW mark of annual PV installed capacity. In contrast eight countries have more than 10 GW total installed capacity, four more than 40 GW and China alone represents 176.1 GW. China, India, Japan, Australia and Korea from Asia, Netherlands, Germany and Turkey from European nations, USA and Mexico are listed in top ten global PV markets. About 87% of the total PV installed capacity is shared by the top ten countries. This shows that PV energy has significant potential, cumulative PV installed capacity from 2016 to 2019 is as shown in Figure 1.

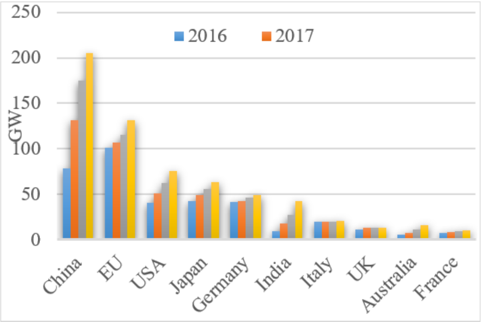

Figure 1. Global annual PV cumulative capacity

Similar to other electrical systems, a grid-connected PV system can fail due to various issues and failures. This issue usually leads to significant economic loss due to the downtime. This is because a PV power system's components are vulnerable to various factors that can affect their lifecycle reliability. With the intense utilization of PV energy reliability, performance and cost becoming more challenge. Nevertheless, reliability performance of PV system is a major concern. About 59% [2] of the total PV system is associated with PV inverter. Hence reliability assessment of PV inverter is needed. Environmental conditions i.e., solar irradiance, ambient temperature also called as mission profile, geographical locations impact the reliability performance of power electronic components in PV inverter. Nonetheless, studies identified the PV inverter as the most unreliable component of the PV system. According to the studies [3-6], the inverter is the least reliable of all due to the power semiconductor switches. Survey in the ref. [7] reported that about 31% of critical components is power electronic switch i.e., IGBT. The PV power station operates in the open air. The continually changing Environmental factors like as wind speed, ambient temperature and irradiance, as well as the variety of devices employed in the system, present significant issues in the design, operation, and maintenance of PV power production systems. As a result, the reliability of power semiconductor switches in the PV system must evaluated in order to reduce the probability of failure and improve system reliability [8-13]. Thermomechanical problems are the most common cause of power electronic switch failures. The most common failures in switches are reported bond wire liftoff, wear out, and so on [14, 15].

The power electronics play a vital role in various industries such as transportation, energy storage, and various other applications. The evolution of power electronics has allowed designers to develop more efficient and dense electrical components. This field has also gained widespread acceptance due to its low-cost and high-quality setups. As the demand for power electronic systems has increased, various research organizations are working on improving the reliability of these components in various applications. Due to the increasing safety requirements of the automobile and aerospace industries, their power electronic systems have become more reliable. This has led to the improvement in the efficiency and cost-effectiveness of these systems. This field has been subjected to various tests and procedures related to reliability. The various topics that are studied include failure analysis and reliability tests. The lifetime and reliability of semiconductor devices are as old as the manufacturing of them. They are assessed using various standards and methodologies. Wire-bonded IGBT modules are commonly used for various applications in a wide range of power levels.

The IGBT module is composed of various materials and is commonly subjected to thermal stress. This issue can cause package-related failures if the temperature difference between the various materials exceeds the specified limit.

This design concept could result in the different thermal loadings of different power devices in real applications. This issue could cause the gap between the lifetime and the rated power of an inverter. This commonly relates to the improper design of power inverters due to the data that is typically provided in the datasheet. The lifetime and reliability test of power semiconductors is done individually. The tests are performed at varying conditions to test the system's longevity.

Therefore, the aim of this work is reliability (lifetime) assessment of PV inverter considering mission profile (Solar Irradiance; Ambient Temperature) and installation locations. To accomplish this, a 3-kW single phase grid connected PV system with full bridge PV inverter is considered as test case. A 600V/30A IGBT from leading manufacturer is considered as power electronic switch in PV inverter. Top ten countries of PV market are identified and selected as installation locations, real time mission profile for one year at each installation location is taken from the ref. [16]. With this mission profile and installation location's reliability assessment of PV inverter is carried out on test case.

2. RELIABILITY ASSESSMENT OF PV INVERTER

The reliability assessment of PV inverter block diagram is as shown in Figure 2. In the step: 1, Mission Profile of top ten countries for PV markets taken from the ref. [16]. The environmental condition such as wind speed, irradiance and temperature (i.e. mission profile) always varies with respect to time and location. This leads to the variation in the temperature at the junction layers of power electronic switch i.e. IGBT module. Furthermore, leads to failure (Ex: wear-out, bond-wire lift-off etc.) in switch [17]. In the step: 2 junction temperature is calculated by foster electrothermal model as shown in Figure 3. In the step: 3 variations of junction temperature i.e., ni, Tjm, ΔT are calculated by using rainflow counting algorithm. In the step: 4 life time is calculated using miners rule as shown in Eq. (1) [18-21].

$$L_T = \frac{1}{L_c} \tag{1}$$

$$L_c = \sum \frac{n_i}{N_{fi}} \tag{2}$$

where,

n_i = No. of Cycles (Calculated using Rainflow).

N_{fi} = No. of Cycles to failure (Calculated using Life Model [20].

$$N_f = K(\Delta T_j)^{\partial_1}.\,e^{\frac{\partial_2}{(T_j+273K)}}.\,t_{on}{}^{\partial_3}.\,I^{\partial_4}.\,V^{\partial_5}.\,D^{\partial_6} \tag{3}$$

Eq. (3) parameters are shown in Table 1.

Table 1. Parameters of the model

Symbol	Value
K	9.3×10^{14}
∂_1	-4.41600
∂_2	1285.00
∂_3	-0.46300
∂_4	-0.71600
∂_5	-0.76100
∂_6	-0.500
I	4 A
V	7 V
D	80 μm

In the Eq. (3) all the parameters are constant. Hence in step: 5 MCS is used to generate 10000 population and parameter variation of 5% is applied for all the parameters in Eq. (3) and fitted in Weibull distribution [22]. Weibull distribution is implemented to evaluate the reliability function for the component level is given as:

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\gamma}} \tag{4}$$

where, α = Scale Parameter, γ Shape Parameter.

The reliability block diagram methodology has been implemented to evaluate the system level reliability of the PV inverter. The system-level reliability can be defined as:

$$R_{total}(t) = \prod_{i=1}^{n} R_i(t) \tag{5}$$

where, $R_i(t)$ individual component reliability.

From the Eq. (5) lifetime metric B_{10} is calculated [11, 12].

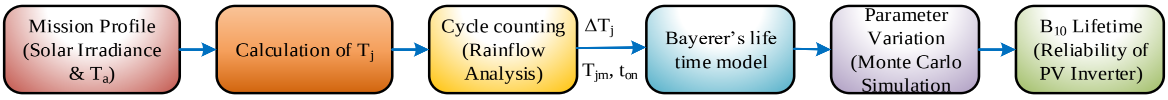

Figure 2. Reliability assessment block diagram of PV Inverter

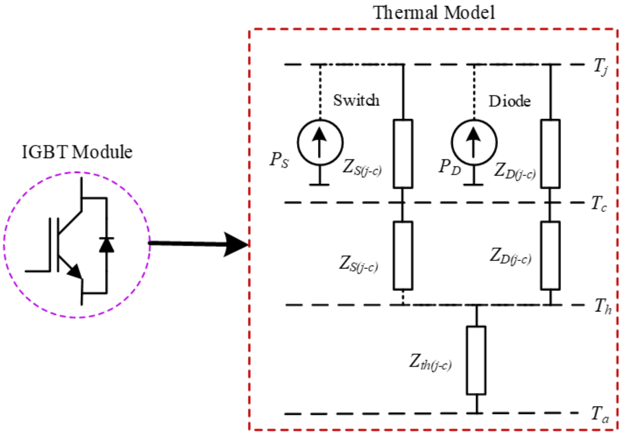

Figure 3. Foster electro thermal model

2.1 Foster thermal model

Normally parameters are provided by the manufacturers on the datasheets. However, the model is a mathematical fitting of Zth and do not show any physical meaning. The analytical formula which relates the thermal impedance with the thermal resistance is described as:

$$Z_{th(j-c)}(t) = \sum_{i}^{n} R_i \left(1 - e^{-\frac{t}{\tau_i}}\right) \tag{6}$$

where, $\tau_i = R_i \times C_i$.

Thus, the junction-to-case thermal model of the power module is modelled as shown in Figure 4 where the number of RC terms is not a fixed value [23-25].

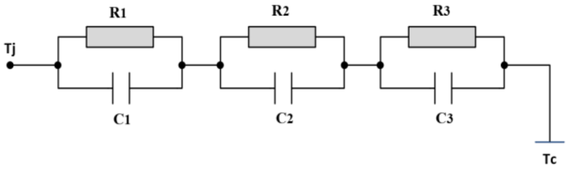

Figure 4. Junction to case thermal model

3. RESULTS AND DISCUSSION

3.1 System description

A test case of grid connected 3-kW PV system with Full bridge inverter is considered is shown in Figure 5 and which is modelled in PLECS.

Full bridge inverter consists of four IGBT's where parameters are considered from Infineon manufacturer datasheet. The specifications of the test case are tabulated in Table 2.

Table 2. 3-KW grid connected PV system specifications

Name	Specification
Model of PV Panel	BP365
Rated Power of Inverter	3000 W
Voltage of Grid	230 V
Frequency of Grid	50 Hz
Capacitance at DC Link	1.5 X 10^{-3} F

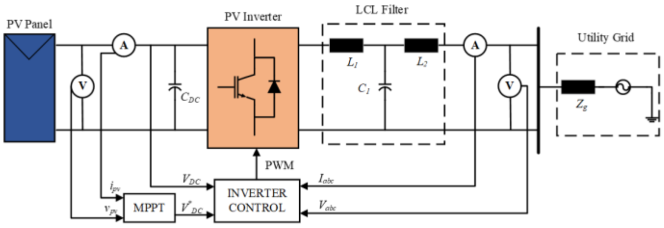

Figure 5. Single-phase grid connected full bridge PV inverter

3.2 Mission profile

The Real time mission profile of one year for the top ten PV makers from September 2018 to August 2019 are logged from NASA. Yearly solar irradiance is shown in Figure 6, yearly Ambient Temperature is shown in Figure 7.

The mean solar irradiance and ambient temperature for each country is tabulated as heat map in the Table 3.

The mean solar irradiance and ambient temperature, maximum is recorded at Australia, India, China, USA, minimum is recorded at UK, Germany, EN, medium is recorded in the other location. This evidences that environmental conditions change from location to location and this will impact the reliability performance of PV inverter.

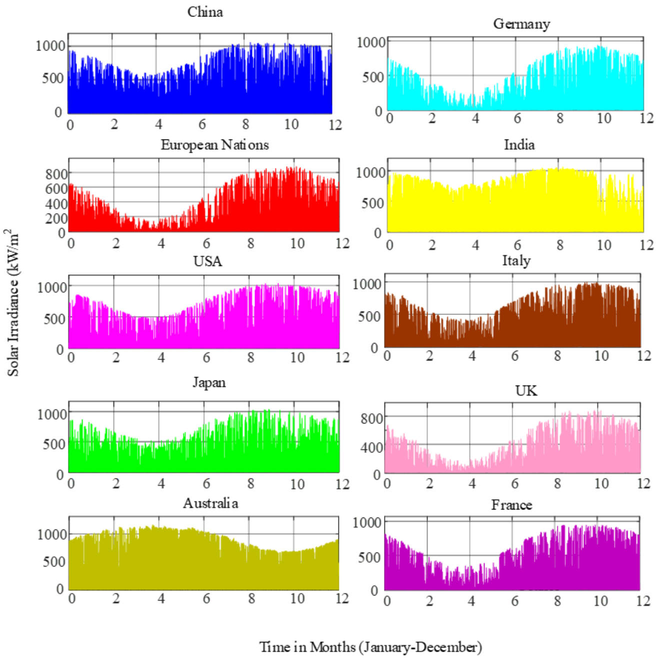

Figure 6. Yearly solar irradiance of the top ten countries of PV market

Table 3. Mean mission profile heat map table

Country	Solar Irradiance (W/m^2)	Ambient Temperature (°C)
CHINA	206.91	10.64
EN	135.53	9.84
USA	202.51	10.71
JAPAN	177.69	10.75
GERMANY	152.02	9.60
INDIA	243.51	23.03
ITALY	188.07	13.55
UK	129.14	9.18
AUSTRALIA	277.35	25.67
FRANCE	171.87	12.40

Red = Maximum, Yellow = Medium, Green = Minimum

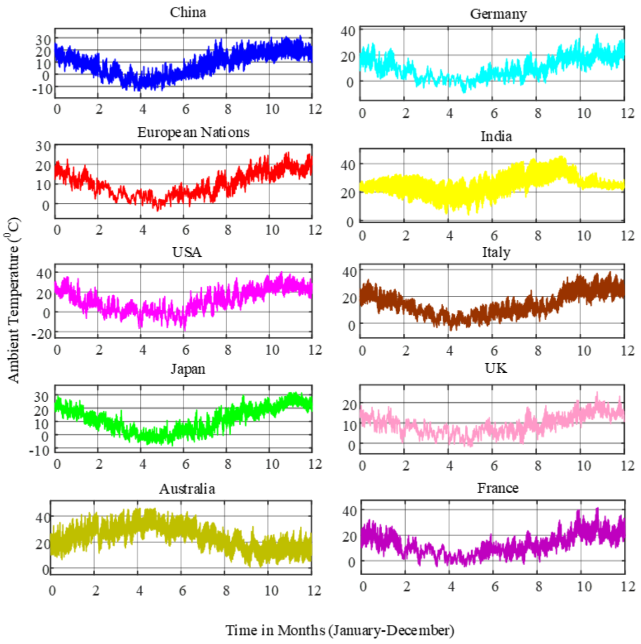

Figure 7. Yearly ambient temperature of the top ten countries of PV market

The maximum mean junction temperature is recorded at Australia, India, China, USA, minimum is recorded at UK, Germany, EN, medium is recorded in the other location according to the mean mission profile (Figure 8).

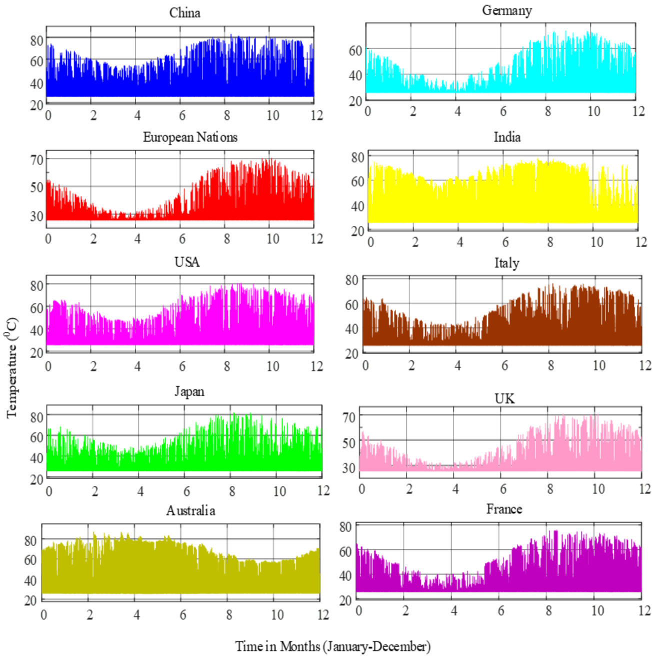

Figure 8. Junction temperature of top ten countries

3.3 Junction temperature calculation

Junction temperature corresponds to yearly mission profile for top ten countries are calculated using the foster electrothermal model and shown in Figure 8. The heat map table for mean junction temperature for top ten countries is tabulated in Table 4.

Australia, India, China, USA, minimum is recorded at UK, Germany, EN, medium is recorded in the other location according to the mean mission profile.

Table 4. Mean junction temperature heat map table

Country	Junction Temperature (°C)
CHINA	34.96
EN	31.33
USA	34.50
JAPAN	33.31
GERMANY	32.08
INDIA	35.92
ITALY	33.65
UK	31.05
AUSTRALIA	37.78
FRANCE	32.94

Red = Maximum, Yellow = Medium, Green = Minimum

3.4 Rainflow analysis

The Steps in rainflow counting algorithm is given below.

Step 1: Analyse the irregular profile of Junction Temperature.

Step 2: Regularise the thermal profile to reduce Junction Temperature variation spectrum.

Step 3: Count the number of cycles.

Step 4: Extract number of cycles, Mean Junction Temperature, Cycle Amplitude.

Mean Junction Temperature T_{jm}, Cycle Amplitude ΔT at each location is shown in Figure 9. Maximum ΔT, T_{jm}, recorded at Australia, India, China, USA, minimum ΔT, T_{jm}, is recorded at UK, Germany, EN, medium ΔT, T_{jm}, is recorded in the other location according to the mean junction temperature.

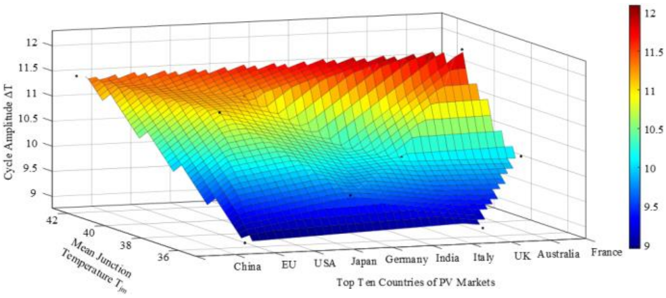

Figure 9. Rainflow analysis of top ten countries

3.5 Monte Carlo simulation and B10 life time

MCS is used to generate 10000 population and parameter variation of 5% is applied for all the parameters in Eq. (3) and fitted in Weibull distribution. Two parameter Weibull distribution is considered and the reliability of PV inverter at component level is shown in Figure 10, system level is shown in Figure 11.

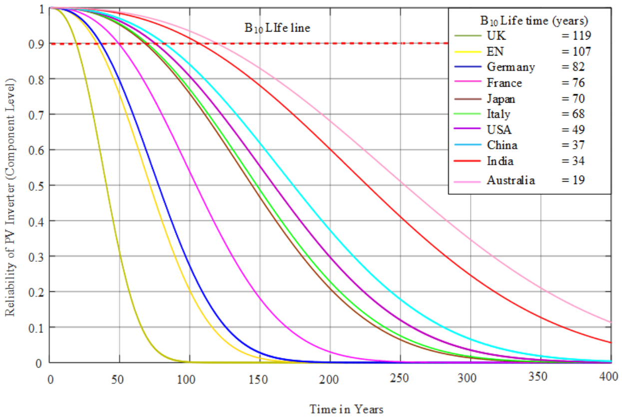

Figure 10. Reliability of PV inverter at component level

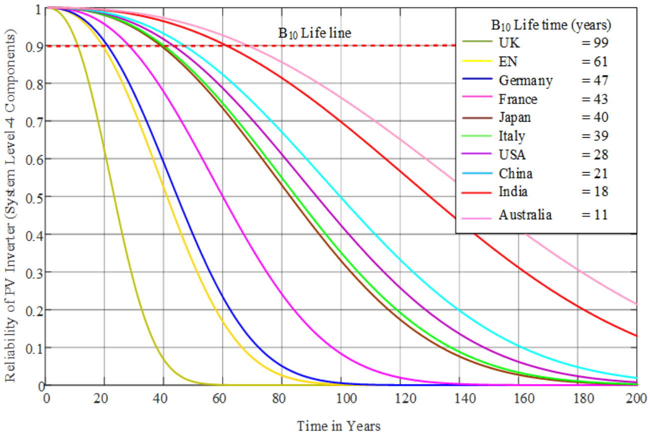

Figure 11. Reliability of PV inverter at system level

3.6 Comparison of B10 lifetime

The comparison of B_{10} lifetime Vs top ten countries of PV markets is shown in Figure 12. B_{10} lifetime maximum is recorded at Australia, India, China, USA, minimum is recorded at UK, Germany, EN, medium is recorded in the other location. The results reveal that locations with relatively hot conditions records minimum B_{10} lifetime, locations with relatively cold conditions records maximum B_{10} lifetime.

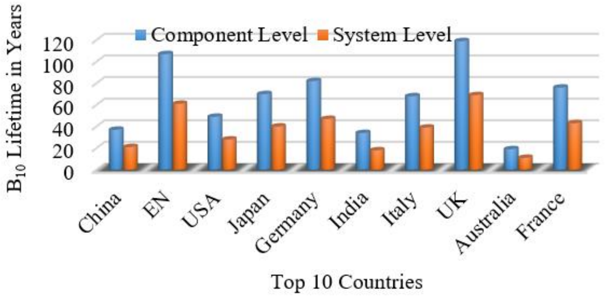

Figure 12. Comparison of B_{10} life time

Also, not just the maximum temperature is of notable importance for the lifetime utilization, but also the temperature cycles caused by the non-uniform solar irradiances and ambient temperatures affect the lifetime consumption of the power devices. This scenario also clearly demonstrates that B_{10} lifespan changes depending on geographical location and environmental circumstances.

4. CONCLUSIONS

In this paper, the impact of mission profile and geographical locations on PV inverter reliability is analyzed by considering the mission profile from top ten countries of PV markets. A grid connected 3-kW PV inverter is considered and modelled in PLECS. IGBT is considered from the Infineon manufacturer. Foster electrothermal model is used for the junction temperature calculation, its variations are analysed using rainflow counting algorithm. Bayerers lifetime model with MCS is used to generate 10000 samples along with 5% variation is implemented. Two parameter Weibull distribution is used to calculate the reliability of PV inverter. The results reveal that the mission profile has the considerable impact on the lifetime of the inverter in grid-connected PV systems.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (grant no. 51777146).

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