IGBT Power Modules Lifetime in 2-Level PV-Inverters under Harsh Environmental Conditions

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***Abstract* – In the last decades, the interest in solar photovoltaic (PV) energy has increased considerable around the world. That are many publications that focus on the temperature assessment of PV modules and solar heat collectors but fewer discuss the temperature and reliability evaluation of PV-inverters components.**

IGBT power modules are the key components from the reliability point of view. Some solar power plants are located in places with harsh ambient conditions, which can reduce drastically the components lifetime. This work presents a detailed study of power modules durability to show the effect of thermal cycling in PV-inverters under harsh environmental conditions.

***Index Terms*–Reliability, availability, IGBT, PV-Inverters, mission critical application, power module lifetime.**

I. INTRODUCTION

In the last decades, the interest in solar photovoltaic (PV) energy has increased considerable around the world. According to European Photovoltaic Industry, solar power had a record year in 2014 with 40 GW being connected worldwide which beats the record of the previous year, when 37 GW were connected. Furthermore, PV system price declines of around 75% in less than 10 years have brought solar power close to cost competitiveness in several countries and market segment [1].

There are many existing publications that focus on the temperature assessment of PV modules and solar heat collectors [1]–[4], but fewer references that discuss the temperature and reliability evaluation for the PV inverter and related components [5]. Manufacturers of photovoltaic modules guarantee lifetimes over 20 years, while the typical guarantee period for inverters according to a survey was 5 years [6]. An analysis of a 3.5MW installation attributes almost 2/3 of the cost associated with unscheduled maintenance events to the inverter [6-7]. In the solar power plant adopted in this study for example, the inactivity of one converter resulted in a loss of approximately $200,000.

From the reliability point of view, IGBT power modules are key components in modern power converters. Operating in harsh and uncertain conditions, such as locomotive traction, electric vehicles, mining industry and renewable energy systems, the IGBT power modules are responsible for making the power converters the weakest link in these processes [8]. In general, power semiconductor devices account for more than 20% of the total failures in power converters [9].

The lifecycle reliability of power electronic devices is highly dependent on operating temperature, which is related to irradiance level and ambient conditions. Fans and heatsinks are employed to mitigate heating of components in an attempt to improve long-term reliability. Nevertheless, some solar power plants are located in places with harsh ambient conditions. Fig.1 shows the power plant in São Lourenço da Mata –PE, Brazil. Due to the environmental conditions, temperatures above 80ºC were recorded inside the PV-Inverters containers. Fig. 2, breaks down the measured temperature from January to December 2015.

Many applications, mainly solar power plants are situated in Sunbelt regions [10]. Likewise, an inefficient ventilation system can subject the inverter to extra high temperatures. Hence, the main goal of this paper is to demonstrate that a detailed lifetime study of power modules, considering the real mission profile and ambient conditions is crucial to guarantee long lifetime inverters, under harsh environmental conditions.

Fig. 1. Power Plant in São Lourenço da Mata – PE, Brazil.

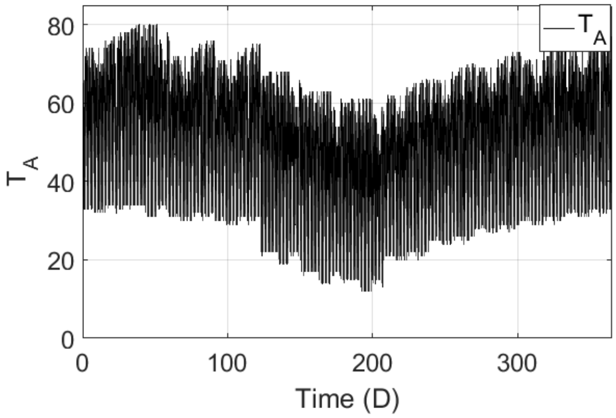

Fig. 2. Annual temperature variation inside the PV-inverters Container.

The outline of this paper is organized as follows: Firstly, some details about the studied power plant is described. Secondly, the IGBT power modules with constructive features and failure modes is briefly described. Then, a detailed lifetime study of IGBT power modules is conducted. Finally, the conclusion is presented, highlighting the main topics of this work.

II. THE SOLAR POWER PLANT

The solar power plant situated in São Lourenço da Mata has the total generation capacity of 1MW. In this way, the common topology with panels connected in parallel and series forming strings is used. 2-level voltage source inverters (2-L VSI) interface the connection with the common coupling point. The power division is taken based on the power capacity of each converter, in this case 250kW, as shown in Fig.3. The generated power is injected into the grid of 13.8kV. A step-up transformer of 1MVA is adopted.

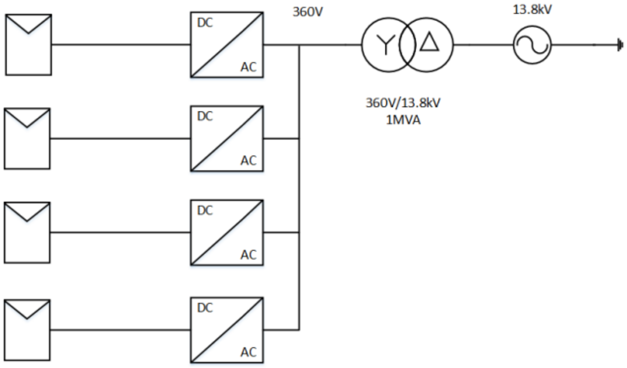

Fig. 3. Power converters diagram of the power plant studied.

III. IGBT POWER MODULES

The Insulated Gate Bipolar Transistor (IGBT) is a three-terminal power semiconductor device. It is used as an electronic switch in many power converters allowing a combination of high efficiency and fast switching. The global market for IGBT is projected to grow from nearly \$5.7 billion in 2015 to \$8.8 billion in 2020, registering a five-year compound annual growth rate (CAGR) of 9.1% [11].

There are two packaging methods for IGBTs: module packaging and press-pack packaging. The module packaging technology, because of the soldering and the bond-wire connection of internal chips may suffer from large thermal resistance, lower power density and higher failure rates. The press-pack packaging technology improves the connections to the chips by direct press-pack contacting, which leads to improved reliability, high power density and better cooling capability. Nevertheless, the module packaging technology has a longer track record of applications due to their lower cost, simpler mounting and maintenance [12].

Fig. 4 shows the structure of a standard IGBT module. This structure is made of several layers consisting of different materials. The silicon is soldered on the direct copper-bonded (DCB) substrate. The DCB substrate insulates the Si chip from baseplate and conducts the heat dissipated by the chip to the cooling system. The top side of the Si chip is contacted by aluminum (Al) bond wires [13].

As shown in Fig. 3, the IGBT module consists of various materials with different Coefficients of Thermal Expansion (CTE). Therefore, the most frequently reported failure modes in power modules are bond-wire lift off and solder fatigue. The first one is a consequence of crack growth at the bond wire/chip interface, while the second is the propagation of cracks or voids between the module substrate and base plate [14].

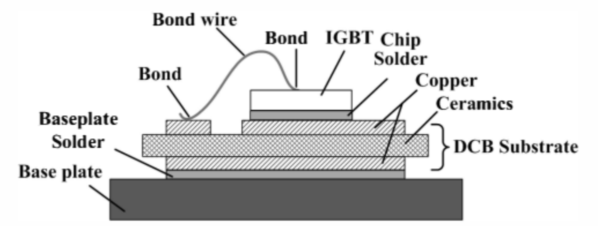

Fig. 4. Structure of a standard IGBT module [13].

IV. IGBT POWER MODULES LIFETIME STUDY

The power modules lifetime is strongly dependent on the mission profile. During its operation, the modules are subjected to a variety of temperature profiles, which cause cyclic thermo-mechanical stress in all components and joints, finally leading the device to fail. In applications with mission critical profile, a detailed lifetime study of power modules is strongly recommended during the design to guarantee the specific lifetime. Fig. 5, shows the detailed flowchart which was adopted in this study

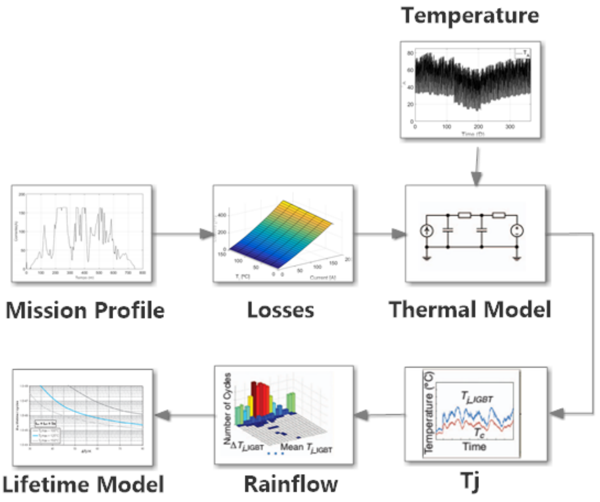

Fig 5. IGBT lifetime study flowchart.

A. The PV-Inverter System Model

To study the power module lifetime, the system was simulated in PLECS. To take the lifetime study, the 2L-VSI was modeled firstly considering 200A IGBT and then 400A IGBT power modules coupled in P16 air cooled heatsinks from Semikron. The parameters adopted in this simulations were extracted from the real plant (Table I).

TABLE I SIMULATION PARAMETERS

Parameters	**Value**
VSI Rated Power	240kW
Output Voltage	360V
Switching Frequency	6kHz
IGBT modules	1200V/200A, 1200V/400A

B. The Mission Profile

The correct transforming of the mission profile of solar power converter into the corresponding loading profile of the power devices is a challenging task: First, many factors which have influence on the thermal loading of devices should be taken into account, like the solar irradiance, and ambient variations, behaviors of nebulosity and behaviors of electrical parts and also grid conditions.

In [15], it is proposed a method to calculate those parameters separately for a wind turbine application. In that case, wind velocity is the long-term cycling, while mechanical turbine variation is the medium cycling and electrical behavior the short cycling. Hence, in this work it is proposed an adaptation for PV application where the irradiance and temperature are the long-term, nebulosity the medium-term and electrical the short-term cycling, as shown in Fig. 6.

Since the annual current profile is known, it is possible to check the influence of irradiance, temperature and nebulosity at the same time. Hence, the long and medium term can be evaluated together. Fig.7 shows one day Pv-Inverter output current (rms) measured from the real system.

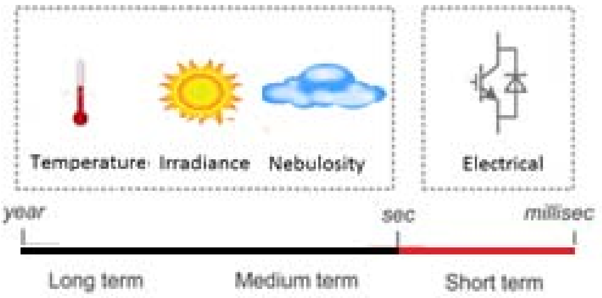

Fig. 6 Thermal cycling of power semiconductors in a PV-Inverter.

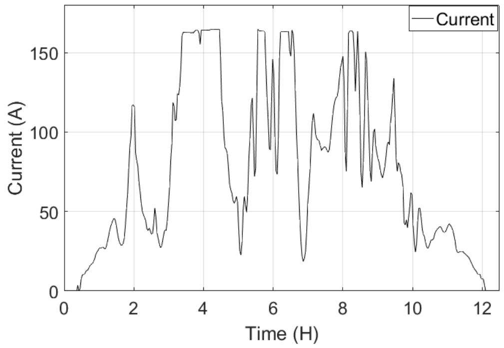

Fig 7. One day PV-Inverter current profile

C. The Long Term and Medium Term Cycling Estimation

In the first step, only the long and medium term cycling are considered. Due to the current sampling at 15 s, the switching and grid output frequency can be neglected in this step. To accelerate the simulation, the relationship between current, junction temperature and losses of each IGBT can be looked up. As shown in Fig. 8, the losses consumed by the power devices are calculated as function of the current profile as well as junction temperature [15]. For the sake of accuracy each of the point of the lookup table is simulated in a detailed circuit with realistic device models [16]. The look-up tables for the 200A and 400A IGBTs are shown in Fig. 9 and Fig.10, respectively. Due to the higher thermal stress in this application, only the IGBTs are considered under analyses.

D. The Short Term Cycling

This group of thermal behaviors in power devices is due to the fast and periodical current alternating in the converter. The junction temperature of power devices swings at relatively smaller amplitude at fundamental frequency [15]. The cycling amplitude of the junction temperature can be estimated as follows:

$$\Delta T_j = P_{loss}.Z_{th}\left(\frac{3}{8f_o}\right) + 2.P_{loss}.Z_{th}\left(\frac{1}{4f_o}\right) \qquad (1)$$

where P_{loss} is the loss of power device which can be looked up from Fig. 9 and Fig.10. Z_{th} is the time-based expression of device thermal impedance; f_0 the fundamental frequency of the converter output.

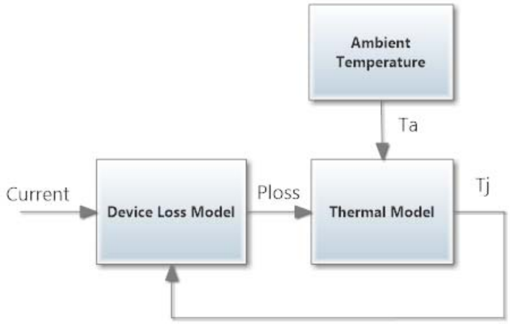

Fig. 8. Determination of the IGBTs junction temperature infunction of the current profile and ambient temperature.

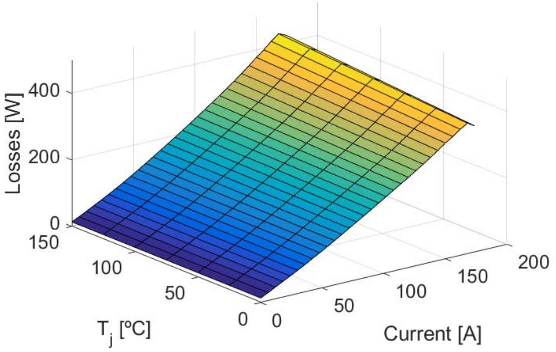

Fig. 9. Three-dimensional lookup table for the 200 A IGBT losses in the given application PV-inverter.

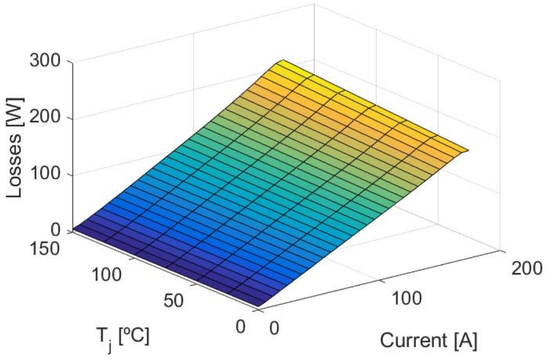

Fig. 10. Three-dimensional lookup table for the 400 A IGBT losses in the given application PV-inverter.

E. Thermal Model

As demonstrated in Fig.8, the thermal model is fed by the losses and ambient temperature. Using the annual current profile and ambient temperature is possible to estimate the annual junction temperature for the IGBTs and diodes of the 2-L VSI. The junction temperature for the IGBTs and diodes for 200A and 400A power modules are shown in Fig.11 and Fig.12. As expected, the temperatures are greatly reduced with 400A power modules.

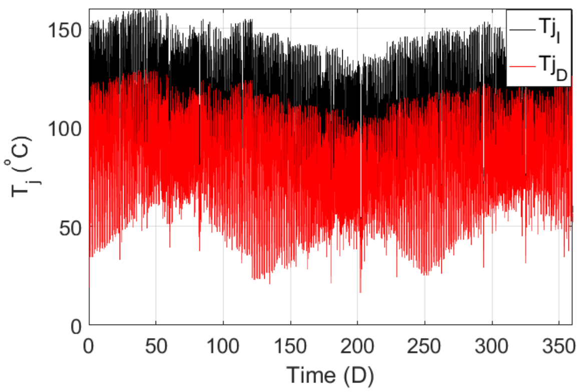

Fig. 11. Annual junction temperatures, IGBTs and diodes for 200 A power modules.

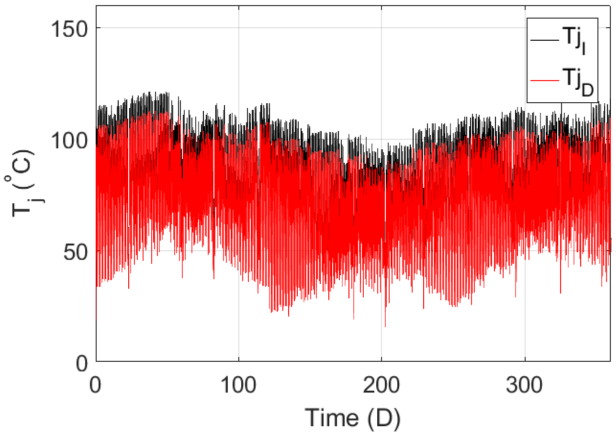

Fig. 12. Annual junction temperatures, IGBTs and diodes for 400 A power modules.

F. Rainflow cycle counting

After the thermal loading of the given IGBTs, a rainflow counting method [17] has to be applied in order to identify the characteristics of each cycle. Each cycle applies different stresses to the module, and further leads to a certain lifetime consumed. As can be seen in Fig. 13, a greater number of cycles are concentrated in the middle of the graph. Showing a higher thermal stress, due to the higher values of ΔT_j, for 200A IGBT power modules.

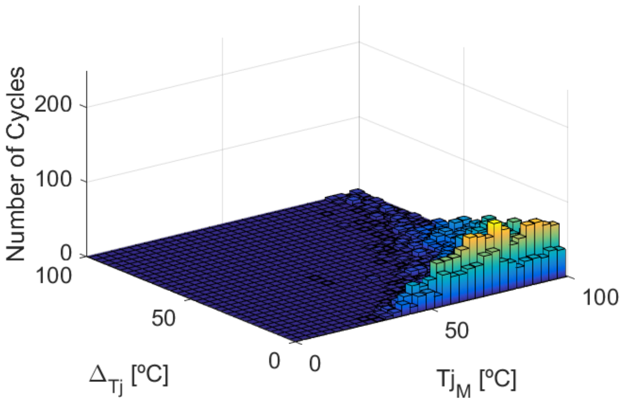

Fig. 13. Number of cycles during a year, their variation and mean value, for 200A power modules.

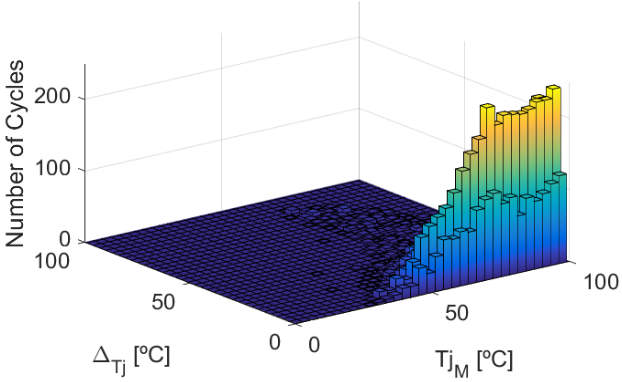

Fig.14. Number of cycles during a year, their variation and mean value, for 400A power modules.

G. The Lifetime Model

To predict the lifetime of power modules analytical modeling are used. The Coffin-Manson model [18] is the most widely used approach. However, it does not take into account the frequency of cycles and can be inaccurate. The Bayerer's model [19] is the most complete, but it is very susceptible to parametric errors. In this way, the Norris-Landzberg lifetime estimation model [20] is used to evaluate the consumed lifetime for each counted thermal cycle.

$$N_f = A.f^{-\alpha}.\Delta_{Tj}{}^{-\beta}.e^{\left(\frac{E_a}{K_B}.T_{jmax}\right)} \qquad (2)$$

where Δ_{Tj} is the difference between maximum and minimum junction temperatures, T_{jmax} is the maximum junction temperature in Kelvin, f = 1 cycle/h is the cycle frequency, K_B= 1.38x10^{-23} is the Boltzmann constant, E_a = 0.42 is the activation energy, A = 310, α = 0.4 e β = 2 [21].

The total consumed lifetime by the counted cycles during a year can be accumulated according to the Palmgren-Miner rule [22]. The lifetime in years is the inverse of the total consumed lifetime. Considering the cycles counted by the rainflow and the short thermal cycles, the lifetime could be evaluated for the IGBTS of the 2-L PV-Inverters as shown in Table II. The lifetime in years may not be accurate, but its small value for 200 A power modules can serve as an alarm. The lifetime in p.u. shows the considerable lifetime improvement with only 9% investment in the total price of the converter. These results can prove the utmost importance of doing a detailed lifetime study of power modules in systems with critical thermal cycling under harsh environmental conditions.

TABLE II LIFETIME AND COST

Topology	Lifetime (years)	Lifetime (p.u.)	Cost (p.u)
200A	2.52	1	1
400A	21.43	8.58	1.09

V. CONCLUSIONS

In this work, it was presented a methodology for the design of power converters for PV-Inverters, under harsh environmental conditions. As a case study, it was used a real power plant located in the northeast of Brazil, where temperatures inside the containers achieved about 80ºC.

The detailed study of power modules lifetime on a mine hoist mission profile was presented. Following the step-by-step methodology, it is possible to properly select the power semiconductors for such application. It was shown that this application has a critical thermal cycling, and without this study the converter lifetime can be drastically reduced. Due to the critical mission profile, the considerable lifetime improvement with only 9% investment in the total price of the converter, suggest that IGBT power modules with the double of current capacity should be used in the design of the converters.

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