

# Critical components test and reliability issues for Photovoltaic Inverter

Marcantonio Catelani, Lorenzo Ciani, Alberto Reatti

*Department of Information Engineering, University of Florence,  
via S. Marta 3, 50139, Florence, Italy  
lorenzo.ciani@unifi.it*

**Abstract** – Reliability requirements are very interesting aspects for plant based on PV panel. In fact these plants are planned to operate for many years. One of the most critical subsystem in the PV plants is represented by the inverter. The analysis of its critical components is a very important task that can be obtained by means a well-designed test plan. This approach allows to improve complex system maintenance policies and, at the same time, to achieve a reduction of unexpected failure occurrences in the system during its functioning in the field.

## I. INTRODUCTION

Reliable systems represent a fundamental aspect of any technology progressing toward commercial maturity and large-scale diffusion. PV system can be considered one of the most widespread with significant margins of improvement while ensuring the generation of energy with low environmental impact. Therefore, the assessment of the quality, reliability and electrical performances of these sustainable energy production systems is becoming more and more important. Although the PV system is considered as a reliable source of electrical energy, field results pointed out that the modules can fail or degrade in a number of ways [1-5]. Photovoltaic modules are often considered as the most reliable element in PV systems. However, statistics and field returns data have shown that PV panel efficiency can drop over time due to installation faults, environmental factors and the exposition to dust and pollution [6-8]. More in detail, the increase of the PV modules installation in urban and industrial context, where the powder levels are high, requires to consider this problem and to adopt maintenance strategies to keep clean PV panels and, therefore, the overall system generation efficiency at an acceptable level. In addition to this phenomenon, other failure modes can be avoided by monitoring the system and optimize maintenance: failures

due to clamp/terminal damaged, aging of contacts between PV panels and PV cell fracture.

Looking for the failure data, we can deduce that the most widespread of faults in PV system are attributed to inverter failures [9-13]. Although a single inverter failure will not typically bring down an entire commercial PV plant, their reliability has a direct effect on plant economics because system availability is a multiplicative factor in energy harvest, just like power conversion efficiency. In particular, the most critical components are represented by the DC capacitors and the insulated-gate bipolar transistors (IGBT) [14-15]. Considering also that PV plant are located in some of the harshest environments with wide temperature range, high humidity level (up to 95%) and, often, salty and corrosive conditions (installation in seaside and/or industrial sites), the inverter internal temperature is one of the most important factor that have to be monitored both to reduce the failure occurrence and to reveal inadequate heat transfer and fans.

In this scenario it's fundamental to guarantee the functionality, the reliability and maintainability performances of the whole plant. Based on these considerations, it's important to note that recognition of reliability, availability and maintainability (RAM) as factors in the early development of today's complex systems, as a PV plant, has placed greater emphasis on the application of design analysis procedures to logistics management. By understanding equipment behavior in the intended operating environment, any needed part improvement or review effort can be identified prior to the expensive test, analyze and fix phase of equipment development. The design analysis, also, defines spare parts requirements and allocation of logistics resources to assure that specified RAM requirements will be met in the equipment's actual operating environment.

The monitoring of the critical components, from the reliability point of view, of a PV system allows to achieve an improvement of the plant performances by means of allows understanding its behavior during the real condition of use and, at the same time, to optimize

both the availability and the maintainability of the most critical subsystem as well as the whole PV plant. In this way, it's possible to deduce useful information about monitoring activities and measurements that should be implemented to maintenance policies.

## II. PV INVERTER: CRITICAL COMPONENTS TEST

A PV plant is a complex system composed by several devices. Among these, a fundamental equipment is represented by the inverter, the fault or failure of which can lead to losses in the electricity production of the plant. For this reason an important task to take into account in the design of PV plant is the performance optimization of this equipment in order to guarantee a high efficiency level of the whole plant.

Reliability performances are correlated to such conditions and the temperature is one of the most important factor, as show in Figure 1 where the trend of the MTBF (Mean Time Between Failure) vs temperature is represented. For this reason, a proper thermal distribution on printed circuit board (PCB) and an adequate heat-sinking for the power stage circuitry should be properly designed. Critical heat sensitive circuitry should be relocated to cooler areas on the PCB. In fact, in the PV inverter thermal design and heat extraction mechanisms of the switching components and capacitors have to be analyzed in detail, being such components highly sensitive to temperature.

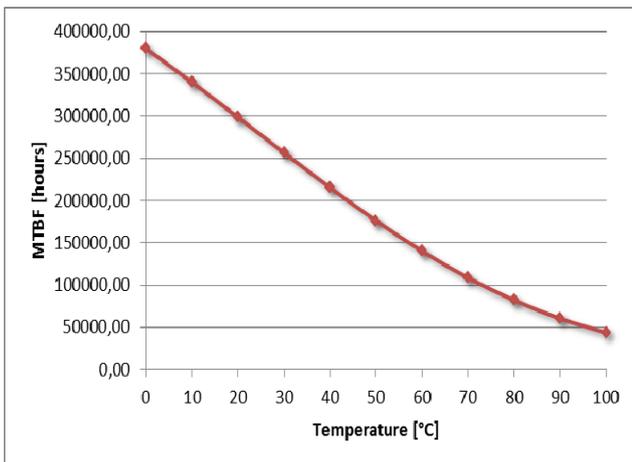


Figure 1 – MTBF (Mean Time Between Failure) vs temperature

A PV inverter 500 kW has been subjected to several tests of thermal stress, in a special thermal chamber (see Figure 2), to evaluate its operating range in temperature simulating the ventilation conditions of a shelter.



Figure 2 - Destructive test set-up

In order to determine the limits of operation, a preliminary destructive test has been performed allowing the internal temperature of the chamber to grow until the breakdown to one or more components of the inverter. Keeping all the other critical parts of the inverter under control, included regulation and efficiency, we found that the first components subject to failure are the DC link capacitors as depicted in Figure 3.



Figure 3 – DC link capacitor voltage and chamber temperature trends during destructive test session

The breakdown of the components starts from 80 °C temperature on the case of the capacitors. It can be considered safe a maximum temperature of the case below 72 °C. Before the breakdown all the other relevant parameters and temperatures of components were in the range. As a general remark we can say that it is necessary to remove the heat produced by the inverter

bridge from the top of the cubicle to prevent any thermal inrush of the internal components.

After replacing all the capacitors in the DC link a normal heat run test has started, using two heaters to increase the temperature of the chamber. The heat produced by the inverter bridge exit from the roof was diverted outside the chamber by an air conveyor, then a full current thermal test has been performed which results are below reported.

Test conditions:

- Vdc = 570 Vdc (MPPT voltage)
- $\theta_a \geq 45^\circ\text{C}$  (stabilized by heaters)
- Iout = 950 A (full current)

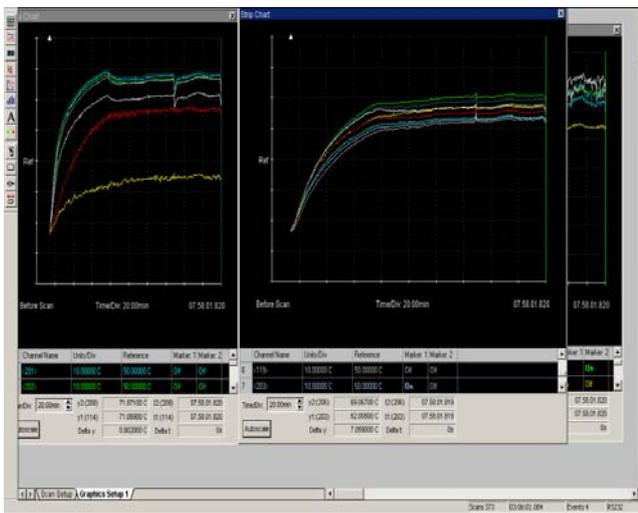


Figure 4 – DC link capacitor voltage during heat run test

It is noted that the temperature of the DC link capacitor reaches  $71^\circ\text{C}$  close to the safe limit. Furthermore, the heat sink temperature is approaching the point of power derating located at  $> 80^\circ\text{C}$ . If we consider the thermal margins on the inverter bridge, we could increase the limit of derating up to  $85^\circ\text{C}$ , but this could be dangerous for the DC link capacitors.

### III. PV INVERTER: RELIABILITY ISSUES

Reliability improvement or growth is one of the main objectives in any system development effort. Two of the most common techniques used for such scope are:

- Derating
- Redundancy

By using derating technique, a part is selected so that it will be operated at less severe stress than the stress level at which it is rated capable of operating. As described in Section II the most prominent stresses in PV inverter are

temperature, voltage, vibration, and temperature rise due to current. The effect of each of these stresses on each of the components must be considered. In order to achieve good reliability, various derating factors have to be applied to these stress levels. The derating has to be traded off against cost and size implications.

Based on these remarks, it is possible to improve the reliability and therefore the MTBF values by means of an optimization of the operating hours or, in other terms, the duty cycle of the inverter. In Table I some results of this analysis are summarized.

Table I – Duty cycle vs MTBF

Duty Cycle	Operating hours	MTBF [h]
40%	9	320.370
50%	12	256.520
60%	15	213.891
75%	18	171.212

The decision to use redundant design techniques should be based on analysis of reliability and test data. Redundancy may prove to be the only available method when other techniques of improving performance (e.g., high quality components, derating) have been exhausted or when methods of item improvements are shown to be more costly than duplications. The use of redundant equipment can allow for repair with no system downtime. A particular active redundancy configuration, often implemented for safety systems, is represented by the k-out-of-n, designed also as *koon* redundancy. The system is operative when at least k items out of a total of n are normally functioning, with  $k \leq n$ . For this configuration it can be assumed k items in active redundancy and the remaining (n-k) in stand-by.

Assuming the system constituted by identical items with independent failures, the probability of k successes out of n units can be evaluated by considering the binomial distribution [16], with parameters k, n and p

$$P\{k, n, p\} = \binom{n}{k} p^k (1-p)^{n-k} \quad (1)$$

where p represents the probability of success on any item. On the basis of the definition given for *koon*, the system successes if k, k+1, ..., n succeed. Consequently, the probability of the system success is

$$R_{\text{SYS}}(t) = \sum_{i=k}^n \binom{n}{i} (e^{-\lambda t})^i (1 - e^{-\lambda t})^{n-i} \quad (2)$$

Eq. (2) represents the reliability of the *koon* configuration for random failures, being  $\lambda$  the failure rate of the item

and

$$\binom{n}{i} = \frac{n!}{i!(n-i)!} \quad (3)$$

the binomial coefficient.

The MTBF can be obtained, in the case of n identical components, as

$$MTBF = \int_0^{\infty} R(t) dt = \frac{1}{\lambda} \sum_{i=k}^n \frac{1}{i} \quad (4)$$

Considering a PV plant characterized by a power equal to 750 kW, it is possible to hypothesize two scenarios:

- 3 out of 4 with 250 kW inverter
- 14 out of 18 with 55 kW inverter

In Table II a comparison of the proposed redundant configuration is shown. The MTBF values are obtained by Eq. (4).

Table II – Redundant configuration comparison

koon Configuration	MTBF [h]
<b>3oo4</b>	<b>188.395</b>
<b>14oo18</b>	<b>58.912</b>

#### IV. CONCLUSIONS

The paper aims to evaluate the behavior of the critical components of a photovoltaic inverter. In particular, the thermal analysis of the inverter is presented and a series of thermal tests were carried out in order to individuate the most critical components. The scope of such analysis is to optimize the inverter design and therefore its efficiency taking into account the real operative condition that are present when the equipment is installed on the field. Finally, by means of the data obtained with this study correlated with some reliability optimization rules, such as derating and redundancy, it is also possible to improve the maintenance policy of the PV inverter hence its availability and that of the whole PV plant.

#### REFERENCES

- [1] Catelani, M., Ciani, L., Graditi, G., Adinolfi, G. "Photovoltaic power optimizers: A comparison in reliability evaluations", *Proc of (2013) 12th IMEKO TC10 Workshop on Technical Diagnostics: New Perspective in Measurements, Tools and Techniques for Industrial Applications*, pp. 254-259.
- [2] Loredana Cristaldi, Marco Faifer, Massimo Lazzaroni, Mohamed Mahmoud Abdel Fattah Khalil, Marcantonio Catelani, Lorenzo Ciani, "Failure Modes Analysis and Diagnostic Architecture for Photovoltaic Plants", *Proc of 13th IMEKO TC10 Workshop on Technical Diagnostics – "Advanced measurement tools in technical diagnostics for systems' reliability and safety"*, June 26-27, 2014, Warsaw, Poland, pp. 206-211.
- [3] G. Zini, C. Mangeant, J. Merten, "Reliability of large-scale grid-connected photovoltaic systems", *Renewable Energy*, Volume 36, Issue 9, September 2011, Pages 2334-2340.
- [4] Oozeki T, Yamada T, Kato K, Yamamoto T. "An analysis of reliability for photovoltaic systems on the field test project for photovoltaic in Japan", *Proc. ISES Solar World Congress*; 2007. pp.1628-1632.
- [5] Eltawil MA, Zhao Z. "Grid-connected photovoltaic power systems: technical and potential problems - A review". *Renewable and Sustainable Energy Reviews* 2010;14: pp.112-129.
- [6] Loredana Cristaldi, Marco Faifer, Marco Rossi, Sergio Toscani, Marcantonio Catelani, Lorenzo Ciani, Massimo Lazzaroni, Simplified method for evaluating the effects of dust and aging on photovoltaic panels, *Measurement*, Vol. 54, Aug2014, pp.207-214, ISSN 0263-2241, <http://dx.doi.org/10.1016/j.measurement.2014.03.001>
- [7] L. Cristaldi, M. Faifer, M. Rossi, L. Ciani, M. Lazzaroni, S. Toscani, Photovoltaic Plant Efficiency Evaluation: A Proposal, *Proceedings of the 12th IMEKO TC10 Workshop on Technical Diagnostics*, IMEKO – International Measurement Confederation, June 6-7, 2013, Florence, Italy, pp. 260 – 265, ISBN 978-88-903149-8-8.
- [8] Marcantonio Catelani, Lorenzo Ciani, Loredana Cristaldi, Marco Faifer, Massimo Lazzaroni, Electrical performances optimization of Photovoltaic Modules with FMECA approach, *Measurement* 46 (2013), pp. 3898-3909, DOI: 10.1016/j.measurement.2013.08.003.
- [9] W. Bower, "Inverters—Critical photovoltaic balance-of-system components: Status, issues, and new-millennium opportunities," *Prog. Photovolt. Res. Appl.*, vol. 8, no. 1, pp. 113–126, 2000.
- [10] A. Pregelj, M. Begovic, A. Rohatgi, and A. Ristow, "Estimation of PV system reliability parameters," *Proc. 17th Eur. Photovolt. Sol. Energy Conf. Exhib.*, Munich, Germany, Oct. 22–26, 2001, pp. 558–561.
- [11] N. G. Dhere, "Reliability of PV modules and balance of system components," *Proc. 31st IEEE Photovolt. Spec. Conf.*, Jan. 3–7, 2005, pp. 1570–1576.
- [12] Ristow, A.; Begovic, M.; Pregelj, A.; Rohatgi, A.; ,

- "Development of a Methodology for Improving Photovoltaic Inverter Reliability," *IEEE Transactions on Industrial Electronics*, , vol.55, no.7, pp.2581-2592, July 2008.
- [13] Petrone, G.; Spagnuolo, G.; Teodorescu, R.; Veerachary, M.; Vitelli, M., "Reliability Issues in Photovoltaic Power Processing Systems," *Industrial Electronics, IEEE Transactions on*, vol.55, no.7, pp.2569,2580, July 2008
- [14] M. Catelani, L. Ciani, E. Simoni, "Thermal analysis of Critical components in Photovoltaic Inverter", *Proc. Of IEEE - International Instrumentation And Measurement Technology Conference (I2MTC) – Graz (Austria) – May 2012*, pp. 1891-1895.
- [15] M. Catelani, L. Ciani, E. Simoni, "Photovoltaic inverter: thermal characterization to identify critical components", *Proc. Of XX IMEKO World Congress - Metrology for Green Growth*, pp. 685-689, Sep. 9 - 14, 2012, Busan, Rep. of Korea
- [16] M. Rausand and A. Høyland, *System reliability theory (2nd edition)*, J. Wiley & Sons, Inc., Hoboken, New Jersey (2004).