Reliability Analysis of Photovoltaic Systems with LEDs Integrated in Lighting Applications

Laurentiu Fara[1,2], Dan Craciunescu[1], Paul Sterian[1,2], Andreea Bobei[1] and Florin Dragan[1]

[1]Polytechnic University of Bucharest, Bucharest, Romania

[2]Academy of Romanian Scientists, Bucharest, Romania

Abstract

This paper is dedicated to the analysis of a PV system based on LEDs application from the point of view of its qualitative and quantitative reliability. This reliability study was conducted based on: 1) the RAMS (Reliability, Availability, Maintenance, and Safety) model applied to a PV system by using a simulation SYNTHESIS platform developed by ReliaSoft, and 2) the simulation of the LED lighting system using the SYNTHESIS platform and TM-21 Calculator software developed by ENERGY STAR. The purpose of the reliability analysis was to obtain a more stable and long-lasting operation of a PV system regarding reliability, maintainability, availability and degradation of the system.

Keywords: Reliability, Maintainability, Availability, Degradation, PV system, LEDs, simulation tools, RBD

1. Introduction

Due to various incentive programs and local market conditions in several European countries, as well as around the world, the PV systems represent a widespread solution for residential houses and other autonomous applications. This approach raises new and important issues related to the efficiency, reliability and safety of the PV systems, either autonomous or integrated in the electrical grid (Huffman and Antelme, 2011; DeGraaff et al., 2011).

In the case of grid-connected PV systems, the occurrence of system failures may affect the operation of other interconnected systems, that is why a thorough reliability analysis of such systems should be carried out (Kececioglu, 1991; IEC International Standard, 1995; Ishii et. al., 2011). The reliability analysis also makes it possible to establish an acceptable maintenance plan for both the user and the system as efficiently as possible (Crow, 2003, 2004). However, a reliability analysis is often missing from the feasibility study of photovoltaic systems or is treated superficially due to an incomplete methodological approach or lack of specific simulation tools (Herrmann et. al. 2010), (Hoffmann and Koehl. 2012). A PV system for LED lighting applications has been analysed (Popescu et al., 2009; Stanciu et al., 2015; Sterian, 2000, 2012), (Handbook, 2010). To overcome the reported inconveniences, it is envisaged the reliability analysis, using RAMS (Reliability, Availability, Maintainability, and Safety) statistical models through accelerated testing and application of stress levels (Nelson 1998; Kijima, 1989; Mettas, 2000; Holley et al., 1996). Starting from ground studies, the failures of PV systems have shown that manufacturers do not correctly perform reliability analysis of their PV modules' lifetime. For this reason, a small part of the PV modules fails before the lifetime specified by the manufacturer (Meydbray et. al., 2008). Reliability analysis applies to both PV systems, and simple systems, such as LED-based lighting lamps (Collins et al., 2009).

The authors proposed and carried out the reliability analysis of solar cells for specific meteorological conditions (Meydbray et al 2008; McMahon, 2004; Aoki et. al. 2010; Dhere et. al. 2010) To assess the reliability of the integrated PV system with LED lighting applications, its operating characteristics have been used for a time period (Wohlgemuth, 2011), and in the case of the simple LED lighting system there were used thermal characteristics of the studied LED lamp (Kim et al., 2006; Handbook, 2007) .

The most relevant analyzes proposed by the authors in this paper are based on Reliability Block Diagrams (RBDs) required for development of RAMS for studied PV systems. RBD diagrams have been developed for: 1)definition of PV systems, 2)description of interdependence between components, 3)identification of how they degrade / fail, and 4)appreciation of how the PV system reliability is influenced.

doi:10.18086/swc.2017.10.01 Available at http://proceedings.ises.org

2. Background, state of the art and simulation tools

2.1. Background

The reliability of a product can be defined as the probability of performing its tasks without incidents within a specified time, under previously established conditions. On this basis, the quality of a product is determined, the reliability concept being applied in almost all areas of engineering, in the preventive maintenance of systems and their components. It is envisaged the modeling of the product's lifetime, represented by the time it has worked successfully or its time until the moment of failure. For the purpose of accurately determining the lifetime, it has been proposed an accelerate product testing (qualitatively or quantitatively during its lifetime) (Wohlgemuth, 2003; Dhere, 2005).

Qualitative accelerated testing only provides information about system malfunctions or ways of failure. Qualitative tests do not quantify the system's life (or reliability) characteristics under normal conditions of utilization, but provide valuable information on the type and level of demands to use during a later quantitative test. In qualitative accelerated testing, the expected result consists in identifying deficiencies and ways of failure without predicting the life of the product under normal conditions of utilization (Crow 2008; DeGraaff, et. al. 2011; Copper, 2016).

Accelerated quantitative testing involves the estimation of product lifetime characteristics, obtained under normal conditions of utilization after an accelerated test. High Accelerated Life Test (HALT) provides various information about the product and its failure mechanisms. Accelerated quantitative testing consists of tests designed to quantify the life characteristics of a product, component or system under normal conditions of utilization, and to provide information on determining the reliability of the system (probability of system failure under various conditions, life expectancy, average lifetime). It can be used to carry out risk assessments or for comparison of different design methods (Hoffmann and Koehl, 2012).

Two acceleration methods were designed (Hoffmann and Koehl, 2012) for use of: 1) acceleration rate and 2) stress acceleration, in order to obtain time data on product failure at an accelerated rate. For products where use of acceleration rate is impractical, a second method can be applied, in which the normal stress level of a product is exceeded.

2.2. State of the art

The reliability of photovoltaic systems and their components/elements (solar cells, PV modules, electrical storage systems, inverters, regulators, etc.) are the key issues in manufacturing performance and financially competitive photovoltaic installations. For this purpose, a number of methods for testing and improving the reliability of PV products have been studied (Nelson, 1998; Mettas, 2000), such as: 1) the accelerated test method for solar cells (Desombre, 1980); 2) analysis of defect detection and degradation mechanisms detection for solar cells (Kijima, 1989), as well as PV systems and their components (Vazquez and Rey-Stolle, 2008); 3) energy production forecasting based on the rate of failure and degradation of PV systems and their applications (Holley et al., 1996).

In this paper the authors proposed in this paper to integrate some of these methods by using a specialized complex simulation platform, namely SYNTHESIS, which allows a physical and statistical approach for PV products; it is envisaged the development of a highly useful RAMS methodology, both in research and in the efficient design of PV systems and their applications (Wohlgemuth, 2003; Van Weeran, 2013; Granata et al., 2009).

2.3. Methodology

In order to perform a fairly accurate reliability analysis of the PV systems and their components, the authors of this paper have chosen to use the SYNTHESIS simulation platform developed by **ReliaSoft (**Synthesis Platform, 2017)**.** The simulation methodology is intended to explain how the simulation platform modules work. On this basis the obtained results regarding: 1) solar cell, 2) PV system, including its components, 3) LED lighting system and 4) integrated PV system can be understood. The following modules of the simulation platform were used in the analysis:

a) The **Weibull++ software tool** is the industry standard in life data analysis (Weibull analysis) for many companies around the world. This software performs life data analysis using multiple lifetime distributions with a clear and concise, reliability-oriented interface. The features of Weibull++ provide the most comprehensive set of tools available for life data reliability analysis. The software supports all types of data and all distributions commonly used throughout the product's lifetime.

b) The **ALTA software tool** provides an intuitive way of complex and powerful mathematical models for quantitative analysis of accelerated life tests. Accelerated lifetime testing techniques, combined with powerful data analysis methodologies, reduce testing time for the product, thus providing faster product launch times, lower product development costs, as well as lower warranty costs.

c) The **BlockSim software tool** provides a comprehensive platform for the reliability, availability, maintenance and related products analyzes. The software provides a graphical interface that allows modeling of both simple and complex systems and processes using reliability block diagrams (RBDs), failure tree analyzes (FTAs), or combinations of both approaches. Using accurate calculations and / or discrete events simulation, BlockSim facilitates a wide range of analyzes: 1) system reliability analysis, 2) identification of critical components (important for reliability), 3) optimal allocation of reliability, 4) system maintenance analysis (determining the optimal intervals for preventive maintenance); 5) analyzing the availability of the system (determining the operating time, availability / unavailability), 6) performing calculations for obstacle identification, production capacity estimation, etc.; 7) estimating the cost of the life cycle.

d) The **RENO software tool** is a platform that allows complex analyzes for any probabilistic or deterministic scenario. Chart models can be created for complex reliability analyzes, risk and safety analyzes, decision making, or maintenance planning. The Monte Carlo simulation methods offer a number of definitions and constructions that allow modeling of the examined situations. Simulation results can be applied to estimate/optimize risk analysis, complex modeling of reliability and maintenance planning.

e) The **RGA software tool** allows the application of reliability enhancement models for data analysis from both development tests and on-site repair systems. In the development phase, the software allows to quantify the increase in reliability achieved for each product prototype and also provides advanced design, planning, and reliability enhancement management methods. The software also offers opportunities for ground-based system analysis, including a test utility for system reliability.

For a deep understanding of LED PV applications, the authors used the TM-21 Calculator software developed by ENERGY STAR to study the reliability of LED systems. The main feature of this software is the application of temperature stress levels that allow the establishment of lumen maintenance degradation during the lifetime of these products.

3. Modeling and numerical simulation of PV system components using RAMS analysis. Discussion of the results

3.1. Basic concepts

The studied integrated PV system is defined as a PV application, which uses a consumer for LED lighting application (see Fig.1). The implementation of the RAMS analysis of the PV system was performed using the modeling and simulation SYNTHESIS platform for system reliability (Craciunescu et al., 2017). When it is analyzed the reliability of studied solar cells, the simulation module used in the SYNTHESIS platform was Weibull / ALTA. This module statistically addresses reliability issues through statistical repartitions and together with the ALTA module contributes to the accelerated life tests. For the analysis of the PV system / LED lighting application studied in the paper, the BlockSim simulation module was used within the same platform. The simulation of the PV systems is based on the RBD diagram, as well as on the component types and the way they are arranged in the system.

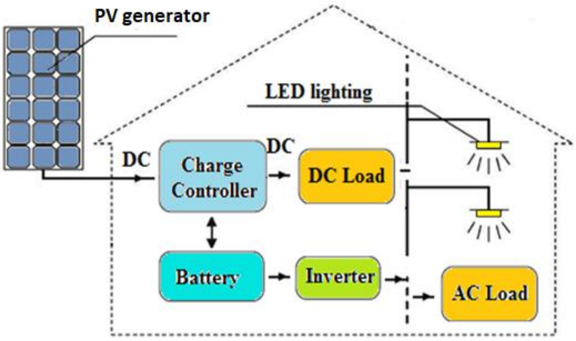


Fig. 1 PV integrated system concept

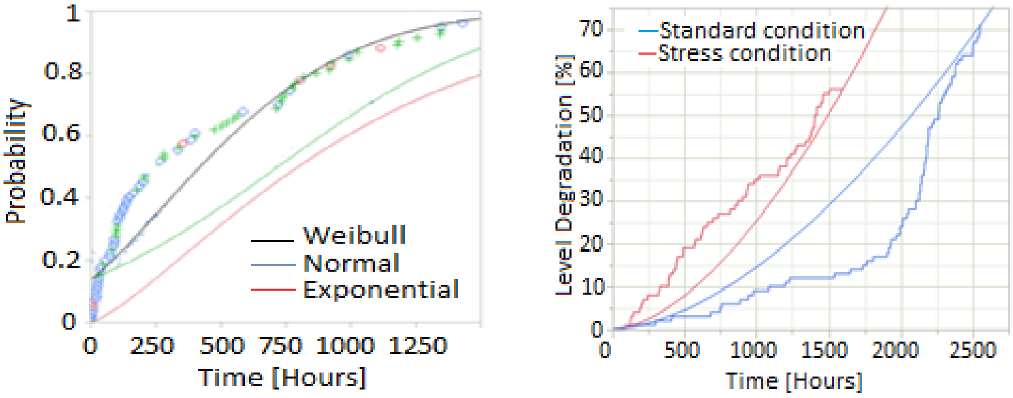
For a rigorous understanding of the RAMS analysis for the PV integrated system, it was analyzed the highlighting of solar cell degradation. By performing a statistical analysis based on the Weibull, Exponential and Normal repartitions, it was possible to estimate the most frequent events (characterized by main meteorological parameters: solar irradiance, temperature and humidity) that contribute to the most probable degradation of solar cells during their lifetime. The statistical approach was correlated with the accelerating lifetime method by stressing solar cells using different meteorological parameters (Fig. 2). The present study considered only the three meteorological parameters mentioned above, which have an essential role in cell degradation.

Fig 2. Accelerated stress test diagram

3.2. Reliability analysis of solar cells

Reliability analysis of solar cells has been developed based on the accelerated testing method, which has certain advantages: 1) avoiding testing in real and more severe conditions that can lead to cell degradation / failure, 2) determining the frequent reasons that determine cell failure. Highly Accelerated Stress Screening (HASS) aimed at identifying defects in as short time as possible compared to the standard method (based on cell monitoring and results analysis), which may take several months / years. Accelerated testing (HASS) can be performed with either a weather parameter (e.g. temperature / solar irradiance) or combined with few weather parameters (such as temperature, humidity and solar irradiance). Within this paper the HASS analysis was implemented in the version of the three key meteorological parameters.

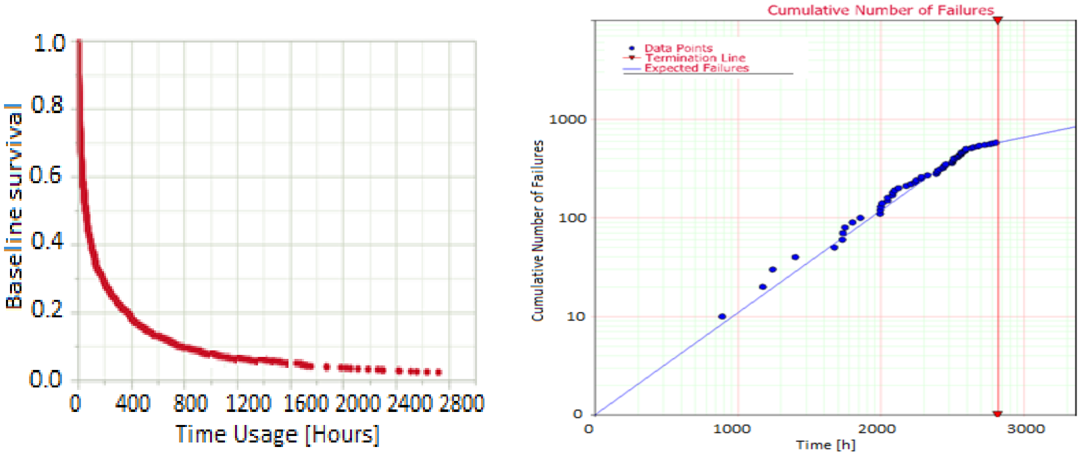
The authors' study also looked at establishing the best statistical reparation used to make the most accurate predictions of the of solar cells life time. Three types of statistical repartitions, namely Weibull, Exponential and Normal, were evaluated using the SYNTHESIS software, and based on the correlation cause (determined by one of the three main meteorological parameters) - occurrence (characterized by the degradation degree of the solar cell) it was possible to obtain the probabilities for the three repartitions (the black curve defines the Weibull repartition, the green one defines the Normal repartition, and the purple one defines the Exponential repartition), using the HASS test. In Fig. 3a the curves of the mentioned statistical repartitions were obtained. It can be seen that Weibull repartition is the closest to the values of the three main meteorological parameters. The accelerated test has highlighted that the most influential meteorological parameter in solar cell degradation (characterized by most occurrences) is temperature, followed by humidity and further by solar irradiance. Fig. 3b shows the temporal evolution (in hours) of the degradation level of solar cells for two operating modes: under stress conditions (purple continuous curve) and in standard conditions (blue continuous curve).



a) b)

Fig.3 a) The life distribution of solar cells for different distribution function b) Degradation level of solar cells simulation in different conditions (standard and stress)

Using the stress results of the HASS test (purple curve in Fig. 3b), it was possible to determine by numerical simulation in the SYNTHESIS platform, the limit value of the cell operating time in normal conditions, respectively 1600 hours, according to the curve in Fig. 4a. The accelerated test also enabled the probable number of solar cell failures (see Fig. 4b) within the range of 1000-2800 hours, with a higher concentration between 1500-2800 hours according to the results from Figure 4a; the linear dependence defines the expected failures curve based on Weibull repartition.



a) b)

Fig. 4 a) Baseline survival of solar cells module simulation in stress conditions b) Cumulative number of failures as function of time

3.3. RAMS analysis of the PV system

The analyzed PV system consists of a set of components, arranged to achieve the established performance and to provide acceptable reliability. The reliability characteristics of the PV system and its components can be presented in RBD-type diagrams illustrating their possible failures. These failures are due to a facile analysis of the failures risk.

The RAMS analysis for the photovoltaic system aimed to determine how the system and its components worked over a 5000-hour period (about 5 months). For this purpose, it was analyzed the time evolution of the PV generator efficiency, as well as of the PV system's battery efficiency. There were noted high fluctuations for the efficiency of PV generator, slower fluctuations in battery efficiency based on Fuzzy Logic Controller (FLC) and Maximum Power Point Tracking (MPPT) methods (see Fig. 5). The LED lighting system (electric consumer) will be discussed further in section 3.5.

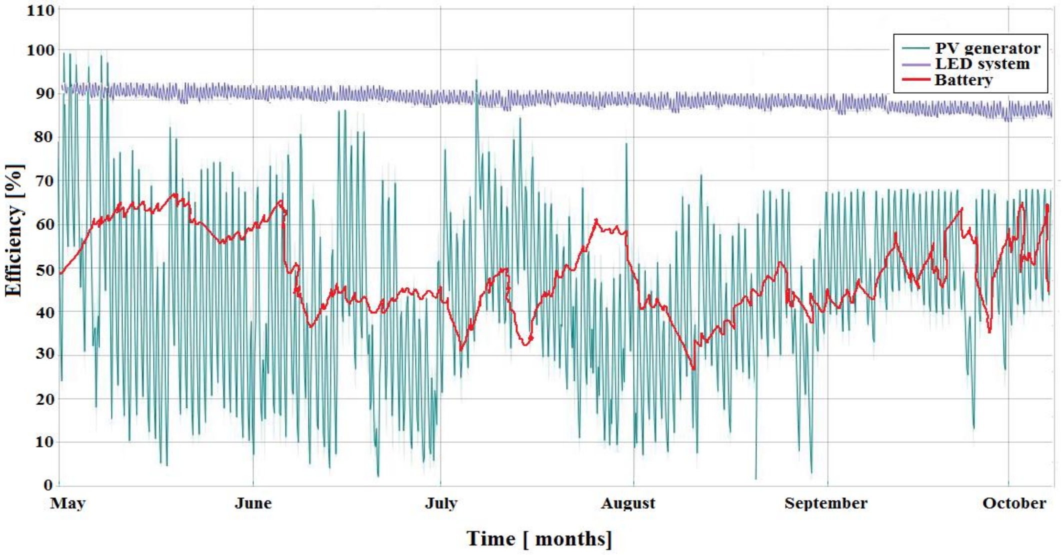
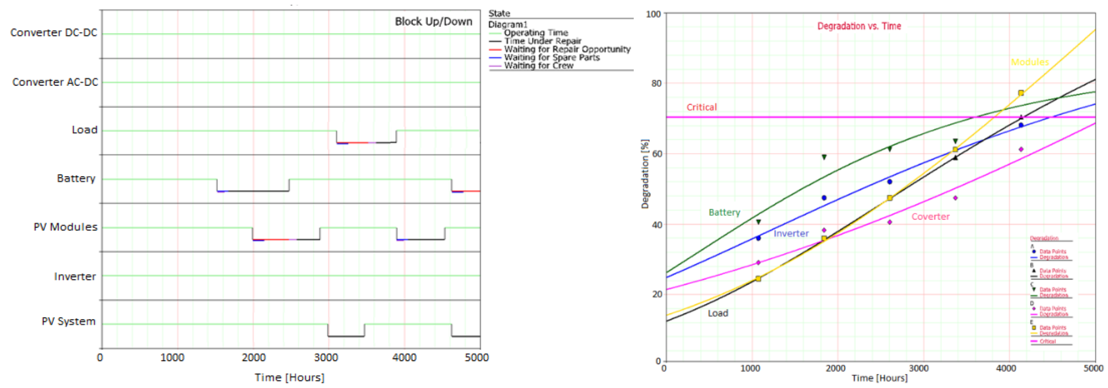


Fig. 5 Efficiency and functionality of a PV system for its main three components: 1) PV generator 2) battery and 3) electrical load

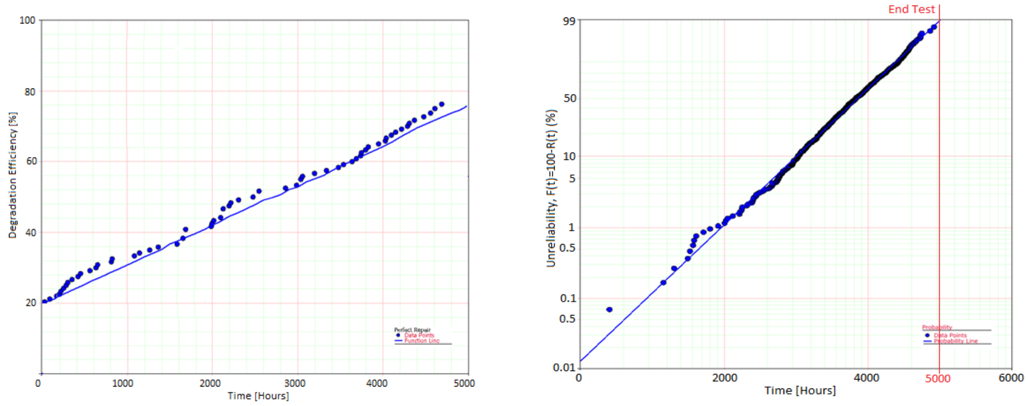
Using the results obtained in Fig. 6a we could establish the availability diagram of the PV system giving the operation time and unavailability periods (when the PV system is not working). The unavailability periods are usually small; after 3000 hours of operation there is a 500-hour period when the PV system has to be repaired due to different failures. In Fig. 6a there are also analyzed the main components of the PV system (PV modules, battery and load) to be maintained. The complex analysis of defect risks and preventive planned maintenance of the components aims at avoiding spontaneous malfunctions and premature degradation of the PV system.



a) **b)**

Fig. 6 a) PV system availability / unavailability diagram b) Degradation of system components based on availability / unavailability diagram

In Fig. 6b the level of degradation for each component of the PV system is presented. Although, excepting the inverter, all other components exceed the critical threshold to the end of the test (3500-4500 hours); however, two components, respectively the PV modules and the storage system, are the most vulnerable to failure (exceeding the critical level much earlier). The simulation tools allowed to obtain the efficiency degradation analysis of the PV system (see Fig. 7a). A good PV system is characterized by small fluctuations of the time evolution of efficiency, determining a usual degradation based on normal operation requirements for the analyzed simulation period (5000 hours).



a) **b)**

Fig. 7. a) Time degradation of PV system efficiency b) Statistical unreliability of the PV system in time

The probability of non-functioning of the PV system over time is sensitive after 2000 hours of the product use (see Fig. 7b). It is noted the role played by this diagram in RAMS analysis; when the components of the PV system start to degrade, the number of failures increases, that leads to the need for more frequent interventions (repairs) on the PV system.

The RAMS approach, based on the SYNTHESIS simulation platform, was able to obtain preliminary information on the time behavior of the PV system and its components (from the point of view of its reliability and maintenance) which could be very useful for its proper design.

3.4. Failure analyses for the LED lighting system

The operation of LEDs is strongly influenced by the thermal conditions that can cause LED degradation. The evaluation of LED degradation is performed by the lumen degradation method, in which higher internal temperatures are produced without heat sink. The RAMS analysis of typical LED lamps, as the one in Fig. 8, is possible with the help of two software environments, namely: 1) TM-21 Calculator developed by ENERGY STAR - to determine LED lamp degradation, and 2) SYNTHESIS simulation platform - to assess the failure of each component of the LED lamp (TM-21 Calculator, 2017; Synthesis Platform, 2017).

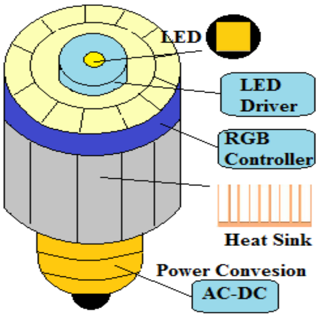
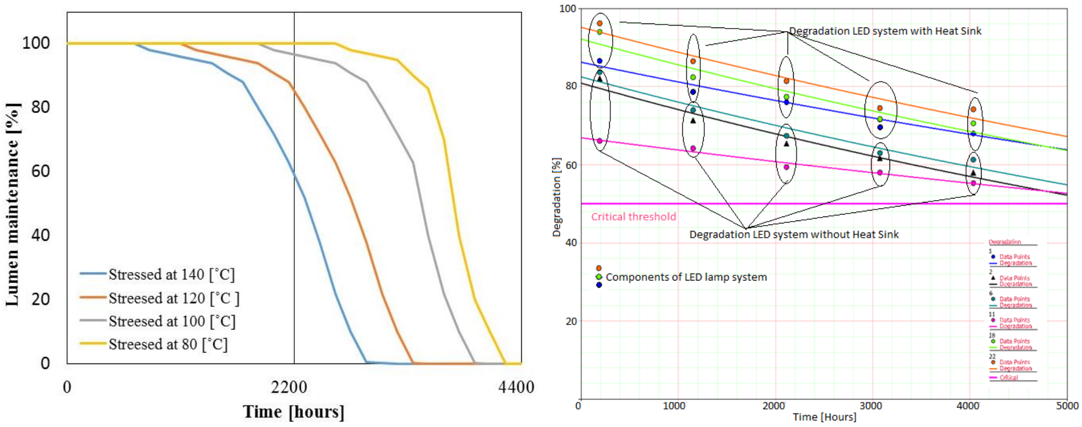


Fig 8. Concept of a typical LED lamp

According to Fig. 9a, at a test temperature of 140 ^{o}C, the lumen flux reaches 60% of its total value; it corresponds to a 2200 hours operation (based on a 5000-hour range for which the simulation was performed). It is remarked that the life duration of the LED lamp was reduced by roughly 1500 hours in the temperature range of 80-140 $^{\circ}$C.

The SYNTHESIS platform, in particular the BlockSim software tool, was used to obtain the degradation diagram of the LED lamp, as shown in Fig. 9b, useful in testing of several efficient cooling systems, which can help to increase the reliability of the LED system. It is noticed that, under standard operating conditions, the LED lamps are getting closer to the critical degradation limit, while using the Heat Sink the LED lamp component functioning is removed from the critical area.



a)

b)

Fig. 9: a) The degradation curve of lumen maintenance [%] for the whole LED lamp, represented by life duration (hours) depending on four values of test temperature (stress). b) Degradation diagram of the LED lamp components

3.5. RAMS analysis specific to a PV system

A PV system based on LED lighting application has been studied. Analysis of the PV integrated system was possible using the availability / unavailability diagram of its components (Fig. 10). This diagram describes the interdependence between the components and defines how the system works. An important parameter of the availability / unavailability diagram is the power load LED system that is influenced by the operating mode (using either serial, parallel or mixed type configurations). Each component of the PV system is characterized by a repairable block, parameterized in the BlockSim simulation module.

A feature of the Up / Down diagram is the planning of the PV system maintenance; thus, as a result of prompt interventions in order to repair its components, spontaneous or irreversible failures are eliminated, the system thus becoming functional over the entire lifetime.

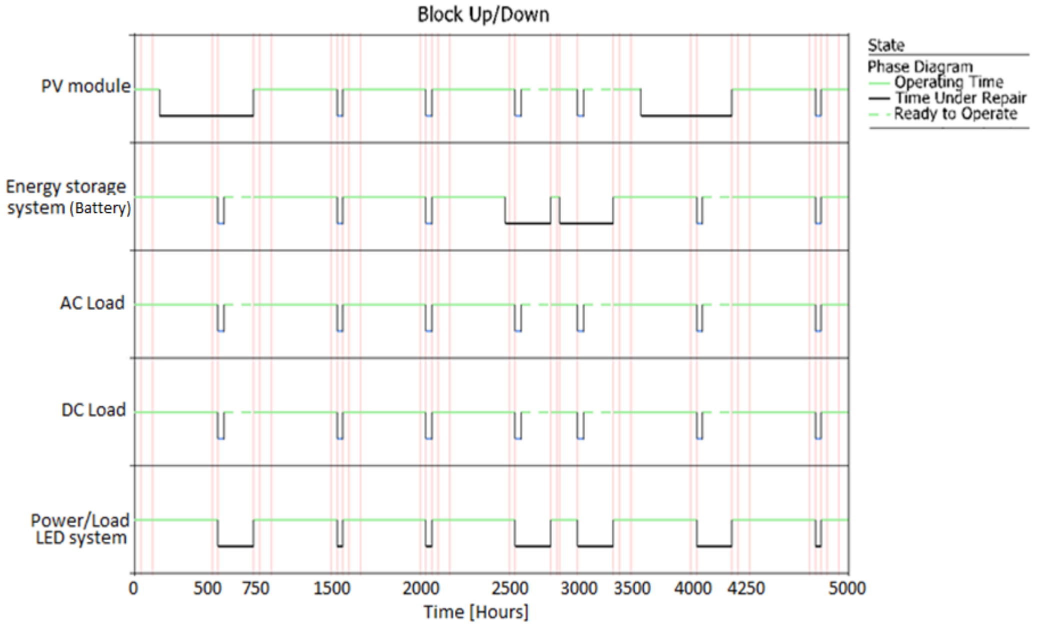


Fig. 10: Diagram of the availability / unavailability (Up / Down) of the PV integrated system

The failure rate for each component of the PV system was also being studied. The highest failure rate is presented, by the PV modules, respectively LED systems, according to the results in Fig. 11. This is due to the specific configurations for these components (series, parallel or mixed) that increase their failure rate compared with other components (battery, inverter, regulator, etc.).

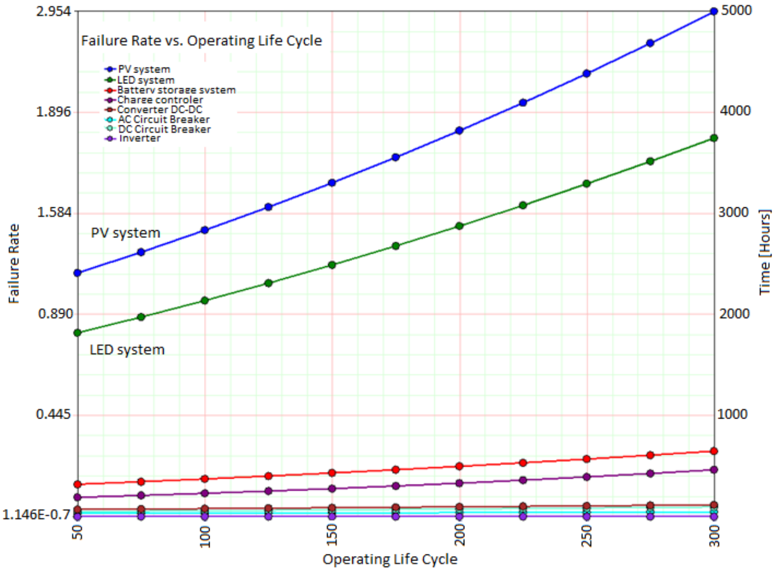


Fig. 11: Time evolution (in hours) of components failure rate of the PV system depending on operating life cycle

4. Concluding remarks

The authors have proposed the reliability analysis of a PV system for a LED lighting application using a performance SYNTHESIS simulation platform, which allowed the system to function more accurately by identifying probable defects in certain components of the system.

This contribution is based on an original approach of RAMS reliability analysis. It was considered the adaptation of Up / Down reliability block diagrams (RBD) from *the reliability theory and applications* for a photovoltaic system in order to determine its functionality and availability and to establish its duration of non-functionality (required to implement the PV system maintenance). The obtained results of this study are in good agreement with the reliability published studies from the point of view of the methods used (Huffman et al., 2009; DeGraaff et al., 2011; Crow 2004; Crow 2003; Collins et al., 2009; Copper et al., 2016; Vazquez et al., 2008).

The main results obtained by the authors in this article could be synthesized as follows:

- the simulation of the solar cells operation on an accelerated test basis (under the influence of three essential meteorological parameters: solar irradiance, temperature and humidity) allowed to put in evidence the normal operating time under normal / stress conditions, defining the initial degradation time of stressed solar cell (determined by a possible degradation of the cell's I-V characteristics). The Weibull most probable statistical repartition has also been identified using a proper solar cells testing; on this basis, the operating duration in which a significant concentration of defects is achieved, was determined.

- the simulation of the PV system operation allowed to obtain information on the availability / unavailability of the system, based on a RBD diagram. Using this diagram, PV components that may exhibit a higher rate of degradation (PV modules, electrical battery) during operation are identified. Also, useful information on degradation of the PV system was obtained (based on the efficiency degradation curve and the non-functional curve).

- the simulation of the LED lamp allowed to study the temperature influence on the lifetime and the degradation of the lamp components.

- the simulation of PV system operation for the LED lighting application allowed also to use the Up/Down diagram as maintenance schedule for elimination of spontaneous or irreversible failures, The results obtained by the authors were partially validated by other authors research studies, regarding the availability and degradation of analyzed systems (Mahdi et al., 2017; Lavrova et al., 2015).

In order to increase the reliability of the PV system and its components, it is necessary to develop an elaborated failure management strategy that involves knowing the initial level of reliability and developing efficient solutions for planning and assessing the probable risks of failure. The essential directions for such a strategy could be as follows:

- experimental accelerated testing of the PV system under the influence of possible degradation factors;
- identifying the cause of failure in experimental conditions, that is intended to isolate possible failures occurring in the PV system;
- implementing effective corrective actions to significantly reduce the failures of the PV system.

Acknowledgment

The authors are grateful for the financial support of Ministry of Research and Innovation, Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI), no. 34/2016 contract, SOLHET project "High-performance tandem hetero-junction solar cells for specific applications".

5. References

Huffman D.L., Antelme F., 2009. Availability analysis of a solar power system with graceful degradation. Proc. of the Reliability and Maintainability Symposium, Fort Worth, TX.

DeGraaff D., Lacerda R.,. Campeau Z, 2011. Degradation Mechanisms in Si Module Technologies Observed in the Field; Their Analysis and Statistics. Presentation at PV Module Reliability Workshop, NREL, Denver, Golden, USA.

Kececioglu, D.B., 1991. Reliability Growth, Reliability Engineering Handbook. fourth ed, Vol. 2, Prentice-Hall, Englewood Cliffs, New Jersey, pp. 415-418.

IEC International Standard, Reliability Growth- Statistical test and estimation methods, IEC 1164 International Electrotechnical Commission, 1995

Ishii, T., Takashima, T., Otani, K., 2011. Long-term performance degradation of various kinds of photovoltaic modules under moderate climatic conditions. Prog. Photovolt: Res. Appl., 19, 170.

Crow, L.H., 2004. Evaluating the Reliability of Repairable Systems. IEEE Proc. Annual Reliability and Maintainability Symposium, 73-80.

Crow, L.H., 2003. Methods for Reducing the Cost to Maintain a Fleet of Repairable Systems. IEEE Proc. Annual Reliability and Maintainability Symposium, pp. 392-399.

Herrmann, W., Bogdanski, N., Reil, F., Kohl, M., Weiss, K., Assmus, M., Heck, M., 2010. PV module degradation caused by thermo-mechanical stress: Real impacts of outdoor weathering versus accelerated testing in the laboratory. Proc. Vol. 7773, Reliability of Photovoltaic Cells, Modules, Components, and Systems III; 777301

Hoffmann, S., Koehl, M., 2012. Effect of humidity and temperature on the potential-induced degradation. Prog. Photovolt: Res. Appl., 22, 173–179

Popescu A., Miclos S., Savastru D., et al. 2009. J. Optoelectron. Adv. M. 11(11), 1874

Stanciu A. E., Cotoros D. L., Cristea L., Baritz M., 2015 J. Optoelectron. Adv. M. 17(7-8), 1146.

Sterian PE., 2000 Fotonica. Printech;

Sterian A. and Sterian P, 2012 “Mathematical Models of Dissipative Systems in Quantum Engineering”, Mathematical Problems in Engineering, vol. 2012, Article ID 347674, 12 pages, doi:10.1155/2012/347674

Power Semiconductor Reliability Handbook, 2010, Alpha and Omega Semiconductor.

Holley, W., Agro, S. Galica, J., Yorgensen, R. 1996. UV stability and module testing of non-browning experimental PV encapsulant. IEEE Photovoltaic Specialists Conference

Nelson, W., 1998. An Application of Graphical Analysis of Repair Data. Qual. Reliab. Eng. Int., 14, 49-52.

Kijima, M., 1989. Some results for repairable systems with general repair. J. Appl. Probab., 20, 851—859.

Mettas, A., 2000. Reliability Allocation and Optimization for Complex Systems. Proc. of the Annual Reliability & Maintainability Symposium.

Meydbray, Y., Wilson, K., Brambila, E., Terao, A., Daroczi, S., 2008. Solder joint degradation in high efficiency all back contact solar cells. IEEE Photovoltaic Specialists Conference.

Collins, E., Miller, S., Mundt, M., Stein, J., Sorensen, R., Granata, J., Quintana, M. 2009. A reliability and availability sensitivity study of a large photovoltaic system. IEEE Photovoltaic Specialists Conference.

Meydbray, Y., Wilson, K., Brambila, E., Terao, A., Daroczi, S., 2008. Solder joint degradation in high efficiency all back contact solar cells. IEEE Photovoltaic Specialists Conference.

McMahon, T., 2004. Accelerated testing and failure of thin-film PV modules. Prog. Photovolt: Res. Appl, 12, 235-248.

Wohlgemuth, J., 2011. Tutorial/short course on reliability: PV cells, modules, and systems. IEEE Photovoltaic Specialists Conference. Seattle, WA.

Aoki, Y., Okamoto, M., Masuda, A., Doi, T., 2010. Module performance degradation with rapid thermal-cycling. Proc. of Renewable Energy.

Dhere, N., Pethe, S., Kaul, A., 2010. Photovoltaic module reliability studies at the Florida Solar Energy Center. IEEE International Reliability Physics Symposium.

Kim S. K., Kim S. Y., Choi Y. D., 2006 Proceedings of 10th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, pp. 377-379,.

Handbook, 2007, Lumileds, understanding power led lifetime analysis. Technical report, Philips Lumileds Lighting Company.

Crow, L.H., 2008. A Methodology for Managing Reliability Growth During Operational Mission Profile Testing. IEEE Proc. Annual Reliability and Maintainability Symposium, 48-53.

Dhere, N., 2005. Reliability of PV modules and balance-of-system components. IEEE Photovoltaic Specialists Conference.

Copper, J. K., Bruce, A., 2016. Calculation of PV System Degradation Rates in a Hot Dry Climate. Asia Pacific Solar Research Conference, Canberra, Australia.

Desombre, A., 1980. Methodology for a reliability study on photovoltaic modules. Proc. of the third European Commission, PV Solar Energy Conference. Cannes, France. 741-745.

Vazquez, M. Rey-Stolle, I., 2008. Photovoltaic module reliability model based on field degradation studies. Prog. Photovolt., 16, 419.

Wohlgemuth, J., 2003. Long-term photovoltaic module reliability. NCPV and Solar Program Review Meeting, NREL/CD-520-33586, 179-183

Van Weeran, N., 2013. Degradation of photovoltaic modules in Alice Springs, Australia. Undergraduate Thesis, School of Photovoltaics and Renewable Energy Engineering, The University of New South Wales.

Granata, J., Boyson, W., Kratochvil, J., Quintana, M., 2009. Long-term performance and reliability assessment of 8 PV arrays. IEEE Photovoltaic Specialists Conference.

Craciunescu D., Fara L., Sterian P., Bobei A. Dragan F., 2017 Optimized Management for Photovoltaic Applications Based on LEDs by Fuzzy Logic Control and Maximum Power Point Tracking, Nearly Zero Energy Communities, Springer Proceedings in Energy, DOI 10.1007/978-3-319-63215-5_23

TM-21 Calculator platform. https://www.energystar.gov/sites/default/files/ENERGY%20STAR%20TM21%20Calculator%20rev%2002-08-2016%20clean_0.xlsx. Accessed October 2017.

Synthesis Platform. http://www.reliasoft.com/synthesis/downloads.htm. Accessed October 2017.

Mahdi I., Chalah S. Nadji B., 2017, Reliability study of a system dedicated to renewable energies by using stochastic petri nets: application to photovoltaic (PV) system, 4th International Conference on Energy and Environment Research, ICEER 2017, 17-20 July 2017, Porto, Portugal, Energy Procedia 136, 513–520.

Lavrova O., Flicker J., Johnson J., Armijo K., Gonzalez S., Schindelholtz E., Sorensen R., Yang B., 2015 PV Systems Reliability: Final Technical Report, Sandia Report-SAND2015-376607.