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Photovoltaic Power Optimizers: a comparison in reliability evaluations

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Abstract- The reliability evaluation of a system is an important task. Mean Time Between Failure and Failure Rate can suggest useful information about diagnostic aspects, maintenance and investments. This is especially true in case of photovoltaic systems. A Power Optimizer reliability is estimated by MIL-HDBK-217F and Siemens SN29500 reliability prediction models.

I. Introduction

Photovoltaic (PV) plant is a complex system constituted by PV modules, converters, tracker systems, optics and others electronic and mechanical equipment. Working points characterizing functioning mode of the PV plant are strongly dependent on the continuous changing of meteorological conditions (ambient temperature, solar radiation, etc.), on their geographical location as well as installation position, presence of shadow, dust, etc. An important task in design of PV plant is to improve the systems performances by increasing efficiency and reliability and, on the other hand, to decrease costs. In fact, a high efficiency PV plant allows to make shorter the energy payback time, while a reliable PV plant allows to make lower the maintenance activities with consequent economic advantages. In this scenario, the reliability evaluation of PV plants becomes an important issue to be considered. To this aim, many reliability prediction models can be used to calculate reliability indices as the Mean Time Between Failure (MTBF) and failure rate (λ). In this paper, the attention is focused on the evaluation of reliability performances of an electronic part of the PV system represented by the Power Optimizer. This is a Distributed Maximum Power Point Tracking (DMPPT) converter dedicated to each PV module. Both MTBFs and failure rates λ of the power optimizer devices are evaluated by means of two different reliability prediction models. In detail, a comparative analysis is carried out between the DC-DC converter reliability indices obtained by the Military Handbook 217F Notice 2, and the industrial handbook Siemens SN29500 version 1.

II. Distributed Maximum Power Point Tracking converter

PV generators usually operate in non uniform conditions of temperature and irradiance. The electrical characteristic of a PV string can be strongly influenced by continuous changing meteorological and environment conditions. In addition, also mismatching phenomena can affect PV modules energetic performances with the consequent decrease of the energy production. A solution to such a problem consists in the use of a DC-DC converter carrying out the MPPT for each module (DMPPT) [1-3]. Many DC-DC topologies [4-5] can be adopted (boost, buck, etc.) for PV applications. Among these, the Diode Rectification (DR) boost converter, represented in Fig.1, is one of the most widely used for its simplicity and the limited number of devices needed.

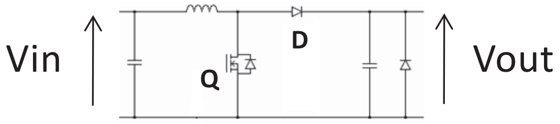

Fig. 1. DR boost converter.

A crucial step in the design procedure of PV Optimizer is represented by the identification of electronic components able to assure feasibility not only in terms of current and voltage rates, but also to assure high performances in presence of temperature variations causing their properties change. So an electro-thermal design method [6] becomes a necessary approach in the development of DMPPT converters to ensure the power devices fulfillment of electrical and thermal requirements which strongly influences the whole PV Optimizers energetic, efficiency and reliability performances. Many methods are available to this purpose such as modern mathematic algorithms, Model Order Reduction (MOR) methods and so on. The electro-thermal design procedure for PV switching converters, represented in Fig.2, will be proposed . At the beginning of the design process, the tool requires ambient temperature data, irradiance values, PV module and load characteristics as input data. Then, since a worst case or reference operating condition cannot be identified in PV applications, the proposed method takes advantage of random choices referring to the converter switching frequency and power stage devices. In detail, a subroutine is developed for each component to accurately evaluate the thermal stress influencing its behavior and its specific properties values to the ambient temperature variation. Then, the randomly chosen devices are considered feasible or unfeasible for the specific application subjecting each of them to constraints verification. In case of one or more unfeasible component, the design tool carries out a new random choice with the consequent thermal cycle and constraints check, until feasible devices are identified. In the next, the so obtained DMPPT converter performances are estimated in terms of efficiency, cost, volume and reliability. Among all the found solutions, designers select the "optimum" one on the base of the most tight requirements.

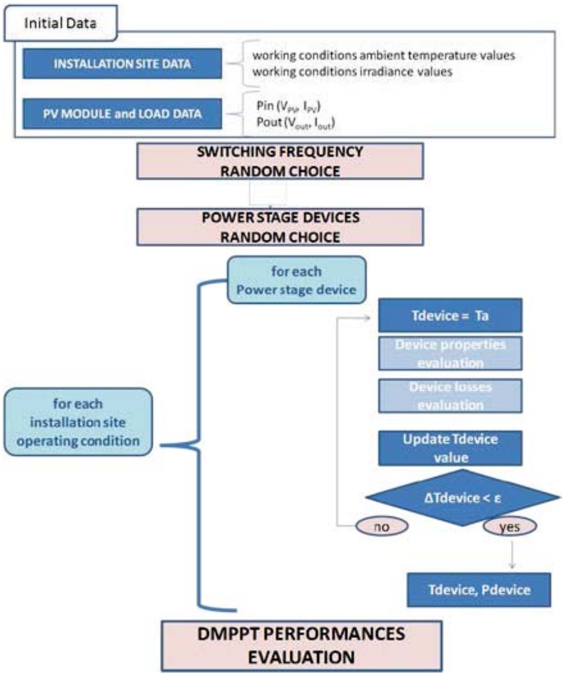

Fig. 2. Power Optimizer Electro-Thermal design procedure.

III. Power Optimizers Reliability Assessment

The efficiency of PV plant is guaranteed by the maintenance of its performances in the time. This aspect involves the concept of Reliability. In fact, the reliability *R(t)* is defined as the probability that an item, in our case the PV plant, will perform the required function, without failure under stated conditions for a stated period of time. From the definition, it is evident that maintaining reliability and providing reliability engineering is an essential need in modern systems. Thus, reliability is an important and crucial issue especially for continuous changing working conditions systems [7-14] such as the PV ones. In detail, the reliability engineering for electronic and mechanical equipment requires a means for a quantitative baseline, or a reliability prediction analysis. In fact, their operations rely on business plans developed over periods of time of at least twenty years which often assume fault-free functioning referring to PV generators lifetime. In this context, the reliability of each component of the PV system has to be carefully analyzed [15-20]. As mentioned before, the reliability parameters and, in particular, the failure rate λ can be evaluated in different ways. Among these, the reliability prediction represents a valid approach used in many fields of engineering application. In particular, the prediction allows to determine the system's failure rate on the basis of information collected in specific databases. In this work the MIL-HDBK-217F NOTICE 2 [22] and the Siemens SN29500 [21] are used in order to evaluate the reliability performances of a DR boost converter used as module-dedicated power optimizer in PV plants. MIL-HDBK-217 was developed by the United States Department of Defense with the purpose, in the origin, to establish and maintain consistent and uniform methods for estimating the inherent reliability of military electronic equipment and systems. It was updated until 1995 in the latest version MIL-HDBK-217F NOTICE 2. However, it has become widely used for industrial and commercial electronic equipment applications throughout the world. The handbook is intended as a guideline, not a specific requirement, to calculate the reliability of equipment being designed. The MIL-HDBK-217F N2 estimates the system reliability by relying on base failure λ_b rates for the components in the system. The base failure rates describe the components while operating under "normal" (determined by the standard) environmental conditions. The base failure rates are then multiplied by various factors (denoted as pi factors) that describe the specific conditions/stress in which the component is used, the operating environment, the quality of the component, the technology, and so on. Table I summaries the formulas to calculate the failure rate of each components of the DMPPT converter under study.

TABLE I. MIL-HDBK-217F N2 FAILURE RATE FORMULAS

Device	*Prediction model*
Inductor	$\lambda_{inductor\_MIL} = \lambda_{b\_ind}\pi_T\pi_Q\pi_E$
Capacitor	$\lambda_{cap\_MIL} = \lambda_{b\_cap}\pi_T\pi_{cap}\pi_V\pi_{SR}\pi_Q\pi_E$
MOSFET	$\lambda_{MOS\_MIL} = \lambda_{b\_MOS}\pi_T\pi_A\pi_Q\pi_E$
Diode	$\lambda_{diode\_MIL} = \lambda_{b\_diode}\pi_T\pi_S\pi_C\pi_Q\pi_E$

where:
λ_{b_ind} - inductor base failure rate
λ_{b_cap} - capacitor base failure rate
λ_{b_MOS} - MOSFET base failure rate
λ_{b_diode} - diode base failure rate

and, for specific component:
π_{Cap}- capacitance factor
π_V - capacitor voltage stress factor
π_T - temperature factor
π_Q - quality factor
π_E - environment factor
π_{SR}- series resistance factor
π_S - voltage stress factor
π_C - contact construction factor
π_A- application factor

As said in the introduction, in addition to MIL HDBK, another handbook was taken into consideration with the aim to compare results. To this scope we select the Siemens SN29500 being this handbook important from the industrial point of view. This document was developed by Siemens AG in Germany and it encompasses Failure Rate Prediction Models for a broad base of components. The SN29500-1 model, published in 2010, consists of several separate Siemens documents that have been packaged together as a standard. The given failure rates were determined from application and testing experience taking into consideration external sources. Components are categorized into different groups, each with a different reliability model.

The Siemens SN29500 model is based on IEC 61709, *Electronic Components - Reliability - Reference Conditions for Failure Rates and Stress Models for Conversion*. It provides frequently updated failure rates data at reference conditions, as well as the Parts Count and Part Stress models necessary for reliability predictions. The reference conditions adopted are typical for the majority of systems applications. If operating conditions differ significantly from reference ones, this model supports failure rates converting factors. The SN29500 formulas to calculate the DMPPT converter devices FRs are shown in Table II.

TABLE II. Siemens SN29500 FAILURE RATE FORMULAS

Device	*Prediction model*
Inductor	$\lambda_{inductor\_SM} = \lambda_{ref\_ind}\pi_T$
Capacitor	$\lambda_{cap\_SM} = \lambda_{ref\_cap}\pi_U\pi_T\pi_Q$
MOSFET	$\lambda_{MOS\_SM} = \lambda_{ref\_MOS}\pi_U\pi_T$
Diode	$\lambda_{diode\_SM} = \lambda_{ref\_diode}\pi_T$

where:
λ_{ref_ind} - inductor base failure rate

λ_{ref_cap} - capacitor base failure rate
λ_{ref_MOS} - MOSFET base failure rate
λ_{ref_diode} - diode base failure rate

and for the specific component:
π_T - temperature dependence factor
π_U - voltage dependence factor
π_Q - quality factor for capacitors

The reliability performances of the DMPPT power stage under investigation are evaluated by means of the calculus of the converter failure rate:

$$\lambda_{DR\_boost} = \lambda_{MOS} + \lambda_{Diode} + \lambda_{Indcctor} + \lambda_{InCap} + \lambda_{OutCap} \tag{1}$$

Eq.(1) is valid in the assumptions of series functional configuration, statistically independent parts and constant failure rates.
In the above assumption the Mean Time Between Failures, in hours, is

$$MTBF_{DR\_boost} = \frac{1}{\lambda_{MOS} + \lambda_{Diode} + \lambda_{Indcctor} + \lambda_{InCap} + \lambda_{OutCap}} \tag{2}$$

A comparison of reliability predictions results concerning the DMPPT converter components are summarized in Table III, while the whole power stage reliability indices are shown in Table IV. Failure rates are expressed in *failures/hours* and the MTBFs in *hours*. The reliability assessment was carried out considering the Power Optimizer worst case operating condition characterized by an irradiance value of 1000W/m^2 and an ambient temperature of 32°C.

TABLE III. Comparison between DR devices failure rates calculated by means of the MIL-HDBK-217FN2 and the Siemens SN29500

Item	*MIL-HDBK-217FN2* λ[h^{-1}]	*SN29500* λ[h^{-1}]
Inductor	1,59E-10	5,00E-09
Input capacitor	5,90E-09	6,00E-09
Output capacitor	7,00E-09	6,00E-09
MOSFET	3,52E-06	1,32E-06
Diode	3,50E-08	5,60E-08

It is clear that, for both prediction approaches, the most likely cause of failure is related to the MOSFET.

TABLE IV. DMPPT converter reliability performances

DMPPT converter	*MIL-HDBK-217FN2*	*Siemens SN29500*
λ [h^{-1}]	3,57E-06	1,39E-06
MTBF [h]	280.264	717.875

From the data shown in Table III and Table IV, it's possible to see that the MIL-HDBK-217 reliability prediction is more conservative in comparison with the SN29500. A reason of this difference obviously stems from the original intended use of the MIL-HDBK-217 for aerospace and military, or mission critical applications. Other aspect that must be taken into account is that the prediction model included in the SN29500 was updated in 2010 whilethe most recent issue of the MIL-HDBK-217 is the Revision F, Notice 2 which was released in 1995 and it does not keep pace with recent device technologies . Finally, considering the model shown in Table I and Table II, there are some differences also in the corrective factor that can give a different weight to the effect of some specific conditions/stress in which the component is used. As advantage, the MIL-HDBK-217 model contains more factors which may affect the devices failure rate. In fact, considering the less reliable component, the MOSFET, and comparing the λ_{MOS_MIL} formula in Table I and the λ_{MOS_SM} one in Table II, it is possible to note that, in addition to the temperature and voltage stress factor, the MIL-HDBK-217F also takes into account the device quality level and the specific environment in which the component is used. It is worth noting that the carried out studio is merely a reliability qualitative analysis since an accurate investigation cannot exclude PCB, connections and solder joints reliability and other aspects not considered in this paper.

IV. Conclusions

In this paper, the reliability evaluation in PV systems is considered, focusing, in detail, on the DMPPT DR boost converter reliability performances. The Power Optimizer components failure rates and MTBF are calculated by means of two different reliability prediction models: the Military Handbook 217F Notice 2, elaborated by the United States Navy, and the SN29599 Version 1, published by Siemens AG. The carried out analysis underlines that the MIL-HDBK-217 reliability prediction is more conservative in comparison with the SN29500 one, since it was destined to very critical applications and due to the number of components stresses factors considered.
The information obtained by means of the reliability prediction are fundamental to optimize the diagnostic strategy: In fact, it is possible to individuate the most critical components from the reliability point of view and therefore suitably monitor it. Moreover the reliability model can be also used to assess key product parameters (voltage, temperature and so on) in order to perform devices stress and derating analyses .

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