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MEASUREMENT AND COMPARISON OF RELIABILITY PERFORMANCE OF PHOTOVOLTAIC POWER OPTIMIZERS FOR ENERGY PRODUCTION

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Abstract

Photovoltaic (PV) power optimizers are introduced in PV systems to improve their energetic productivity in presence of mismatching phenomena and not uniform operating conditions. Commercially available converters are characterized by different DC-DC topologies. A promising one is the boost topology with its different versions. It is characterized by its circuital simplicity, few devices and high efficiency values - necessary features for a Distributed Maximum Power Point Tracking (DMPPT) converter. PV power optimizer designs represent a challenging task since they operate in continuously changing operating conditions which strongly influence electronic component properties and thus the performance of complete converters. An aspect to carefully analyze in such applications is the thermal factor. In this paper, a necessity to have a suitable temperature monitoring system to avoid dangerous conditions is underlined In addition, another important requirement for a PV power optimizer is its reliability, since it can suggest a useful information on its diagnostic aspects, maintenance and investments. In fact, a reliable device requires less maintenance services, also improving the economic aspect. The evaluation of the electronic system reliability can be carried out using different reliability prediction models. In this paper, reliability indices, such as the Mean Time Between Failure (MTBF) or the Failure Rate of a Diode Rectification (DR) boost, are calculated using the evaluation of the Military Handbook 217F and Siemens SN29500 prediction models. With the reliability prediction results it has been possible to identify the most critical components of a DMPPT converter and a measurement setup has been developed in order to monitor the component stress level on the temperature, power, voltage, current, and energy in the DMPPT design phase avoiding the occurrence of a failure that might decrease the service life of the equipment.

Keywords: photovoltaic, DMPPT converter, reliability, MIL-HDBK-217F, Siemens SN29500.

1. Introduction

A photovoltaic (PV) plant is a complex system constituted by PV modules, converters, tracker systems, optics and others electronic and mechanical equipment. Working points characterizing a 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 the installation position, the presence of a shadow, dust, etc. An important task in designing PV plants is to improve the performance of the systems by increasing their efficiency and reliability and, on the other hand, to decrease their costs. In fact, a high efficiency PV plant allows to shorten the energy payback time, while a reliable PV plant allows to reduce maintenance activities with consequent economic advantages. In this scenario, the reliability performance measurement of PV plants becomes an important issue to be considered. For this purpose, a reliability prediction model can be used to evaluate

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the reliability versus time (the reliability law), as well as the statistical reliability indices, such as the Mean Time Between Failure (MTBF) and the failure rate λ. Two principal approaches can be taken into account: in the first one - laboratory tests - specific environmental conditions are simulated with the aim to induce a failure, whereas in the second approach data sets are used as a collection of the experimental results and the field data. In this paper, the attention is focused on the evaluation of the reliability performance 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 the MTBF and the failure rate λ of the power optimizer devices are evaluated with two different reliability prediction models. After a description of the DMPPT converter in Section 2, the reliability measurements and assessment of the Power Optimizer is presented in Section 3. Here, a detailed analysis of the DC-DC converter is obtained using the Military Handbook 217 (MIL-HDBK) and compared with that obtained using the Siemens SN29500 industrial handbook. In order to maintain the efficiency of the PV plant and to satisfy the long-term reliability it is fundamental to monitor and control the component stress level on the temperature, power, voltage, current and energy in the DMPPT. A measurement system for thermal stress monitoring is designed and proposed in Section 4. Also, in this section the measurement results are discussed.

2. Distributed Maximum Power Point Tracking converter

PV generators usually operate in non-uniform conditions of the temperature and irradiance. The electrical characteristics of a PV string can be strongly influenced by continuously changing meteorological and environmental conditions. In addition, also mismatching phenomena can affect the energetic performance of the PV modules and cause in consequence a decrease of the energy production. A solution to such a problem consists in using a DC-DC converter carrying out the MPPT for each module (DMPPT) [1-5]. Many DC-DC topologies [6-7] can be adopted (boost, buck, etc.) for PV applications. Among these, the Diode Rectification (DR) boost converter, presented in Figure 1, is one of the most widely used for its simplicity and a limited number of devices needed. The boost topology is used to convert the input DC voltage into a higher one. As shown in the next figure, it consists of an inductor, an input capacitor, an output capacitor, and two switching devices. In detail, the DR boost circuit is characterized by the presence of a MOSFET Q and a diode D used as switches.

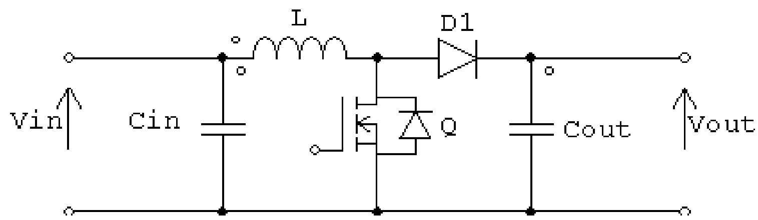

Fig. 1. DR boost converter.

The crucial step in the PV Optimizer design procedure is the identification of electronic components able not only to assure its feasibility in terms of current and voltage rates, but also to assure its high performance in the presence of temperature variations causing a change of their properties. So, an electronic-thermal design method [8-11] becomes a necessary approach in the development of DMPPT converters to ensure fulfilling by the power devices the electrical and thermal requirements which strongly influence the energetic, efficiency and reliability performance of the complete PV Optimizers. Many methods are available to reach this purpose, such as modern mathematical algorithms, Model Order Reduction (MOR) methods, and so on. The electronic-thermal design procedure for PV switching converters, represented by the flowchart shown in Fig. 2, is proposed . At the beginning of the design process, the tool requires the ambient temperature data, the irradiance values, and the load characteristics of the PV module as the input data. Then, since the worst case or the reference operating condition cannot be identified in PV applications, the proposed method takes an 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 the values of its specific properties to the ambient temperature variation. In fact, many properties characterizing the behaviors and the performance of electronic devices are strongly influenced by the temperature. In PV applications, differently from other cases, the parameters of MOSFETs, diodes and other components not only depend on the ambient temperature, but are also affected by the temperature of PV generators. In a similar scenario, the study of changing these device properties with the temperature is necessary. The dependence of the inductor and MOSFET behavior on the temperature of the PV module is next reported.

A thermal cycle is necessary to verify whether the randomly chosen devices are considered feasible or unfeasible for a specific application under continuously changing operating conditions. In case of at least one unfeasible component, the design tool carries out a new random choice with consequent checking the thermal cycle and constraints, until feasible devices are identified. The so obtained DMPPT converter performance is next estimated in terms of the efficiency, cost, volume and reliability. Among all found solutions, the designers select the "optimum" one on the basis of the most critical requirements.

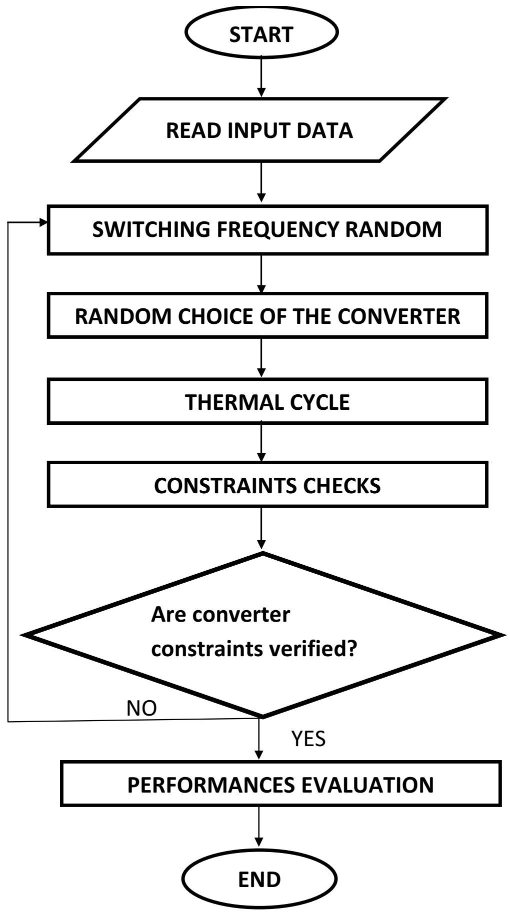

Fig. 2. Power Optimizer Electronic-Thermal design procedure.

As said before, to completely characterize a PV Optimizer MOSFET, its properties and formulas describing its dependence on the PV generator temperature have to be considered. In fact, a crucial parameter is the MOSFET junction temperature value T_j. A value higher than the one recommended by the manufacturer has to be surely avoided [8], since beyond that limit, the MOSFET could break, damaging not only itself, but also the complete system including it. T_j depends on the ambient temperature T_a, on the dissipated power P_d and on the device thermal resistance R_{thja}, as shown by the Eq.1. The dissipated power P_d depends on many other parameters both concerning the characteristics of the MOSFET as well as the other converter devices and the installation site. So, the formulation of T_j dependencies is complex. It is not here reported since it is not the aim of the paper. In DMPPT applications, the complexity level increases, since T_j depends on the PV module temperature T_{PV} instead of T_a. The details of this specific aspect with relative formulas are reported in [8,14, 21].

$$T_j = T_a + P_d R_{thja} . \qquad (1)$$

An interesting task consists in the analysis of the T_j range characterizing a DMPPT converter MOSFET. For this purpose, considering the PV plant installed at the ENEA Research Center and the meteorological data (irradiance, ambient temperature) there monitored, the above described design methodology is applied and T_j values are calculated. Fig. 3 shows T_j variations caused by an increase of the irradiance. In addition, the drain-source resistance R_{DS} and the threshold voltage V_{th} of the considered component can be calculated by the Eq.2 and Eq.3, respectively. Their values are represented in Fig. 4 and Fig. 5.

$$R_{DS}(T_j) = R_{DS\_25°C}\left[1 + \frac{dR_{DS}}{dT}(T_j - 25°C)\right], \qquad (2)$$

$$V_{th}(T_j) = V_{th\_25°C}\left[1 + \frac{dV_{th}}{dT}(T_j - 25°C)\right], \qquad (3)$$

where:

- R_{DS} is the MOSFET drain-source resistance
- $R_{DS\_25°C}$ is the MOSFET drain-source resistance at the ambient temperature of 25°C
- V_{th} is the MOSFET threshold voltage
- $V_{th\_25°C}$ is the MOSFET threshold voltage at the ambient temperature of 25°C

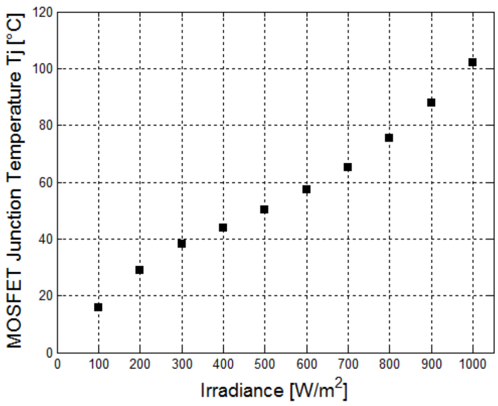

Fig. 3. MOSFET junction temperature.

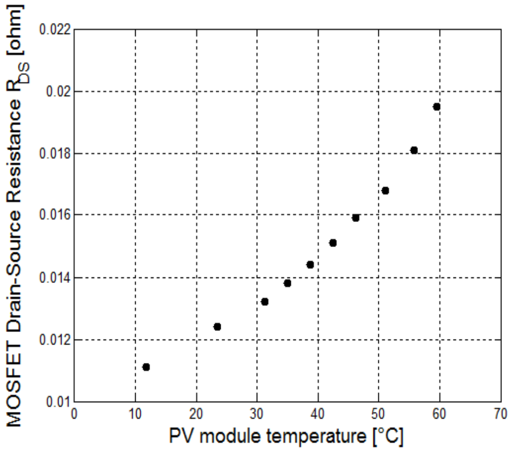

Fig. 4. MOSFET Drain-Source Resistance vs PV module temperature.

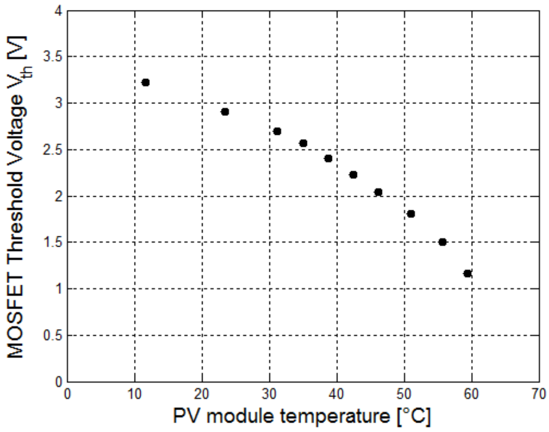

Fig. 5. MOSFET Threshold Voltage vs PV module temperature.

As shown in Fig. 3, regarding the ambient temperature values ranging from 9°C to 32°C, the MOSFET T_j can vary between 15°C and 102°C. However, its maximum value is lower than the recommended one (175°C), otherwise a suitable heat-sink could be necessary. Furthermore, increasing of the MOSFET drain-source resistance with the temperature and decreasing its threshold voltage with the temperature are observed, which are well known issues. The above reported graphs demonstrate that - for the considered PV module temperature range - a Power Optimizer MOSFET R_{DS} can reach values higher by 62% than the datasheet reference one, measured at the temperature of 25°C, while V_{th} can be lower by 60% than the value provided by the manufacturer.

In addition, details on changing inductor parameters caused by the thermal factor action are considered in [8,31] and partially reported below. The Eq.4 and Eq.5 describe the dependence of the inductor temperature and the coil resistance on the ambient ones.

$$T_L = T_a + T_r * 0.00385 * (234.5 + T_a), \tag{4}$$

$$R_L(T) = R_{L\_25^\circ C}\left[1 + \alpha(\mathrm{T} - 25^\circ C)\right], \tag{5}$$

where:

- T_L is the component temperature
- T_r is the data sheet temperature rise due to the rated current through the inductor
- α is the temperature coefficient of the resistance (for copper α= 0.00385/°C)
- R_L is the inductor resistance
- $R_{L\_25^\circ C}$ is the inductor resistance at the ambient temperature of 25°C

The R_L variations of the device under study versus the PV module temperature are shown in Fig. 6.

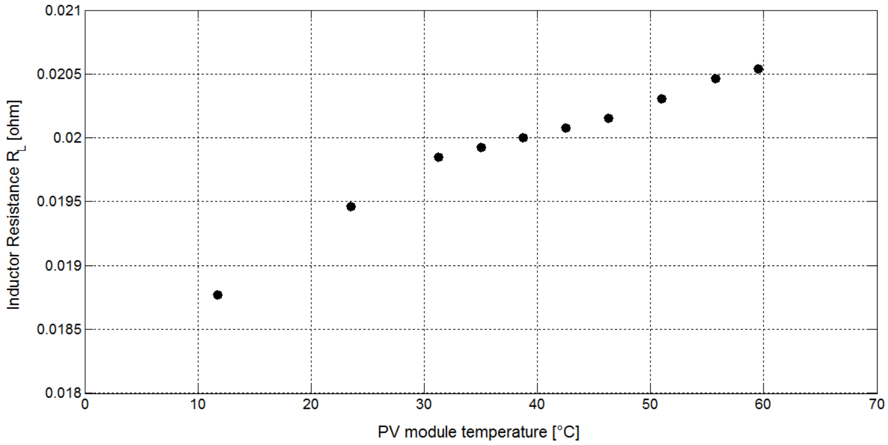

Fig. 6. Inductor resistance dependence on PV module temperature.

Since all the considered parameters are used to evaluate the converter losses and to estimate the complete DMPPT optimizer efficiency, the data provided by manufacturers at the specific ambient temperature of 25°C are not sufficient. In fact, during design and development processes, a suitable temperature monitoring system is necessary to diagnose possible warning or dangerous conditions.

3. Power Optimizers Reliability Assessment

The efficiency of a PV plant is guaranteed by the maintenance of its performance in time. This aspect involves the concept of Reliability. In fact, the reliability *R(t)* is defined in [9] as the probability that an item, in our case the PV plant, performs the required function, without a failure under stated conditions for a stated period of time. From the definition, it is evident that maintaining the reliability is an essential need in modern systems, especially in continuously changing working conditions of systems [10–21], such as the PV ones. In detail, the reliability engineering of an 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 the lifetime of PV generators. In this context, the reliability of each component of the PV system has to be carefully analyzed [22–28]. 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 application. In particular, the prediction allows to determine the system failure rate basing on the information collected in databases. In this work, the MIL-HDBK-217F NOTICE 2 [29] and the Siemens SN29500 [30] are taken into account in order to evaluate the reliability performance of a DR boost converter used as a module-dedicated power optimizer in PV plants. The MIL-HDBK-217 was developed by the US Department of Defense for the purpose, in the origin, of establishing and maintaining consistent and uniform methods for estimating the inherent reliability of electronic equipment and systems. As said above, the database is a collection of the field data, i.e. the data obtained for the system used outdoors in normal operating conditions of the temperature, humidity, and so on, and the data from laboratory, i.e. the data obtained in stress conditions, and being essential in the case of lack of the field data. In addition, another source of information consists of the results of the failure analysis performed on components and the experience acquired by specialists, the latter being of a fundamental importance during the data evaluation.

The availability of the laboratory data and the field data allows the MIL-HDBK 217 to be a reference database for industrial and commercial electronic equipment applications throughout the world. The handbook is intended as a guideline, not a specific requirement, for calculating the reliability of the equipment being designed. The MIL-HDBK-217F N2 estimates the system reliability relying on base failure λ_b rates for the components in the system. The base failure rates describe the components operating under "normal" (determined by the standard) environmental conditions. The base failure rates are then multiplied by 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 component of the DMPPT converter under study.

Table 1. 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} - the inductor base failure rate
λ_{b_cap} - the capacitor base failure rate
λ_{b_MOS} - the MOSFET base failure rate
λ_{b_diode} - the diode base failure rate

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

As said before, in addition to the MIL HDBK, another handbook was taken into consideration in order to compare results. We have selected the Siemens SN29500, a 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 wide basis 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 the 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 rate data at reference conditions, as well as the Part Count and Part Stress models necessary for reliability predictions. The adopted reference conditions are typical for the majority of systems applications. If operating conditions differ significantly from the reference ones, this model supports converting factors of the failure rates. The

SN29500 formulas to calculate the DMPPT converter device failure rates are shown in Table II.

Table 2. 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} - the inductor base failure rate
λ_{ref_cap} - the capacitor base failure rate
λ_{ref_MOS} - the MOSFET base failure rate
λ_{ref_diode} - the diode base failure rate

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

The reliability performance of the DMPPT power stage under investigation is evaluated with the converter failure rate calculation:

$$\lambda_{DR\_boost} = \lambda_{MOS} + \lambda_{Diode} + \lambda_{Indcctor} + \lambda_{InCap} + \lambda_{OutCap}. \quad (6)$$

The Eq. (6) is valid assuming a serial functional configuration, statistically independent parts and constant failure rates.
Therefore, the Mean Time Between Failures, in hours, can be expressed as follows:

$$MTBF_{DR\_boost} = \frac{1}{\lambda_{MOS} + \lambda_{Diode} + \lambda_{Indcctor} + \lambda_{InCap} + \lambda_{OutCap}}. \quad (7)$$

A comparison of reliability prediction results concerning the DMPPT converter components is summarized in Table III. The complete 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 the irradiance value of 1000W/m^2 and the ambient temperature of 32°C.

Table 3. Comparison between dr device failure rates calculated using the mil-hdbk-217fn2 and the siemens sn29500.

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

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

Table 4. DMPPT converter reliability performances.

DMPPT converter	*MIL-HDBK-217FN2*	*Siemens SN29500*
λ [h^{-1}]	$3{,}57 \cdot 10^{-06}$	$1{,}39 \cdot 10^{-06}$
MTBF [h]	280.264	717.875

From the data shown in Table III and Table IV, it is possible to see that the MIL-HDBK-217 reliability prediction is more conservative in comparison with that of the SN29500. The reason of this difference obviously stems from the original intended use of the MIL-HDBK-217 for aerospace, military, or mission critical applications. 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 an advantage, the MIL-HDBK-217 model contains more factors which may affect the device 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 study is merely a reliability qualitative analysis since the accurate investigation should not exclude the reliability of PCBs, connections and solder joints, as well as other aspects not considered in this paper.

4. Temperature Testing System

In order to satisfy the long-term reliability requirements, it is fundamental to verify the component stress level on the temperature, power, voltage, current, and energy in the DMPPT design phase. For example, using components ageing in high temperatures leads to a failure and shortening the service life of the equipment.
The measurement set-up used for monitoring the thermal tests proposed in this work is shown in Figure 7. It is made up by a thermal chamber with several type K thermocouples connected to a Data Logger HP 34470A. The thermal data are acquired and stored by a PC via RS 232. The DMPPT under test is powered and functioning during the test. Also the equipment under test is controlled by a PC via RS 232.

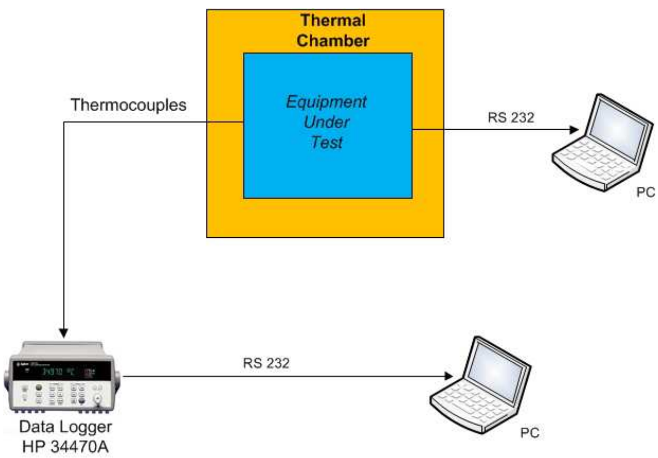

Fig. 7. Measurement set-up.

By means of a dedicated thermocouple it is possible to monitor the internal temperature that is also acquired by the PC.
The first thermal test phase was carried out with the internal temperature of the chamber of 50°C and using the device under test at the maximum operating temperature and at the maximum output power. The aim is to put in evidence the behavior of the critical components.

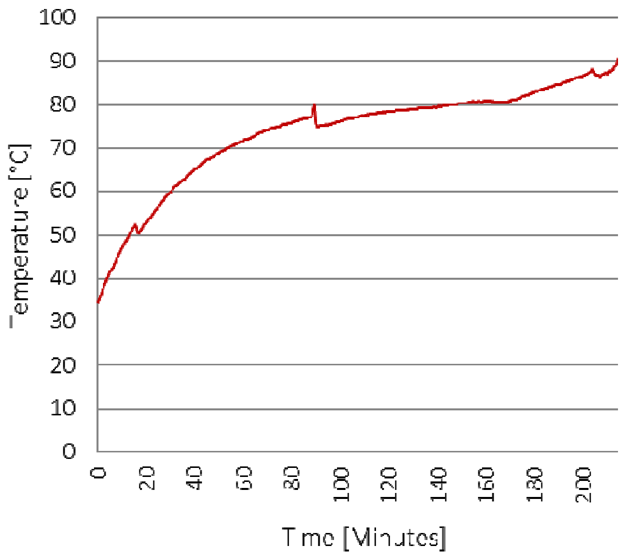

Fig. 8. MOSFET temperature vs time.

Figure 8 shows the temperature trend in function of time for a MOSFET. It is possible to observe a constant increase of the temperature without a stabilization due to an anomalous behavior of the MOSFET. This trend represents a typical case of an uncorrected operation of the equipment with the presence of the thermal escape that could lead to a failure of the device.
In detail, the experimental activity confirms that for the MOSFET the case temperature higher than 75°C (or the junction temperature higher than 100°C) is considered an unsafe condition due to the high thermal stress. At this temperature, a short circuit event could happen at any moment.

In Figure 9, the temperature of capacitors shows that there are no problems in functioning of these components, but taking into account the temperature of almost 80°C it could lead also to an increase of the temperature of other internal components.

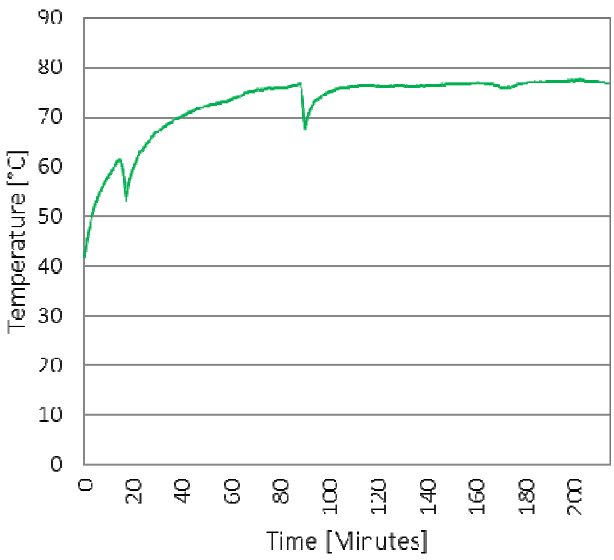

Fig. 9. Capacitor temperature vs time.

Therefore, a design upgrade is necessary to avoid the particular temperature trend in the PCB area where the MOSFET is located. In particular, two cooling fans are added and a new hot air path is provided.
In Figure 10 the temperature trend of the MOSFET after the design modifications is shown. Now it is possible to note a normal trend in function of the time and the temperature is stabilized below 70 °C. In this case the DMMPT is working properly and, more important, thanks to the decrease of the operating temperature it is possible to obtain an increase of its operating life.

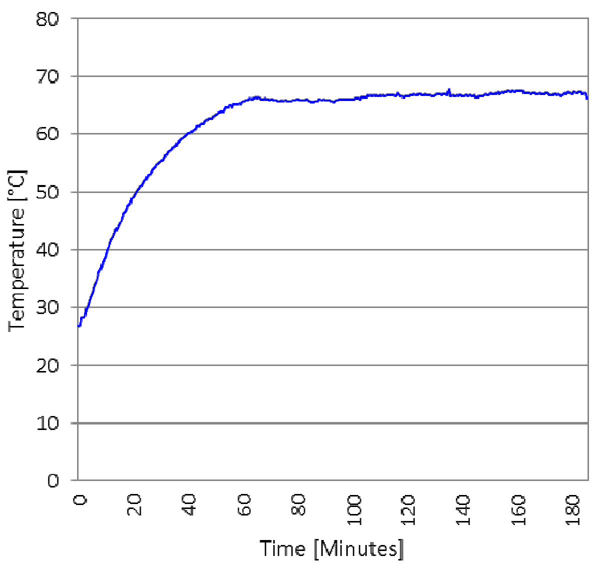

Fig. 10. MOSFET temperature vs time after design upgrade.

By using both the reliability prediction data and the experimental results, it has been possible to optimize the DMPPT design and the operating performance. In fact, throughout the design process, a particular attention has been put to the selection of the most critical components that would perform in the best way under the thermal and electrical stress.

In terms of the maintenance it is important to remember that a new equipment begins to deteriorate with its installation. This is normal and - if uncontrolled - the deterioration can progress and lead to an equipment fault or failure. As already said, harsh environmental conditions and system stresses, such as an overload, a severe duty cycle, load increases, circuit alterations, and changing voltage conditions can accelerate the deterioration process. An effective preventive maintenance program can detect and mitigate these conditions. The overall availability of the system depends also on the repair time, i.e. how long a unit is offline after a failure. To reduce the downtime due to the maintenance and repair, the DMPPT must be designed allowing an easy replacement of the components and boards in the field. The approach described in this paper allows also the optimization of the maintenance scheduling.

5. Conclusions

In this paper, the reliability evaluation in PV systems is considered, focusing - in detail - on the DMPPT DR boost converter reliability performance. The Power Optimizer component failure rates and MTBF are calculated using two different reliability prediction models: the Military Handbook 217F Notice 2, and the SN29500 Version 1. The carried out analysis underlines that the MIL-HDBK-217 reliability prediction is more conservative in comparison with that of the SN29500 one, since it was destined to very critical applications and due to the number of component stress factors considered.

In order to satisfy the long-term reliability requirements, it is fundamental to verify the component stress level on the temperature, power, voltage, current, and energy in the DMPPT design phase. For this reason a dedicated measurement set-up was developed to monitor the behavior of the most critical components.

The information obtained by means of the reliability prediction is fundamental to optimize the diagnostic strategy and to develop a more appropriate measurement test setup. In fact, it is possible to indicate the most critical components from the reliability point of view and therefore to suitably monitor it that also allows to avoid the occurrence of component failures that might decrease the service life of the equipment. Moreover, the reliability model can be also used to assess the key product parameters (voltage, temperature and so on) in order to perform device stress and derating analyses.

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