15th IMEKO TC10 Workshop on Technical Diagnostics
Technical Diagnostics in Cyber-Physical Era
Budapest, Hungary, June 6-7, 2017

# A Statistical Algorithm for Photovoltaic Modules Reliability Assessment

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*Abstract* **–In this paper, a statistical algorithm for the assessment of Photovoltaic (PV) modules reliability is presented. The algorithm is based on the application of Monte Carlo simulations for the propagation over time of the stochasticity of the various failure modes occurrence time and their effect on the output power degradation.**

## I. INTRODUCTION

Photovoltaic (PV) modules are often considered as the most reliable element in PV systems. The high reliability associated to PV modules is indirectly reflected in the output power warranties usually provided in this industry. A PV module warranty usually refers to two different items [1]:

- a warranty for materials and workmanship, which usually ranges from 1 to 5 years;
- a warranty on the power produced by the PV module which typically guaranties that the output power of the module will be at least 90% and 80% of its initial nominal power after the first 10–12 years and 20–25 years of operation respectively.

The producers expectations, however, are usually based on laboratory tests performed in standard conditions that may largely differ from the field conditions in which the modules operate.

The scope of this work is the definition of an algorithm for the assessment of the field reliability of Photovoltaic Modules. In particular, a deep literature investigation has been carried out for the definition of the most relevant failure modes and the associated occurrence statistical distributions, which heavily depends on the geographical area of installation. The impact of each failure mode on the output power of the module is then evaluated through a physical model that allows to include in the analysis technical features of the module such as number of cells, their active area, the type of connection between the cells, the number of bypass diodes and so on.

## II. PV MODULE PHYSICAL STRUCTURE

A PV module is typically constituted by a number $N_{cell}$ of series-connected cells. The cells represent the core of PV production, as they are devoted to the conversion of the solar radiation into electrical power. A key role, however, is played also by the bypass diodes (BDs) that are used to minimize the power losses due to modules shading and hotspot phenomena. Typically, if a module is equipped with a number $N_{bd}$ of bypass diodes, each diode is connected in antiparallel to a group of $N_{c,bd}$ cells, being $N_{c,bd}$ equal to the ratio between $N_{cell}$ and $N_{bd}$. Such configuration is represented in Fig. 1 where a module characterized by $N_{cell}$=36, $N_{bd}$=2, $N_{c,bd}$=18 is taken into account.

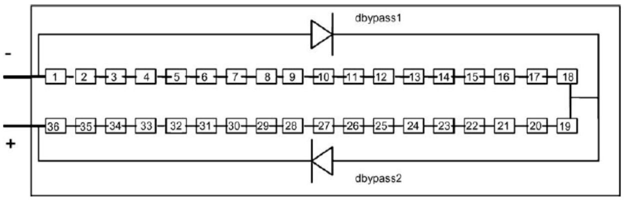

*Fig. 1 PV module with 36 cells in series and 2 bypass diodes [2]*

However, this is not the only possible architecture. Other configurations and the related benefits and drawbacks are analyzed in [2].

In the normal operation of a PV module, bypass diodes are reverse biased so that the current flows through all the cells. When a group of cells becomes shaded or a hotspot occurs, however, they experience a decrease of their short circuit current, which may fall to a value lower than the current imposed by the healthy cells. The only way for a cell to operate at a current higher than its short circuit current is to operate in a region of negative voltage. It is trivial to understand that such situation would cause a decrease of the module output voltage. One way to minimize this effect is to use bypass diodes. The Kirchhoff Voltage Law establishes that, because of the antiparallel connection, the voltage $V_{bd}$ across each bypass diode is equal to:

$$V_{bd} = -\sum_{i=1}^{N_{c,bd}} V_i \tag{1}$$

being $V_i$ the voltage across each single cell. A bypass diode enters in conduction state if its voltage is higher than a certain threshold $V_T$, that is, from (1), if the following condition $C$ is met:

$$C : -\sum_{i=1}^{N_{c,bd}} V_i \geq V_T \qquad (2)$$

The forward bias of the bypass diode ensures a voltage output for the related group of cells equal to $V_T$; such voltage is larger than the voltage that would be obtained without the intervention of the diode, so that a limitation of the power loss is guaranteed. It is important to highlight the importance of the bypass diodes also from a reliability point of view. The intervention of the diode in condition of shading, indeed, prevent the shaded cells to operate for long time in a region of negative voltage (where they behave as load for the rest of cells so that the power is dissipated through them) which may cause a significative raise of their internal temperature and potentially a permanent degradation.

## III. PV MODULE RELIABILITY STRUCTURE

The Reliability Block Diagram (RBD) of a PV module can be represented as a series structure of $N_{bd}$ identical subsystems, each of which is composed by $N_{c,bd}$ cells connected in series (in the following referred as PV block (PVB)) and a bypass diode in standby redundancy. In particular, the diode works only when condition $C$ is met, that is after a failure of the related PVB. The proposed RBD is represented in Fig. 2.

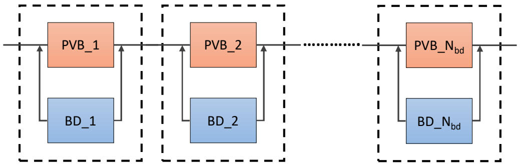

*Fig. 2 RBD of a PV module*

The series connection in the RBD implies that the failure of a PVB and of the related BD represents a critical failure for the PV module. In particular, a PV module is considered to have failed its mission if either such condition is verified or a power loss higher or equal to a limit of 20% of its nominal power occurs.

## IV. PV MODULE FAILURE MODES ANALYSIS

The analysis of PV modules failures reports found in the literature has led to the definition of the most relevant failure modes. In particular, starting from the results presented in [3][4] it can be stated that the most predominant failure modes affecting the power delivery of a PV module are the followings:

- Aging
- Hotspot formations
- Cell cracks

For what concerns aging phenomenon, PV modules can experience a degradation of their performance as result of different factors such as degradation of packaging materials, of cell interconnection, of the semiconductor device, moisture introduction and loss of adhesion of encapsulants. In the case of traditional crystalline silicon PV modules, however, the degradation of the semiconductor is not important because of the stability of the semiconductor material. Field experience, indeed, indicates that the primary causes of performance losses are associated with mechanisms external to the cell itself such as solder joints, encapsulant browning, delamination and interconnection problems [1].

Hot spots heating occurs in a PV module when the current capability of a particular cell or group of cells is lower than the operating current of the cells string. As already said, this condition results in a substantial temperature raise of a single cell or portion of cells so that hotspots will permanently degrade the PV module and decrease its overall performance.

Cells cracking is a common problem encountered in PV modules. They may develop in different stages of the module lifetime: during manufacturing when the soldering induces high stresses into the solar cells but also handling and vibrations in transportation can induce or expand cracks. Finally, a fielded module experiences mechanical loads due to wind (pressure and vibrations) and snow (pressure).

Table 1 reports all the possible states in which a PVB may be found.

*Table 1 PVB possible states*

| State | Index |
|---|---|
| Healthy state | 0 |
| Hotspot occurrence | 1 |
| Crack occurrence | 2 |
| PVB not bypassed (no verification of condition C) after a crack occurrence | 3 |
| PVB bypassed (verification of condition C) after a crack occurrence | 4 |
| Crack and hotspot occurrence | 5 |

As for the bypass diode, it is considered to have reliability equal to 1 when in inactive state, whereas it can be characterized by only two states when forward biased, that is either healthy or failed.

A simplified transition state diagram for a single PVB is represented in Fig. 3:

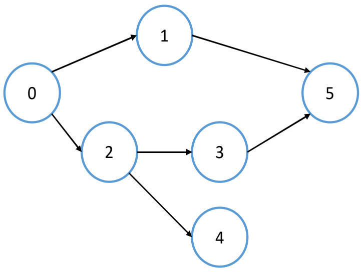

*Fig. 3 PVB state transition diagram*

In particular, it is possible to observe that the formation of a hotspot (state 5) after a crack occurrence (state 2) may take place only if the crack failure mode has not caused the activation of the bypass diode (state 3). Conversely, being the failure mechanism leading to crack development of mechanical nature, the occurrence of the crack failure mode after a hotspot formation is always possible.

### A. Failure modes occurrence

In Table 2, the occurrence statistical distribution of hotspots and cracks in the photovoltaic blocks and of the bypass diodes failure are reported.

*Table 2 PV module failure modes occurrence*

| Component | Failure Mode | Statistical Distribution |
|---|---|---|
| PVB | Hotspot | Weibull [5]:<br>scale $\lambda_{occ,hs}$=29.1371 year<br>shape $k_{occ,hs}$=5.0164 |
| PVB | Crack | Exponential [6]:<br>$\lambda_{occ,cr} = 0.7387$ year$^{-1}$ |
| BD | BD failure | Exponential [4]:<br>$\lambda_{occ,BD} = 0.0059$ year$^{-1}$ |

As for the aging, it is considered to act constantly over time.

### B. Failure modes effects on output power

The power losses determined by each PVB failure mode (i.e. the failure of the bypass diode is not considered) are reported in Table 3.

*Table 3 PVB failure modes effects on output power*

| Failure Mode | Power Loss |
|---|---|
| Aging | Weibull distribution [7]:<br>scale $\lambda_{PL,ag} = 0.0490$ %/year<br>shape $k_{PL,ag} = 1.0871$. |
| Hotspot | Activation of the bypass diodes (i.e each activated diode implies a percentage of power loss equal to 100/$N_{bd}$). |
| Crack | A cell affected by a crack can be modeled as a cell of smaller active area connected in parallel with a resistance. The number of cells affected by crack, the value of new active area and of the parallel resistance are stochastic parameters which depends on the type of occurred crack. More details can be found in Section V, sub-section C. |

The failure of the BD is not associated to a power loss as it represents a critical failure of the PV module such that it would be considered to have failed its mission.

## V. PV MODULE RELIABILITY ASSESSMENT

The reliability assessment methodology presented in this work is based on the idea to simulate the occurrence of failures and the corresponding power loss profile over time up to a Mission Time (MT) through the application of Monte Carlo (MC) simulations. In particular, the simulations are repeated for a very high number *NMC* (number of MC) of times, so that a high number of estimates of module failure time are obtained. This number may be lower than *NMC* if the module failure is not generated in some simulations. Finally, it is trivial from these results to estimate the PV module failure cumulative distribution function and reliability function over time. A schematization of the proposed framework is proposed in Fig. 4.

### A. Generation of hotspots and cells crack occurrence time

It has been already stated that aging acts continuously over time, whereas the bypass diode failure is verified only if it enters the conduction state after a failure of the related PVB. It follows that the first step of the methodology is the generation of occurrence of hotspot and cell cracks phenomena. The occurrence time of such failure modes, denoted respectively as $t_{Fail,hs}$ and $t_{Fail,cr}$, is randomly generated according to the Inverse Transform Sampling Method (ITSM) starting from the corresponding statistical distributions presented in Table 2. A time indicator $t$ is initialized and increased step by step. When the time indicator $t$ is equal to whether $t_{Fail,hs}$ or $t_{Fail,cr}$, the features of the corresponding failure mode are generated.

### B. Generation of hotspot failure

In reality, a hotspot may occur in the same PV module for more than one cell. A realistic approximation introduced in the model is that the hotspot formation may occur only once during the module life and that the cells affected by such failure mode belong to the same PV block (i.e. they are connected to the same bypass diode). Therefore, if the module is equipped by $N_{bd}$ diodes an integer number $N_{hs}$ between 1 and $N_{bd}$ is extracted, so that the $N_{hs}$-th block will undergo a state transition according to Fig. 3.

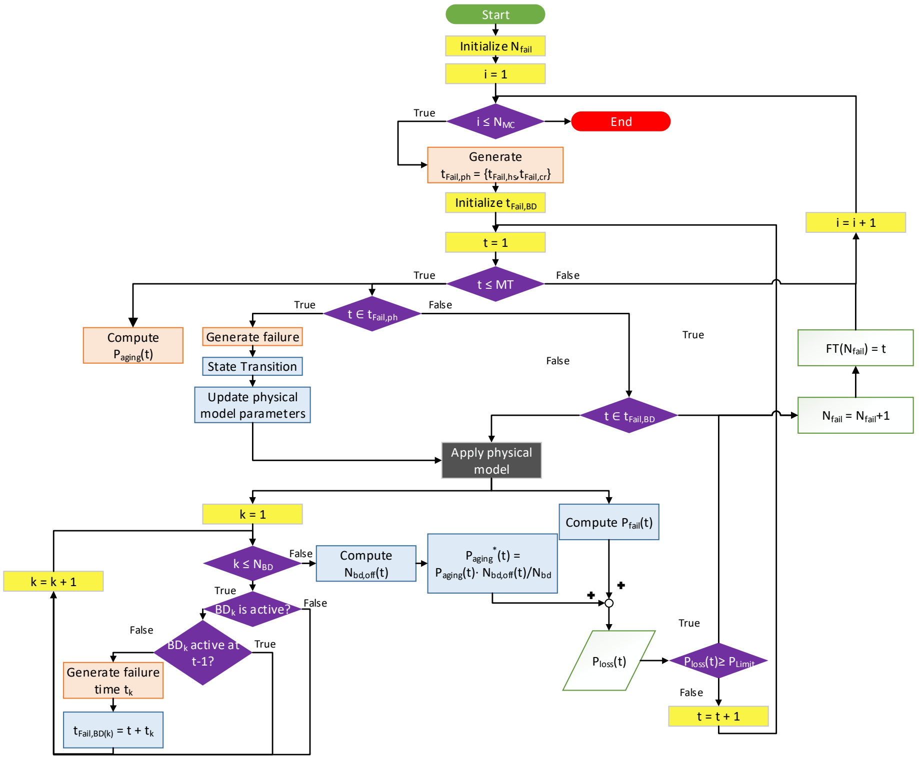

*Fig. 4 Proposed framework for the evaluation of the reliability of a PV module*

## *C. Generate cells cracks failure*

In order to simulate cells crack phenomenon the reference [6] is taken into account. According to the authors, the number of cells experiencing such failure mode is random. Further, each cells may undergo different types of crack (7 type of cracks have been identified) at each of which corresponds a different value of percentage of cell broken area. In particular, a cell crack may be modelled through the insertion of breaking resistance $R_b$ in parallel to the cell itself. A typical value for $R_b$ is in the range [0.01, 10] Ω. However, breaking resistance up to $10^4$ Ω may occur. In this work, we exploit the data provided in [6] about the statistical distributions of the number of broken cells in a cracked module, occurrence probability of each failure type and corresponding extent of broken area. Starting from these statistical distributions, a random number of cracked cells is generated through the ITSM; then, applying the same technique, for each broken cell, a failure type is extracted and the broken area is selected from the statistical distribution associated to that failure type. At this point, it is intuitive to correlate the value of breaking resistance $R_b$ to the amount of broken area $BA$. For this purpose, the following relation, based on the experimental results reported in [6] and on the personal experience of the authors, is proposed:

$$R_b = \begin{cases} \dfrac{10}{80} BA & \text{if } BA \le 80\% \\ 10^{\frac{3(BA-80)}{20}+1} & \text{if } BA > 80\% \end{cases} \tag{3}$$

that is $R_b$ increases linearly up to a value of 10 Ω for broken area percentage $BA$ lower than 80%. Then, for value of $BA$ between 80% and 100% the value of $R_b$ increases exponentially (maximum value $10^4$ Ω when BA=100%) in order to emphasize the high electrical resistance determined by the physical structure of a PV cell severely damaged by the crack.

## *D. Output Power Computation*

In order to determine the power output of the module the physical model presented in [8] is considered. Such model determines the relationship $V(I)$ between output voltage $V$ and current $I$ of a PV cell based on physical parameters. In particular, the cell is modeled through the inclusion of three diodes, one avalanche diode $D_A$ to simulate the reverse current behavior of the cell and two recombination diodes $D_1$ and $D_2$. The current $I$ is modeled as sum of three contributions:

$$\begin{aligned} I = I_{D1}\left(V_{int}, j_{01}, A_{act}\right) + I_{D2}\left(V_{int}, j_{02}, A_{act}\right) - \\ I_R\left(B_e, V_b, \phi_T, V_{int}, j_{sc}, R_p, A_{act}\right) \end{aligned} \tag{4}$$

where $I_{D1}$ and $I_{D2}$ are the currents through the diodes

$D_1$ and $D_2$,respectively, which are function of the cell internal voltage $V_{int}$, the diodes saturation current ($j_{01}$ and $j_{02}$) and the cell active area $A_{act}$. The reverse current $I_R$, instead, is function of $V_{int}$, the short current density $j_{sc}$, the cell parallel resistance $R_p$, the active area $A_{act}$ and the parameters $B_e$, $V_b$ and $\phi_T$, which are related to the reverse $V$-$I$ characteristic of the cell. A compact formula for the computation of $I_R$ is provided in [9] where also a methodology for the determination of the parameters of the reverse characteristics is presented. The reference [10] instead proposes a simple method for the characterization of the two recombination diodes $D_1$ and $D_2$. Finally, the output voltage of a cell is equal to:

$$V = V_{int} - R_s\left(A_{act}\right)I \tag{5}$$

where is taken into account the voltage drop across the series resistance $R_s$ which is a lumped parameter describing the series resistance of the cell, the interconnectors and the contact resistance between interconnector and cells. Also the value of $R_s$ depends on the active area of the cell.

If it is assumed that the module is controlled by a DC-DC converter, which makes the module to work at the maximum power point, the module output power can be expressed as:

$$P = \max_{I}\left(\sum_{i=1}^{N_{cell}} V_i(I)I\right) \tag{6}$$

where $I$ is the current flowing in the module and $V_i$ is the voltage across each cell, which depends on their state. In particular:

$$V_i = \begin{cases} V\left(I, A_{act}\right) \text{ if cell } i \text{ in state 0} \\ V_{R_b,cr}\left(I, A_{act}^{'}\right) = V\left(I^{*}, A_{act}^{'}\right) \text{if cell } i \text{ is cracked} \\ 0 \text{ if cell } i \text{ is bypassed} \end{cases} \tag{7}$$

where $V_{Rb,cr}(I,A'_{act})$ represents the characteristic of a cracked cell with breaking resistance $R_b$ and active area $A'_{act}$, which is a percentage of the nominal active area $A_{act}$ depending on the percentage of broken area $BA$. It is easily demonstrable that the voltage $V_{Rb,cr}(I,A'_{act})$ is equivalent to the voltage $V$ of a not cracked cell with active area $A'_{act}$ generating a current $I^{*}=I+V/R_b$. A cell is bypassed if whether is in state 1 or it is cracked and the converter sets a working current $I$ such that the related bypass diode is conducting (state 4). If at time $t$ the $k$-th bypass diode is activated as consequence of failure of the $k$-th PVB, a time failure $t_k$ for that diode is generated according to the statistical distribution reported in Table 2. Since the diode is activated at time $t$, however, the actual time failure of the diode $t_{fail,BD(k)}$ will be equal to $t+t_k$.

### *E. Power Loss Computation*

The power loss $P_{loss}(t)$ at time $t$ of a PV module with respect to its nominal power, can be expressed as sum of two contributions:

$$P_{loss}(t) = P_{fail}(t) + P_{aging}^{*}(t) \tag{8}$$

In particular $P_{fail}(t)$ is the total power loss computed as percentage difference between the nominal power of the module and the power computed in (6). $P^{*}_{aging}(t)$ instead is the loss due to the aging of the module. More in detail:

$$\begin{cases} P_{aging}(t) = P_{aging}(t-1) + p \\ P_{aging}^{*}(t) = \dfrac{N_{bd,off}(t)}{N_{bd}} P_{aging}(t) \end{cases} \tag{9}$$

where $N_{bd,off}(t)$ is the number of the reverse biased bypass diodes ($N_{bd,off}$ multiplied by $N_{cell,bd}$ is equal to the number of conducting cells) at time $t$ and $p$ is an increment of power loss due to aging computed at each iteration step according to the statistical distribution reported in Table 3. In particular, $P^{*}_{\text{aging}}(t)$ is proportional to $N_{bd,off}$ since the power loss due to bypassed (hence not conducting) cells is already taken into account through $P_{fail}(t)$.

A single MC simulation is ended when the time indicator is equal to MT.

## VI. RESULTS

The methodology presented in Section V has been applied to two different PV modules equipped with the same number of cells ($N_{cell}$=60) but different number of bypass diodes (6 in the first case and 3 in the other one). The two modules have the same constructive parameters; in particular, the parameters presented in Table 1 in [8] are considered. The obtained results are reported in Fig. 5.

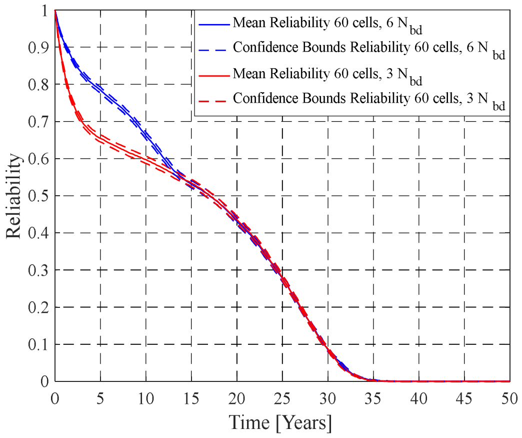

*Fig. 5 Reliability of two PV modules with equal number of cells ($N_{cell}$=60) but different number of bypass diodes, $N_{bd}$=6 for blue curves and $N_{bd}$=3 for*

*red curves*

The confidence bounds have been obtained applying the bootstrap technique to the generated sample of module failure time estimates.

It was expected the module equipped with a higher number of bypass diodes having a higher reliability than the module with less diodes. The power loss due to the forward conduction of a diode in the case of $N_{bd}$=6, indeed, leads to a power reduction of 16.67% (less than critical power loss of 20%) whereas in case of $N_{bd}$=3 it is sufficient a single diode in conduction (power loss 33.33%) to overcome the critical threshold. However, from Fig. 5, it is evident that the differences in the reliability curves are verified only in the first phase of the lifetime since between 10 and 15 years the reliability of the two modules becomes practically equal. The reason of this behavior has to be found in the fact that at that time the effect of aging is prominent, so that, no matter the number of the diodes present in the module, the activation of just one of them contributes to overcoming the loss threshold of 20%. The producers usually guaranty that after 20–25 years of operation the output power of the module will be at least 80% of its initial nominal power. Simulations, however, have shown that in the interval 20-25 years the modules reliability ranges in the interval of about 0.30-0.45 highlighting how the field exposure conditions of the modules affect their performances and decrease their reliability with respect to producers expectations which are usually based on laboratory tests performed in standard conditions.

## VII. CONCLUSIONS

In this paper, a statistical methodology for the reliability assessment of PV modules is presented. The proposed framework is based on the application of Monte Carlo simulations for the propagation of the stochasticity of the different failure modes occurrences and their effect on the power degradation. The model is easily applicable to PV plants operating in different climate areas. Nevertheless, the introduction of a physical model for the calculation of the power loss due to failures enables to customize the model according to the constructive parameters of the module such as number of cells, number of bypass diodes, cells active area and so on. The results have highlighted how a higher number of diodes in the module guarantees a higher reliability, but only during the first years of operation, since at around 10-15 years the effect of the aging becomes prominent so that the reliability performances of modules with different number of diodes are practically equal. Finally, it has been demonstrated that the field exposure conditions heavily affect the module reliability as at the 20-25 years of warranty claimed by producers only a percentage in the range of 30-45% of modules delivers an output power higher or equal than the 80% of the nominal power.

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