Reliability and availability estimation of a photovoltaic system using Petri networks

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ABSTRACT: Many photovoltaic (PV) systems are nowadays installed all around the world. However, the reliability and the availability estimation of photovoltaic systems have not been received great attention from researchers. Reliability and availability are important consideration in the life-cycle of such systems. This paper presents a methodology for estimating the reliability and the availability of a photovoltaic system using Petri networks. Each component - module, wires and inverter - is detailed in Petri networks and several laws are used in order to determine the reliability and system availability. The degradation function of each component has been taken into account. Results show that Petri networks simplify the reliability and availability modeling and analysis.

1 INTRODUCTION

Photovoltaic (PV) systems are installed all around the world to produce electricity from solar energy. However, photovoltaic modules and systems lifetime and availability have not been received great attention from researchers. These estimates are important to insure the performance (MTBF, number of outage days per year and steady state availability) of such a system over its life cycle.

Reliability and availability of a stand-alone photovoltaic system are discussed by Díaz et al. (2007) using exponential law for different components. They use operational photovoltaic systems data deduced from feedback record by Jahn & Nasse (2003) and Maish et al. (1997).

In this paper, we propose a methodology using Petri networks to estimate the reliability and availability of a photovoltaic system. The main advantage of Petri networks is the ability to simulate large systems with a complex configuration of its components, while considering many types of lifetime distributions. Laronde et al. (2010a) studied a photovoltaic system using Petri networks assuming constant failure rate for each component. The main objective of this paper is to take into account the components’ degradation and the power evolution of the photovoltaic system.

We first present the photovoltaic system under study, and then an overview of Petri networks, followed by modeling of the system as a Petri network. Finally, a simulation using several photovoltaic arrays is carried out and reliability and availability are estimated. The influence of the installation parameters and the capacity of the repair facility on system power output and availability are investigated.

2 PHOTOVOLTAIC SYSTEM

The system under study is a grid-connected photovoltaic system as shown in Figure 1. This system consists of a photovoltaic array with modules connected in a series-parallel configuration and balance-of-system (BOS) components which are not photovoltaic components: there are an inverter which transforms the direct current from photovoltaic array to alternating current and wires which transmit the continuous energy from PV modules to an inverter (DC wires) and a wire which transmits the alternating energy from the inverter to the electric grid (AC wire).

Photovoltaic modules are connected in a series-parallel configuration in order to obtain significant power by balancing the voltage and amperage delivered to the inverter. Generally, two DC wires are used to connect photovoltaic modules to the inverter.
The size of a photovoltaic installation is determined using the peak power of the photovoltaic array. This corresponds to the photovoltaic array output power when there are an irradiance of 1000 W.m$^{-2}$ and a module temperature of 25°C (IEC 61215 standard for crystalline silicon modules, IEC 61646 standard for thin-film modules and IEC 62108 standard for contractor modules). A photovoltaic system is considered failed when no output electricity which occurs when the irradiance is less than or equal to 1000 W.m$^{-2}$ and the modules temperature is less than or equal to 25°C.

3 AN OVERVIEW OF PETRI NETWORKS

3.1 Petri networks: working states

Petri networks can be used for modeling the working and non-working states of complex systems (Charki et al. 2009). This method provides a convenient graphical representation of a place-transition net which consists of (Demri et al. 2008):
- places $P_i$ (drawn by a circle) which model states or objects,
- tokens (drawn by black dots) which represent the specific value of the states or objects,
- transitions $T_j$ (drawn by rectangles) which model activities that change the values of states and objects,
- arcs which specify the interconnection of places and transitions thus indicating which objects are changed by a certain activity.

Petri networks present an accurate depiction that describes the process of sequential dynamics of a photovoltaic system. The evolution of a dynamic system can be seen in terms of the markers (number of tokens in places). Figure 2 illustrates a simple example in order to explain the principle of a Petri network.

![Figure 2. Working states of a Petri network (T1, T2: working transitions).](image)

This network has no failures and T1 and T2 are representing transitions from state $P_1$ to $P_2$ and inversely.

In classical Petri networks, durations are not taken into account. The synchronized Petri networks consider external events and associated transitions. A Petri network is called temporized when durations are associated with space network ($P$-temporized) or transitions ($T$-temporized). Stochastic Petri networks take into account probabilistic transition durations.

3.2 Petri networks: non-working states

The non-working part can be modeled in similar way to the working part of the system. Figure 3 shows the Petri network for both working and non-working states.

![Figure 3. Petri Network for both working and non-working states (T3: P2 component failure, T4: P2 component repair).](image)

Different lifetime distributions can be used for the failure transition $T_3$. When the failure rate $\lambda$ is constant, the exponential distribution is used and the failure probability at time $t$ (Yang 2007), is expressed as follows:

$$P_f(t) = 1 - e^{-\lambda t} \quad (1)$$

Weibull distribution is one of the most widely used lifetime distributions when the failure rate is non-constant (Nelson 1990). It is a versatile distribution based on respectively the value of shape and scale parameters $\beta$ and $\eta$. The failure probability is:

$$P_f(t) = 1 - \left(\frac{t}{\eta}\right)^\beta \quad (2)$$

In general, the repair rate $\mu$ is assumed constant. Therefore, the repair probability is expressed as follows:

$$P_r(t) = 1 - e^{-\mu t} \quad (3)$$

3.3 Availability and reliability

The instantaneous availability $A_S(t)$ of a system $S$ at time $t$ is the probability that the system is in operating condition at time $t$. $A_S(t)$ and the reliability $R_S(t)$ of a system (Laronde et al. 2010a) are determined for several components in a series-parallel configuration ($m_i$ components connected in series to form subsystem $i$ and $n$ subsystems connected in parallel to form the system $S$) as:
\[ A_i(t) = 1 - \prod_{j=1}^{n} \left( 1 - A_j^m(t) \right) \]  
(4)

\[ R_i(t) = 1 - \prod_{j=1}^{n} \left( 1 - R_j^m(t) \right) \]  
(5)

\( A_i(t) \) and \( R_i(t) \) are respectively the availability and the reliability of component \( i \) at time \( t \).

When the time-to-failure and the time-to-repair follow exponential distributions, the component availability is given by the following expression:

\[ A_i(t) = \frac{\mu_i}{\mu_i + \lambda_i} + \frac{\lambda_i}{\mu_i + \lambda_i} e^{-(\mu_i + \lambda_i)t} \]  
(6)

Let us consider for example a series system, its availability is:

\[ A_S(t) = \prod_{i=1}^{n} \left[ \frac{\mu_i}{\mu_i + \lambda_i} + \frac{\lambda_i}{\mu_i + \lambda_i} e^{-(\mu_i + \lambda_i)t} \right] \]  
(7)

and the asymptotic availability, defined for an infinite duration, is:

\[ A_S(\infty) = \prod_{i=1}^{n} \left[ \frac{\mu_i}{\mu_i + \lambda_i} \right] \]  
(8)

However, as we show later, time to failure and time to repair do not usually follow exponential distributions for photovoltaic systems. Therefore the use of MOCA-RP\textsuperscript{c} software is necessary to simulate the availability and the reliability of such complex system.

4 PHOTOVOLTAIC SYSTEM DESCRIPTION USING PETRI NETWORKS

4.1 Working system

As mentioned before, a photovoltaic system is composed of photovoltaic modules, wires and inverter. All these components are connected in series. Thus, if a component fails, the system fails. The functional Petri network of a photovoltaic module is illustrated in Figure 4 (path from \( T_1, T_2, T_3, T_4, T_5 \) with a place for each kind of components: \( P_2 \) for photovoltaic array, \( P_3 \) for DC wires, \( P_4 \) for inverter and \( P_5 \) for AC wire. \( P_1 \) is a waiting place for the Petri network.

The time to transmit the electric power in the different components of photovoltaic system is instantaneous. Using a classical Petri network, time is not taken into account in working transitions (\( T_1, T_2, T_3, T_4 \) and \( T_5 \)). Thus, we use a temporized Petri network using a delay of one hour for the transition \( T_1 \) to separate the simulation in discrete time steps.

4.2 Non-working system

For each component, the non-working system is shown in the bottom of Figure 4. Non-working transitions \( T_6, T_8, T_{10} \) and \( T_{12} \) correspond to the time to failure of the different components of the photovoltaic system. Transitions \( T_7, T_9, T_{11} \) and \( T_{13} \) allow taking into account the time to repair of the components.

The initial condition (system in state \( P_1 \)) of the Petri network, as shown in Figure 4, is:

\( (P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, P_9, P_{10}) = (1,0,0,0,0,0,0,0,0,0) \).

4.2.1 Photovoltaic array

Gautam & Kaushika (2002) and Ristow et al. (2005) propose different methods to estimate the failure probability of photovoltaic arrays, which consists of modules connected in series, parallel and series-parallel.

In the Petri networks under study (Fig. 4), the transition \( T_6 \) corresponds to the failure probability of the photovoltaic array. In our case, the failure probability of a series-parallel array made up of \( n \) series of \( m \) photovoltaic modules connected in parallel can be estimated by:

\[ P_f(t) = \prod_{j=1}^{n} \left( 1 - \prod_{i=1}^{m} (1 - P_{ji}(t)) \right) \]  
(9)

The failure probability of each photovoltaic module is taken into account in order to estimate the failure probability of the photovoltaic array. To estimate the failure probability of a photovoltaic module, we need to identify the failure modes of the modules. The major failure modes for crystalline silicon modules are (Wohlgemuth & Kurtz 2011):

- Broken interconnects
- Broken cells
- Corrosion
- Delamination of encapsulants
- Encapsulant discoloration
- Solder bond failure
- Broken glass
- Hot spots
- Junction box failures
- Bypass diode failures.

For each failure mode, the failure probability can be estimated by carrying out a feedback analysis or by conducting accelerated life testing (Wohlgemuth & Kurtz 2011). In order to estimate the failure probability using accelerated life testing, it is possible to use the methodology presented by Laronde et al. (2010b, 2011). The main factors they consider are temperature, relative humidity and UV radiation (which generate corrosion, junction box adhesion, delamination of encapsulant and encapsulant discoloration).

In the transition $T_6$ of the Petri network, the major failure modes of the modules are taken into account as shown in Figure 5.

![Petri Network Diagram](image)

**Figure 5. Details of the failure modes of transition $T_6$.**

### 4.2.2 Wires

Wires are considered to be secondary components but important for the transmission of the electricity. The main failure mode of wires is the oxidation of the connector.

Guides using data obtained from feedback in transport and military domains (FIDES, MIL-HDBK-217) can be used to determine failure probabilities of DC and AC wires. Thus, the failure probability is considered to follow an exponential distribution because guides give constant failure rates. In our case, FIDES Guide provides failure rates of $48.3 \times 10^{-9} \text{ h}^{-1}$ for the DC wires of 1 meter and $13 \times 10^{-9} \text{ h}^{-1}$ for the AC wire of 1 meter.

#### 4.2.3 Inverter

The inverter is an expensive and complex component in a photovoltaic system; the majority of system failures involve the inverters (Maish et al. 1997). The main causes of inverters’ failures are mainly due to design problems, manufacturing flaws and poor management practices (Realini 2003).

Although photovoltaic inverters are the most mature of any distributed energy resources (wind, fuel cells, micro-turbines), their lifetime is from 8 to 12 years (Realini 2003).

Electronic systems reliability can be estimated using databases such as the military handbook MIL-HDBK-217 or the electronic guide FIDES. In our study, we use the FIDES guide and the lifetime distribution of an inverter is considered to follow an exponential distribution with failure rate of $7.61 \times 10^{-6} \text{ h}^{-1}$.

#### 4.2.4 Degradation

Degradation is a phenomenon where the performance of a unit (product) degrades with time due to the environmental condition or materials properties. When the degradation reaches an unacceptable threshold level, the unit is considered in failed state.

Most of components of the PV system exhibit degradation or sudden failure and therefore the PV system is considered in failed state when the power level is below a certain percent of the initial power. Moreover, some components such as inverter though it may be a working state but the input power range is below the minimum acceptable value, it fails to convert the current from DC to AC. All the above are taken into account when simulating the system.

We briefly describe the degradation models of key components as follows. The photovoltaic module power output degradation due to the encapsulant discoloration is given by Pan et al. (2011):

\[
D_{\text{discoloration}}(t) = 1 - e^{-bt^a}
\]

where $a$ and $b$ are parameters of the model.

The power degradation due to corrosion for the PV module and DC wires is proportional to the wear rate and is given by Baussaron (2011):

\[
D_{\text{corrosion}}(t) = C t^n
\]

where $C$ is the effective rate of corrosion and $n$ is a parameter which depends on material and environment properties (equal to 1 in a linear degradation behaviour).

Broken interconnects, broken cells and solder bond failures are considered some kind of degradation which depends on the number of surviving photovoltaic cells in the module. Indeed, for the broken cell, we consider that the power output degradation is:

\[
D_{\text{broken cells}}(t) = \frac{\text{number of surviving cells}(t)}{\text{number of cells}}
\]
Moreover, there are two interconnects and two bonds per cell. Thus, we consider that the degradation due to broken interconnects is:

\[ D_{\text{broken interconnect}}(t) = \frac{\text{number of surviving interconnects}(t)}{2 \times \text{number of cells}} \]  

(13)

and the degradation due to the solder bond failure is:

\[ D_{\text{solder bond failure}}(t) = \frac{\text{number of solder bond failure}(t)}{2 \times \text{number of cells}} \]  

(14)

For each failure mode (interconnect, cell and solder), we consider that the failure time follows an exponential law. The overall degradation of the module is estimated as:

\[ D_{\text{PV module}}(t) = 1 - \prod_{i=1}^{n} (1 - D_i(t)) \]  

(15)

where \( n \) is the number of degradation modes.

For each degradation model, we consider that the component failed when its output reaches 70% of the initial output. The component output power \( P_{\text{component}}(t) \) is estimated as:

\[ P_{\text{component}}(t) = P_{\text{component input}}(t) \times (1 - D_{\text{component}}(t)) \]  

(16)

where \( P_{\text{component input}}(t) \) is the component input power (it is the constant initial power for photovoltaic modules) and \( D_{\text{component}}(t) \) is the component degradation due to all modes. Moreover, the system is considered failed when the inverter input power is below the minimal input value required by the inverter to produce an output.

5 SIMULATIONS

The Petri network of Figure 4 and data of Tables 1, 2, 3 and 4 are implemented in the MOCA-RP\textsuperscript{©} (MOnte-CArlo based on Petri networks) software. The availability, the mean time between failures (MTBF) and outage periods are estimated. Simulations are carried out for a photovoltaic system power of 3 kWp which corresponds to 18 multicrystalline modules considering three different configurations as discussed later.

Each module has a bypass diode, which permits to short-circuit the module in case of failure. Thus, the series power is proportional to the number of surviving modules. We consider the output power of the array as the product of the number of surviving series (a series is failed when the series power is lower than 25% of the initial series power) and the lower power output of any of these series.

The maintenance is launched when the photovoltaic system is failed (i.e. the system does not produce electricity). For each maintenance period, all failed components are changed. However, a repairman cannot perform the maintenance of 2 components at the same time.

### Table 1. Photovoltaic module failure data.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Law</th>
<th>Law data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot spot</td>
<td>Exponential</td>
<td>( \lambda = 4.57 \times 10^{-6} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>Bypass diode failure</td>
<td>Exponential</td>
<td>( \lambda = 3.46 \times 10^{-6} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>Junction box failure</td>
<td>Exponential</td>
<td>( \lambda = 5.71 \times 10^{-6} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>Delamination</td>
<td>Exponential</td>
<td>( \lambda = 5.44 \times 10^{-6} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>Broken glass</td>
<td>Weibull</td>
<td>( \beta = 7 , \text{h}^{-1} ), ( \eta = 374584 , \text{h} )</td>
</tr>
</tbody>
</table>

### Table 2. BOS components failure data.

<table>
<thead>
<tr>
<th>Component</th>
<th>Law</th>
<th>Law data</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC wire</td>
<td>Exponential</td>
<td>( \lambda = 4.83 \times 10^{-8} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>Inverter</td>
<td>Exponential</td>
<td>( \lambda = 7.61 \times 10^{-8} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>AC wire</td>
<td>Exponential</td>
<td>( \lambda = 1.30 \times 10^{-8} , \text{h}^{-1} )</td>
</tr>
</tbody>
</table>

### Table 3. Degradation data.

<table>
<thead>
<tr>
<th>Component</th>
<th>Degradation mode</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module</td>
<td>Broken interconnect</td>
<td>( \lambda = 2.85 \times 10^{-3} , \text{h}^{-1} )</td>
</tr>
<tr>
<td></td>
<td>Broken cell</td>
<td>( \lambda = 3.81 \times 10^{-3} , \text{h}^{-1} )</td>
</tr>
<tr>
<td></td>
<td>Solder bond failure</td>
<td>( \lambda = 5.19 \times 10^{-3} , \text{h}^{-1} )</td>
</tr>
<tr>
<td></td>
<td>Discoloration</td>
<td>( \alpha = 3.08 , \text{h}^{-1} ), ( \beta = 7.94 \times 10^{-18} )</td>
</tr>
<tr>
<td></td>
<td>Corrosion</td>
<td>( n = 1 , \text{h}^{-1} ), ( C = 1.43 \times 10^{-6} )</td>
</tr>
<tr>
<td>DC wire</td>
<td>Corrosion</td>
<td>( n = 1 , \text{h}^{-1} ), ( C = 1.71 \times 10^{-6} )</td>
</tr>
</tbody>
</table>

### Table 4. Reparation data.

<table>
<thead>
<tr>
<th>Component</th>
<th>Repair law</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module</td>
<td>Exponential</td>
<td>( \mu = 8.33 \times 10^{-3} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>DC wire</td>
<td>Exponential</td>
<td>( \mu = 4.17 \times 10^{-3} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>Inverter</td>
<td>Exponential</td>
<td>( \mu = 4.17 \times 10^{-3} , \text{h}^{-1} )</td>
</tr>
<tr>
<td>AC wire</td>
<td>Exponential</td>
<td>( \mu = 4.17 \times 10^{-3} , \text{h}^{-1} )</td>
</tr>
</tbody>
</table>

A simulation is conducted to study the performance of the system for a period of 30 years (i.e. \( 262800 \) hours). We estimate the availability of a photovoltaic system as well as the asymptotic availability, the mean time between failure (MTBF) and outage periods. The simulation was replicated for 100,000 times.

The performance of one module during 30 years is presented in Figure 6. It shows the effect of the degradation and the failures on the module.

During the 30 years of operation, it is observed that the photovoltaic module is repaired twice. The two failures are due to a failure mode (not the degradation because the output power of the system is not lower than the threshold level). The time to repair estimated after the first failure of the module is long but the system continues to work and is not considered failed because of the operational state of other modules. In this case, the maintenance of the system is not launched just after the failure of the...
module but when the entire system is failed according to the condition on the power output defined previously.

Figure 6. Example of a photovoltaic module output power.

First, the influence of different types of configurations is studied. One repairman is considered and we use three cases of configurations as described below:
- Case 1: 3 series of 6 modules ($m=6$ and $n=3$);
- Case 2: 2 series of 9 modules ($m=9$ and $n=2$);
- Case 3: 1 series of 18 modules ($m=18$ and $n=1$).

The availability of these cases is shown in Figure 7 and reliability data are given in Table 5.

The configuration has a little effect on the outage periods, MTBF and system availability. As expected, the series system (case 3) shows the worst performance among all cases.

The MTBF difference between the case 1 with 3 series and the case 3 with 1 series is equal to about one year (8240 hours) over the 30 years period. Moreover, the analysis shows that case 1 produces higher current (on average) than case 3 which may directly affect the choice of the wire size and type of inverter. Economic analysis of such system may then become necessary.

Second, the influence of the number of repairmen on the system performance is studied. This is accomplished by studying case 1 using different number of repairmen (1, 2 and 3 repairmen). The availability is shown in Figure 8 while Table 6 shows MTBF, steady state availability and outage per year.

Using case 1, it is observed that with 2 and 3 repairmen, we have almost the same MTBF and higher availability than with one repairman.

As expected, the number of repairmen increases the system’s availability as well as its performance.

6 CONCLUSION

In this paper, we investigate and simulate a photovoltaic system under different conditions and considering failure and degradation distributions of its components. We also investigate the effect of the system’s configuration and number of repairmen on the system’s performance (MTBF, outage per day and steady state availability). Using Petri networks
in conjunction with MOCA-RP® software enabled us to consider different failure time distribution and degradation models which could not have been investigated using traditional reliability modeling.

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