Photovoltaic system lifetime prediction using Petri networks method

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ABSTRACT

Photovoltaic modules and systems lifetime and availability are difficult to determine and not really well-known. This information is an important data to insure the installation performance of such a system and to prepare its recycling. The aim of this article is to present a methodology for the availability and lifetime evaluation of a photovoltaic system using the Petri networks method. Each component - module, wires and inverter - is detailed in Petri networks and several laws are used in order to estimate the reliability. Several guides (FIDES, MIL-HDBK-217 ...) allow determining the reliability of electronic components using collections of data. For photovoltaic modules, accelerated life testing are carried out for the evaluation of the lifetime which is described by a Weibull distribution. Results obtained show that Petri networks are very useful to simulate lifetime thanks to its intrinsic modularity.

Keywords: Petri networks, Reliability, Availability, Lifetime, Malfunctioning, Photovoltaic system, Failure probability

1. INTRODUCTION

Photovoltaic systems are installed all around the world to produce electricity from solar energy. However, photovoltaic modules and systems lifetime and availability are difficult to determine and not really well-known. This information is important data to insure the installation performance of such a system and to prepare its recycling.

In the literature, the reliability and the availability of a stand-alone photovoltaic system were discussed by Díaz [1] using exponential law for different components. Díaz [1] used operational photovoltaic systems data deduced from feedback recorded by Jahn [2] and Maish [3] respectively from 1992 to 2003 and from 1996 to 1997.

In this paper, we propose a methodology using Petri networks to estimate the lifetime or the availability of a photovoltaic system. The main advantage of Petri nets is to simulate a large number of samples for a complex system. All kind of lifetime distribution can be implemented using this method. In the following application, we use exponential and Weibull distributions.

First, the photovoltaic system and the Petri networks method are presented. Then, the Petri network of a photovoltaic system is built. Finally, a simulation using several photovoltaic arrays are carried out and lifetime, availability and maintenance cost are estimated.

2. PHOTOVOLTAIC SYSTEM

The studied system is a grid-connected photovoltaic system (cf. Figure 1). The system is composed of a photovoltaic array with modules connected in series-parallel, an inverter integrating a DC-AC converter, wires which permit to deliver successively the continuous energy from photovoltaic modules to inverter (DC wires) and the alternative energy from inverter to grid (AC wire).

The study is done for each inverter of the installation (one inverter is only considered). Photovoltaic modules are connected in series-parallel in order to obtain significant power by balancing the voltage and amperage delivered to inverters. Generally, two DC wires are used to connect photovoltaic modules to the inverter.

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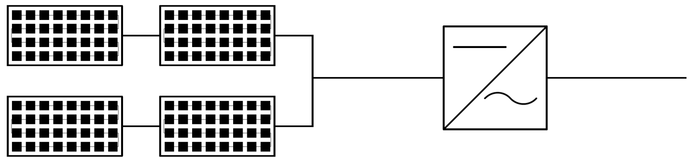

Figure 1. Studied photovoltaic system.

3. PETRI NETWORKS METHOD

3.1 Stochastic Petri Networks method

Petri networks can be used for modeling the functioning and the malfunctioning of complex systems [4]. This method provides a convenient graphical representation of a place-transition net comprising [5]:

- places P_i (drawn by a circle) which models states or objects,
- tokens (drawn by black dots) which represent the specific value on the states or objects,
- transitions T_j (drawn by rectangles) which model activities that change the values of states and objects,
- and arcs which specify the interconnection of places and transitions thus indicating which objects are changed by a certain activity.

Petri networks are an accurate solution to describe the process of sequential dynamics of a photovoltaic system. Petri networks allow us to simulate the behavior of the system in normal operating conditions as well as in the case of component failure. The evolution of a dynamic system when represented by a Petri network 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.

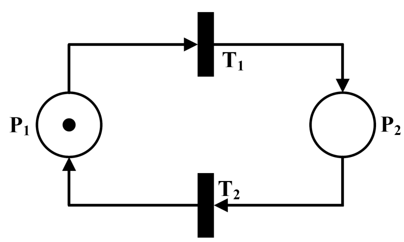

Figure 2. Functional Petri network (T_1, T_2: Functional transitions).

The diagram of Figure 2 shows a functional Petri network using the functional analysis. This network has no failures and T_1 and T_2 are functional transitions from state P_1 to P_2 and inversely.

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

The dysfunctional part can be modeled in the same network that the functional part of the system. This superimposition gives us the network shown in Figure 3, which illustrates a functional and dysfunctional modeling of the system.

Several lifetime distributions can be used for the dysfunctional transition T_3. When the failure rate λ is constant, the exponential distribution is used and the failure probability at time t [6] is expressed as follows:

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

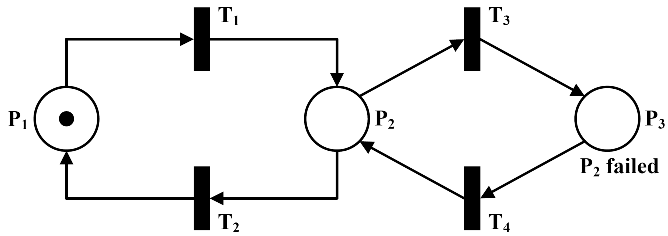

Figure 3. Functional and Dysfunctional Petri Network (T_3: P_2 component failure, T_4: P_2 component repair).

When the failure rate is not constant, the Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. This distribution is accurate for the three stages of the product life: infant mortality, steady state and wear out period [7]. It is a versatile distribution based on respectively the value of shape and scale parameters β and η. The failure probability [6] becomes:

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

For repair transition, the exponential distribution is used because the repair rate μ is assumed constant. The repair probability is expressed as follows:

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

MOCA-RP© (MOnte-CArlo based on Petri networks) software is used for estimating the lifetime, availability, productivity and reliability of a system.

3.2 Availability and reliability

The instantaneous availability (respectively, mean availability) of a system is its ability to achieve a required function, under given conditions and in a given time (respectively, in a given time interval) by assuming that the external resources are supplied [8].

The availability $A_S(t)$ of a system S at time t is the probability that the system is in operating condition at time t. $A_S(t)$ depends on the availability of the components that constitute the system.

The instantaneous availability $A_S(t)$ and the reliability $R_S(t)$ of a system [9] are determined as:

- for several components in series: $A_S(t) = \prod_{i=1}^{n} A_i(t)$ and $R_S(t) = \prod_{i=1}^{n} R_i(t)$
- for several component in parallels: $A_S(t) = 1 - \prod_{i=1}^{n} (1 - A_i(t))$ and $R_S(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t))$
- for several component in parallel-series: $A_S(t) = \prod_{i=1}^{n} (1 - A_i^{m_i}(t))$ and $R_S(t) = \prod_{i=1}^{n} (1 - R_i^{m_i}(t))$

  with m_i redundant components in subsystem i and n subsystem in the system S.

where $A_i(t)$ 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:

$$A_i(t) = \frac{\mu_i}{\mu_i + \lambda_i} + \frac{\lambda_i}{\mu_i + \lambda_i} e^{-(\mu_i + \lambda_i)t} \tag{4}$$

Thus the availability for a series system is:

$$A_S(t) = \prod_{i=1}^{n} \left[\frac{\mu_i}{\mu_i + \lambda_i} + \frac{\lambda_i}{\mu_i + \lambda_i} e^{-(\mu_i + \lambda_i)t} \right] \tag{5}$$

And the asymptotic availability, defined for an infinite duration, for a series system is:

$$A_S(\infty) = \prod_{i=1}^{n} \left[\frac{\mu_i}{\mu_i + \lambda_i} \right] \tag{6}$$

However, as we will show further, each time to failure and time to repair do not follow exponential distributions in photovoltaic systems. Thus the use of MOCA-RP© software is necessary to simulate the availability and the reliability of a complex system.

4. PHOTOVOLTAIC SYSTEM MODELING

4.1 Functional Petri network

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, all the system is failed. The functional Petri network of a photovoltaic module is illustrated in Figure 4 (way [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 electricity traffic in the different components of photovoltaic system is instantaneous. Using a classical Petri network, time is not taken into account in functional transitions (T_1, T_2, T_3, T_4 and T_5). Thus, we decided to use a temporized Petri network using a delay of one hour for the transition T_1 to separate the simulation in discrete time steps.

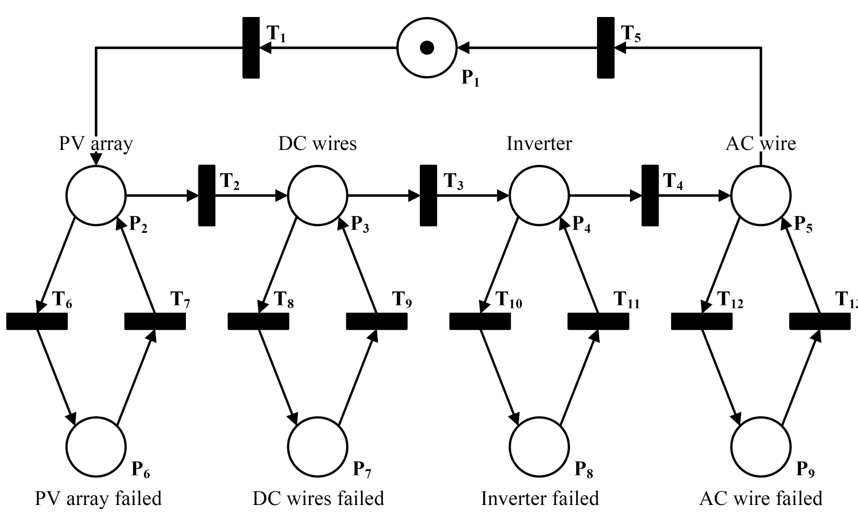

Figure 4. Petri network of the studied photovoltaic system.

4.2 Dysfunctional Petri network

For each kind of components, the dysfunctional modeling is represented as drawn in Figure 4.

Dysfunctional transitions T_6, T_8, T_{10} and T_{12} correspond to the failure probability of the different photovoltaic system components. Transitions T_7, T_9, T_{11} and T_{13} allow taking into account the repair probability of the components.

At the beginning, the system is considered safe. Thus the initial condition of the Petri network, as shown in Figure 4, is $(P_1,P_2,P_3,P_4,P_5,P_6,P_7,P_8,P_9)=(1,0,0,0,0,0,0,0,0)$.

4.2.1 Photovoltaic array

The transition T_6 of the Petri network (cf. Figure 4) corresponds to the failure probability of photovoltaic modules installation. The failure probability of the photovoltaic array of the system has to be determined.

Gautam et al. [10] and Ristow et al. [11] propose different methods to estimate the failure probability of photovoltaic arrays. However, most of these studies present lifetime estimation without taking into account the statistical distribution of influent parameters.

A photovoltaic array can be made up of photovoltaic modules connected in series, parallel and series-parallel. The reliability study of each configuration of photovoltaic arrays was carried out by Gautam [10]. In our case, the failure probability of a series-parallel array made up of *n* parallel strings with each string having *m* photovoltaic modules connected in series can be estimated by [10]:

$$P_f(t) = \prod_{j}^{n}\left(1 - \prod_{i}^{m}\left(1 - P_{f_{ij}}(t)\right)\right) \tag{7}$$

The failure probability of each photovoltaic module is taken into account in order to estimate the failure probability of the photovoltaic array. It can be estimated either carrying out a feedback analysis or with realizing accelerated life testing thanks to the method of Laronde [12][13] using influent parameters like module temperature and relative humidity.

From Laronde [13] the failure probability of a single photovoltaic module follows a Weibull distribution with $\beta = 2.6$ and $\eta = 369038$ hours.

4.2.2 Wires

Wires are considered to be secondary components but important for the transfer of the electricity. The main failure mode of wires for the photovoltaic system 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, a study with FIDES Guide has permitted to estimate a failure rate of 48.3×10^{-9} for the DC wires of 1 meter and 13×10^{-9} for the AC wire of 1 meter. The study has to be carried out for each kind of wires and for the wire length of the studied installation.

4.2.3 Inverter

The inverter is an expensive and complex component in a photovoltaic system; the majority of system failures involved the inverters [3]. The problems that exist with inverters are mainly design problems, manufacturing flaws and poor management practices [14].

Although photovoltaic inverters are the most mature of any Distributed Energy Resources (wind, fuel cells, micro-turbines) inverter, their Mean Time To Failure (MTTF) is very low (from 8 to 12 years in 2003 [14]).

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 have decided to use the FIDES guide. The lifetime distribution of an inverter is considered to follow an exponential distribution. The failure rate of 7.61×10^{-6} is determined thanks to the guide.

5. SIMULATIONS

The Petri network of Figure 4 and data of Table 1 are implemented in the MOCA-RP© software. Then, the availability, the mean time to failure (*MTTF*) and the mean time between failures (*MTBF*) are estimated. Several cases of photovoltaic arrays are studied using the same number of modules and therefore the same photovoltaic power (3kWp with 18 multicrystalline modules for example):

- 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 law data of the transition T_6 are calculated using the equation (7) for all cases. Table 1 presents the different distribution laws which are implemented in the Petri networks.

Table 1. Initial data.

Transition	**Law**	**Law data**
T_6	Weibull	Case 1: $\beta = 7.56$ and $\eta = 198993$ h Case 2: $\beta = 5.03$ and $\eta = 171248$ h Case 3: $\beta = 2.6$ and $\eta = 121415$ h
T_7	Exponential	$\mu = 1.19 \times 10^{-3}$ h^{-1}
T_8	Exponential	$\lambda = 48.3 \times 10^{-9}$ h^{-1}
T_9	Exponential	$\mu = 2.98 \times 10^{-3}$ h^{-1}
T_{10}	Exponential	$\lambda = 7.61 \times 10^{-6}$ h^{-1}
T_{11}	Exponential	$\mu = 0.926 \times 10^{-3}$ h^{-1}
T_{12}	Exponential	$\lambda = 13 \times 10^{-9}$ h^{-1}
T_{13}	Exponential	$\mu = 2.98 \times 10^{-3}$ h^{-1}

Moreover, as mentioned by Maish [15], the ultimate metric that is common to all aspects of reliability is cost. Thus, the maintenance cost of the system for each case are estimated using maintenance costs of the different components as shown in Table 2.

Table 2. Maintenance costs.

Component	**Maintenance cost***
Module	3.33
DC wire	1.33
Inverter	6.67
AC wire	1.00

** This cost is expressed as the ratio between the cost of the considered component and the cheapest one*

For each case, the availability of a photovoltaic system is simulated (10000 simulations) during 30 years (i.e. 262800 hours). The availability versus time is represented in Figure 5 for the 3 cases.

Then, using the same 10000 simulations, the asymptotic availability ($A(\infty)$), the mean time to failure (*MTTF*), the mean time between failure (*MTBF*) and the mean maintenance cost are obtained. These values are presented in Table 3 for each case.

Table 3. Output data.

Case	MTTF	MTBF	A(∞)	Outage per year	Maintenance cost*
1: 3 series of 6 modules	106270 h	34140 h	98.860 %	100 h	16.8 (+0.0%)
2: 2 series of 9 modules	98617 h	32133 h	98.784 %	107 h	17.2 (+2.4%)
3: 1 series of 18 modules	78590 h	35139 h	98.655 %	118 h	19.0 (+13.1%)

** This cost is expressed as the ratio between the cost of the considered component and the cheapest one*

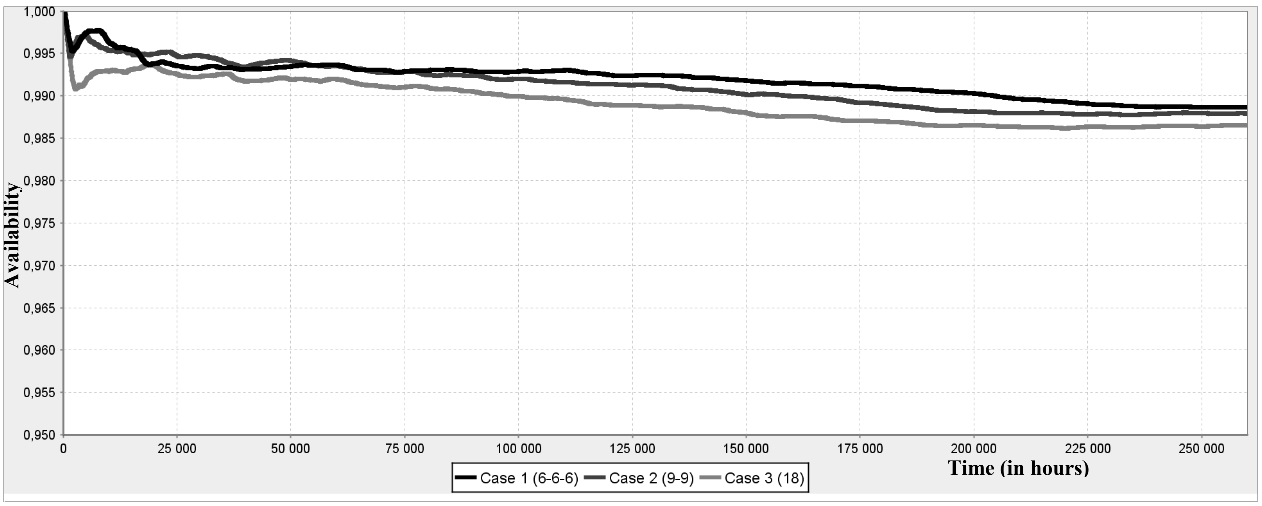

Figure 5. Photovoltaic system availability.

During 30 years, the mean availability of a photovoltaic system is very high, superior to 98.65% which corresponds to a mean outage lower than 4 days per year for the different studied cases.

If the maintenance is not carried out, the lifetime of the photovoltaic system is between 9 years and 12 years (78590 hours and 106270 hours) for the different cases. After the first operation of maintenance, the product changing is predictable every 4 years. However, it is not possible without an accurate study to determine the component to change. In this case, where photovoltaic modules are connected in only one series, there is an over-cost of 13.1% versus a photovoltaic array with 3 series. Moreover, we obtained outage duration of 18% upper. This is due to the non-redundancy of the module. So, if a module is outage in a series configuration, all the system is outage which is not true in the other case (parallel and series-parallel configurations). For solving this problem, it is possible to add by-pass diode in parallel of photovoltaic modules parts but this solution is costly.

6. CONCLUSION

In practice, engineers and researches need to wait for 20 or 30 years in order to estimate the lifetime of a photovoltaic system using experimental data. In this paper, we propose a methodology to estimate the availability and the lifetime of a photovoltaic system (from photovoltaic modules to the grid) by a simulation. The Petri networks method is used with functional and dysfunctional parts and the simulation is carried out using the MOCA-RP© software. The modularity of this method allows us to combine different lifetime distributions for several types of components. Moreover, one failure mode is used in the simulation for the photovoltaic array which is due to temperature and humidity. It would be possible to add other failure mode which permits to precise the real lifetime and availability of the photovoltaic system.

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