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Reliability study of a system dedicated to renewable energies by using stochastic petri nets: application to photovoltaic (PV) system

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Abstract

Access to energy is essential to reduce poverty. Globally, around 1.2 billion people, about 16% of the global population, still do not have access to electricity. Knowing that photovoltaic (PV) energy already lengthily showed its evidence in terms of operation and reliability, its development observed an improvement of technologies in terms of solar energy transformation output by the semiconductor, and the research in this field does not cease to progress. However, reliability and availability study of PV systems have not been received great attention from researchers, for that we decided to give it a consideration in our research works. So, we seek to study the reliability of such system by using functional and dysfunctional analysis methods. In this paper, we will be interested in the two parts of PV system: "PV module" composed by Silicon cells, and "the converter" which is the expensive component and the most complex in a PV system.

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Keywords: Converter; module; Petri nets; reliability

1. Introduction

Nations through the world have finally started to use the various green energy resources, also called renewable energies, in order to satisfy their needs. Nowadays, we find several photovoltaic (PV) stations installed around the world. Knowing that PV energy have proven its strength in terms of yield and reliability and its development has observed a great interest in solar energy transformation. However, reliability and availability study of PV systems

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have not been received great attention. Therefore, we try, through this work, to estimate some parameters to insure the performance (in term of reliability and availability) of such system by using results discussed by authors in [1]. They used operational PV system data deduced from feedback record by [2] and [3]. In this paper, we will present our approach using Stochastic Petri Nets (SPN) [4], which simplifies the reliability and availability modeling and analysis. The main advantage of the SPN is to allow the tasks modeling with non-deterministic execution times, to validate the obtained model and to simulate the system behavior and to have thereafter digital results. As well as the possibility of taking into account some random breakdowns. First, we present our PV system and a turn on the flow states graph especially SPN used in modeling our system, and then we carry out a depth analysis of the obtained model. Finally, obtained results will be shown and discussed.

2. Photovoltaic (PV) systems

The system to be studied is very simple, it is composed of: (1) A photovoltaic field composed by PV modules connected in parallel-series; (2) A PV converter transforming direct current, coming from photovoltaic field, to alternating current; (3) Wires which transmit direct current from PV modules to the converter (DC wires) and wires which transmit alternating current from the converter to the electric network (AC wires).

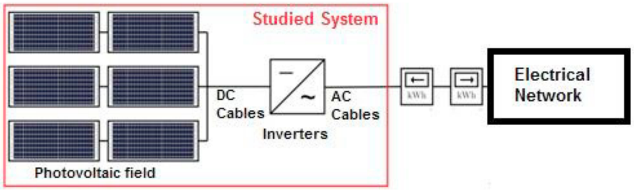

Fig. 1. Studied photovoltaic system.

Each component of our system is sensitive to the climatic conditions and their performances are variable according to time. The manufacturers of modules guarantee their products 5 years and offer a warranty of power of 90% at the end of 10 years and 80% at the end of 20 years (even 25 to 30 years today). Otherwise, the converter, which is the expensive component and the most complex in a PV system, its lifetime and warranty of power does not exceed sometimes 15 years. The system is considered failed when it delivers a degraded power (< MPPT), or there is no output electricity (generally when the irradiance is ≤ 1000 W/m^2 and the module temperature is ≤ 25 °C).

3. Stochastic Petri nets SPN

Petri Networks are a tool for analysis of the structure and the behavior of dynamic systems with discrete events. The dynamic aspect in Petri Networks is described by: the marking (tokens) which represent the state of the system, and transitions crossing which simulate the behavior of the system (the state of the system). In SPN, we initiate “time factor”, the associated times on each transition are random variables which follow distribution laws (generally exponential ones for PV systems). We can also associate Monte-Carlo simulations, Markovian chains or other state diagrams. In SPN an exponentially distributed delay is associated with each transition in the net structure. Thus each transition has a firing rate which is the parameter of the corresponding exponential distribution, and transitions are sometimes termed timed transitions. SPN is a six-tuple (P, T, Pre, Post, M_0, Λ) where [5]:

- P: places represent a set of states
- T: transitions which model activities that change the values of states
- Pre and Post: incidence matrix
- M_0: initial marking designed by tokens (black dots drawn inside places)
- Λ: firing rates λ associated with the transitions, which are random variables designed by the function λ (M) of the current marking

The dynamic behavior of SPN is described with a stochastic process; we associate with each transition from the network a stochastic process.

4. Photovoltaic system modeling and analysis using SPN

4.1. Availability and reliability determination

Using the proposed model of SPN, this study quantitatively evaluates the reliability and availability of the PV systems in the presence of intermittent faults (modeled by discrete processes) [4]. The results of this study can provide important insights into the design of PV systems with improved reliability. The availability A(t) and reliability R(t) of PV system are given by [6]:

$$A(t) = 1 - \prod_{i=1}^{n} (1 - A_i^{m_i}(t)) \tag{1}$$

$$R(t) = 1 - \prod_{i=1}^{n} (1 - R_i^{m_i}(t)) \tag{2}$$

With m_i set of components connected in series in each subsystem i, and n subsystems are connected in parallel to form the global system (parallel-series). Time to failure $\lambda_i(t)$ and time to repair $\mu_i(t)$ both of them follow exponential distributions; the availability A(t) is given by [6]:

$$A_i(t) = \frac{\mu_i}{\mu_i + \lambda_i} + \frac{\lambda_i}{\mu_i + \lambda_i}.e^{-(\mu_i + \lambda_i)t} \tag{3}$$

4.2. Software tool support

Complex system modeling and evaluation would not be practical without the support of software tools. For that we have used Petri Module of GRIF-TOTAL (no-marketed or demo version) (Fig. 2). It is based on Moca-RP (Monte-Carlo – Petri Nets), TOTAL high speed calculation engine based on the Monte-Carlo simulation. It produces several results [7]:

- Analysis of the different obtained values
- Transition firing frequency
- Attendance time in each place and the mean marking of each place

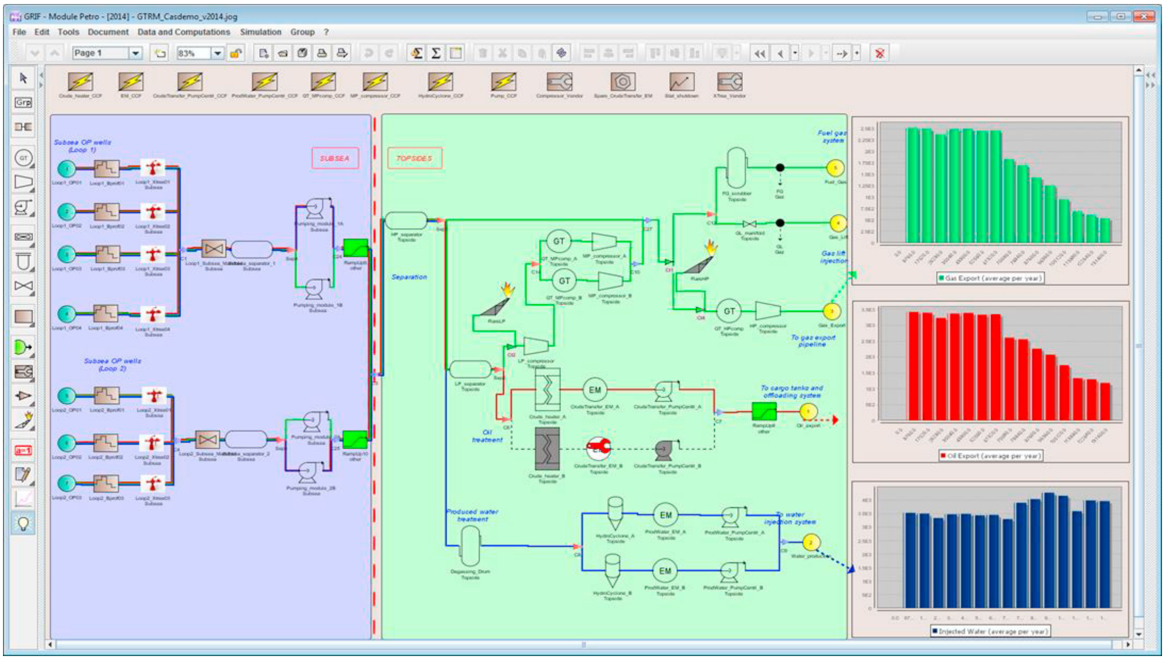

Fig. 2. Screenshot Petri module of GRIF-TOTAL [7].

The flexibility of the module will enable to us to obtain the availability and the reliability values. It is also possible to exploit data results in [7]:

- Synthesis of input data in the form of tables to make easy the control of input values
- Possibility of automating calculations by creating batch run, executable files, etc
- Results stored in the same document and exportable in different formats (csv, xml, xlsx, etc)
- Visualization of results as curves, pie charts or histograms
- Printing of graphic elements and curves in PDF format which maintains high quality of pictures
- Possible connection to SQL, Access and Excel databases to recover the values later

4.3. Working system modeling

Our system is composed of: a field of PV modules composed by silicon cells, converter and wires, all of them are connected on series. If one component fails, global system fails. A functional SPN of a PV system is shown on Fig. 3. The delay associated on transition T1 is estimated to one hour to separate the simulation in discrete time steps.

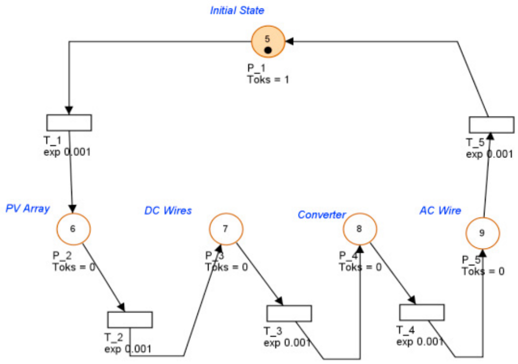

Fig. 3. SPN of working PV system.

4.4. Non-working system modeling

The scenario of non-working system is illustrated in the figure below. Each component can pass from initial state (safe case) to: failing mode (T1, T4), degraded - failing mode (T2, T3, T4) and degraded – repaired mode (T2, T5). We will focus our study of reliability, initially, only on the two parts of our system: the PV module and the converter (Fig. 4).

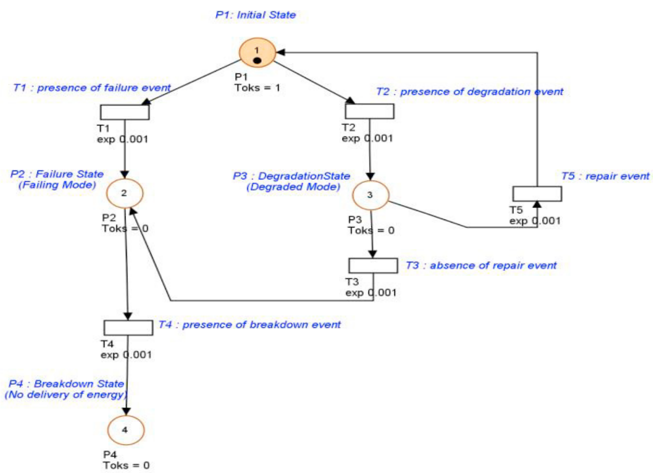

Fig. 4. SPN of non-working PV system.

The initial marking token (in state P1) of the SPN of working system in Fig. 4 is: (P1, P2, P3, P4) = (1, 0, 0, 0)

4.4.1 Photovoltaic module

Authors in [8, 9] proposed methods which give possibility to estimate the reliability of PV module by using models given in section 4 of this paper. For our studied system, PV arrays are arranged in parallel-series, so we must consider in each time the failure rate of each PV module. The major failure modes for crystalline Silicon modules are [10]:

- Hot spots
- Bypass diode
- Junction box failures
- Encapsulant delamination
- Broken glass
- Broken cells
- Solder bond failure
- Broken interconnects

With these failure modes, the system can't deliver any power in the output. In addition, we can cite two other degradation modes which are: corrosion and encapsulant discoloration. In presence of one of these two degradation modes, the system is considered failed (it delivers a degraded power) if it were still not repaired (Fig. 5).

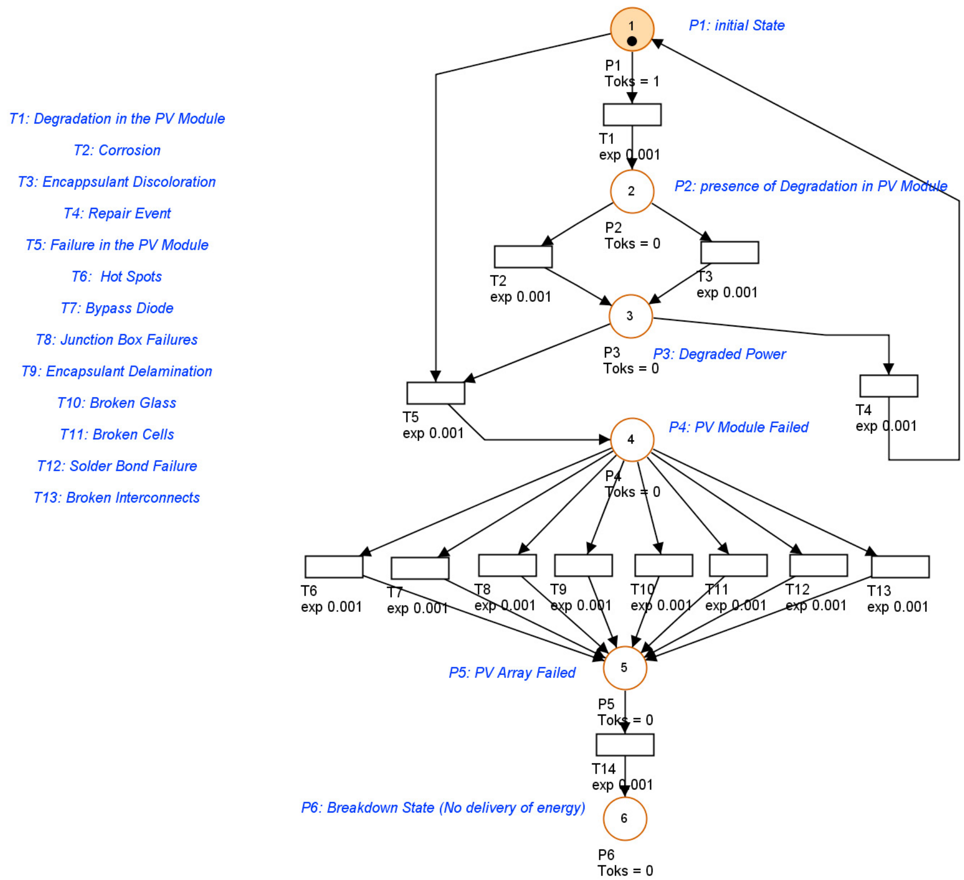

Fig. 5. SPN of non-working PV system – PV module.

4.4.2 Converter

The converter is the expensive component and the most complex in a PV system, its lifetime does not exceed sometimes 15 years. The main causes of converter failures are due to design problems, manufacturing flaws and poor management practices [11], other causes (failure modes) will be shown in the converter SPN. Its reliability can be estimated using databases such as MIL-HDBK-217F, the electronic guide FIDES, etc. In our study, we have used the MIL-HDBK-217F guide and the converter lifetime distribution follows an exponential law. The converter reliability is estimated relying on base failure rates λ_b for each component in the converter. 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. The table below summaries the formulas to calculate the failure rate of each component of the converter [12]:

Table 1. MIL-HDBK-217F 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

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

The SPN for the converter in our PV system is given by this network (Fig. 6):

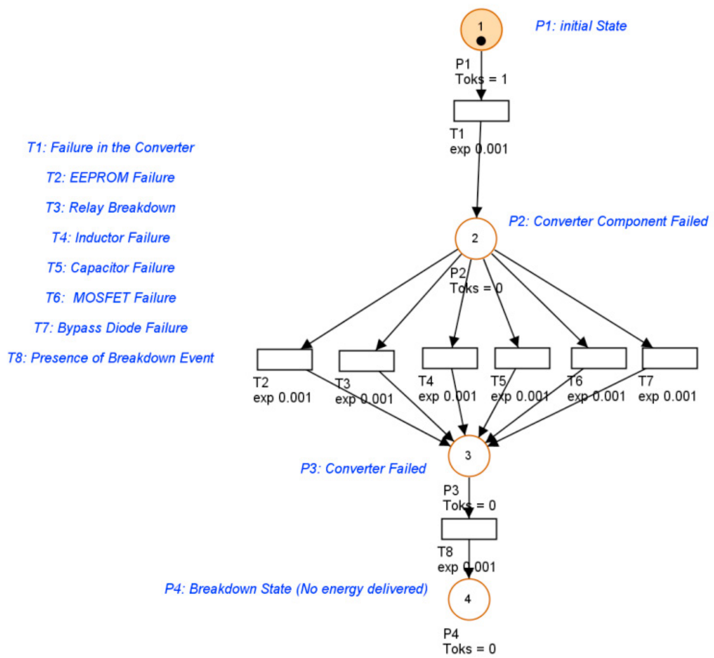

Fig. 6. SPN of non-working PV system – converter.

5. Results and discussion

Using SPN generated in the bottom for each component, availability, reliability and MTBF can be estimated. We have used necessary data to evaluate the PV system availability. These data are shown in tables below [2], [3]:

Table 2. PV system component failure rate data.

Component	Failure Mode	Distribution Law	Law Data (Failure Rate)
PV Module	Hot spots	Exponential	$\lambda = 7{,}13 \, . \, 10^{-7} \; h^{-1}$
	Bypass diode	Exponential	$\lambda = 5{,}85 \, . \, 10^{-7} \; h^{-1}$
	Junction box failures	Exponential	$\lambda = 7{,}87 \, . \, 10^{-7} \; h^{-1}$
	Encapsulant delamination	Exponential	$\lambda = 5{,}44 \, . \, 10^{-7} \; h^{-1}$
	Broken glass	Exponential	$\lambda = 5{,}71 \, . \, 10^{-7} \; h^{-1}$
	Broken cells	Exponential	$\lambda = 7{,}13 \, . \, 10^{-6} \; h^{-1}$
	Solder bond failure	Exponential	$\lambda = 4{,}84 \, . \, 10^{-6} \; h^{-1}$
	Broken interconnects	Exponential	$\lambda = 4{,}68 \, . \, 10^{-6} \; h^{-1}$
Converter	EEPROM failure	Exponential	$\lambda = 7{,}61 \, . \, 10^{-6} \; h^{-1}$
	Relay breakdown	Exponential	$\lambda = 7{,}61 \, . \, 10^{-6} \; h^{-1}$
	Inductor failure	Exponential	$\lambda = 7{,}61 \, . \, 10^{-6} \; h^{-1}$
	Capacitor failure	Exponential	$\lambda = 7{,}61 \, . \, 10^{-6} \; h^{-1}$
	MOSFET failure	Exponential	$\lambda = 7{,}61 \, . \, 10^{-6} \; h^{-1}$
	Bypass diode failure	Exponential	$\lambda = 7{,}61 \, . \, 10^{-6} \; h^{-1}$

Table 3. PV module degradation data.

Component	Degradation Mode	Data
PV module	Corrosion	$n = 1 \quad C = 1{,}43 \, . \, 10^{-6}$
	Encapsulant discoloration	$a = 3{,}08 \quad b = 7{,}94 \, . \, 10^{-18}$

Table 4. PV components repair data.

Component	Repair Law	Repair Rate Data
PV module	Exponential	$\mu = 8{,}33 \, . \, 10^{-3} \; h^{-1}$
Converter	Exponential	$\mu = 2{,}45 \, . \, 10^{-3} \; h^{-1}$

The study of the performance of our PV system is estimated for a period of 20 years (ie 175200 hours). In this paper, we have considered the simulation applied on the PV module component. Its performance, during this period of 20 years, shows the effect of the degradation and failure modes on the PV module. The time to repair is estimated after the first failure.

We use 24 PV modules in 3 different configurations like that:

- Configuration 1: 3 series of 8 modules (m=8, n=3)
- Configuration 2: 2 series of 12 modules (m=12, n=2)
- Configuration 3: 1 serie of 24 modules (m=24, n=1)

The availability rates and MTBF of these 3 configurations are given in the table below:

Table 5. PV system availability.

Configuration	A(t) % (t = 20 years)	MTBF (h)
m=8 n=3	64,28 %	13340,96 h
m=12 n=2	56,38 %	15428,17 h
m=24 n=1	43,51 %	18834,17 h

6. Conclusion

In this paper, we have modeled and simulate a PV system including the major degradation and failure modes of each component. We have focused our study only on two components: PV module and converter. For that, we have used SPN thanks to Petri Module of GRIF-TOTAL Software. Results are interpreted by the evaluation of the availability rates and the MTBF of each supposed configuration.

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