Stochastic reliability evaluation of the stand-alone photovoltaic systems

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Move to the installation of the stand-alone photovoltaic (PV) systems for the remote and critical areas has been increased due to the technical advantages of them alongside the low investment cost. However, accurate reliability calculation of the stand-alone PV system is essential to verify its suitability for being a sustainable energy system. This paper proposes a new method for calculation of the stand-alone PV system's reliability without any assumption. In order to consider the uncertainty of the global solar irradiation on the output power of the system, stochastic modeling is hypothesized in this paper. Fast forward scenario reduction approach is used to reduce the number of the scenarios so as to decrease the execution time. Moreover, the effect of the ambient conditions such as temperature and humidity on the failure rate of the components, and the aging issue of the PV modules are taken into account to evaluate the reliability metrics precisely. The proposed approach for reliability assessment has been examined on the test system. The calculated results manifested that the stand-alone PV system can be utilized as a reliable system; however, the ambient conditions would reduce its availability.

keywords: *Reliability, PV systems, Uncertainty, Monte Carlo Simulation (MCS).*

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NOMENCLATURE

Indices:

t	Index for time.
yr	Index for year.
i	Index for subassemblies connected in series.
j	Index for subassemblies connected in parallel.
b	Index for battery.
k	Index for PV module.
l	Index for scenario reduction steps.
w	Index for the solar irradiation scenario.
δ	Index for MCS scenario.

Superscripts:

θ	Index for the system' components.
min	Superscript for min value of the variable.
max	Superscript for max value of the variable
ch	Superscript for charging mode of the battery.
dis	Superscript for discharging mode of the battery.
Up	Superscript for the up state of the system.
$Down$	Superscript for the down state of the system.
nom	Superscript for nominal quantity of the variable.
$\circ$	Superscript for displaying basic amount of the parameter.

Scalers and Parameters:

m	Constant slop for aging of PV.
c	Constant parameter used in the humidity modeling.

K	Boltzmann constant.
E_a	Activation energy.
$\overline{N}$	Years of operation.
ξ_w	Number of selected scenarios.
N_{series}	Number of components connected in series.
$N_{parallel}$	Number of components connected in parallel.
N_{module}	Number of PV modules.
N_b	Number of batteries.
N_{run}	Reference time for the simulation.
$Cycle^{life}$	Cycle life of the battery.
$G_{STD.}$	Standard global solar irradiation.
$G_{Crt.}$	Certain irradiation amount.
G_a	Global solar irradiation.
DOD	Depth of charge amount of the battery.
λ	Failure rate of the component.
$\eta^{ch,dis}$	Efficiency rate of charging/discharging %.
$SoC^{initial}$	Initial energy level of the battery.
HP	Humidity percentage of the ambient.
T_{temp}	Ambient temperature.
Δt	Time interval (1 hour).
$\nu(w)$	Amount of the each irradiation scenario.
$MTTF$	Mean time to failure.
$MTTR$	Mean time to repair.
P^{load}	Active power requirement of the area.

Sets:

Φ	Set of total irradiation scenarios.
Φ^+	Target set of the irradiation scenarios.
Φ^-	Set of non-selected irradiation scenarios.

Variables:

Ava	Availability of the system.
Uva	Unavailability of the system.
P_{module}	Output power of the module.
$P_{b,ch}, P_{b,dis}$	Charging/Discharging power of the battery.
SoC_b	Energy level of the battery.
$EENS_{syst}$	Average expected energy not supplied of the system.
ENS_t	Amount of expected energy not supplied within a t.
Γ	Kantorovich distance cost function.
$f(t)$	Failure density function.
$r_{1,2}$	Uniformly random variables on the [0 1] interval.
R	Reliability of the each component.
R_{syst}	Reliability of the system.
F_{syst}	Unreliability of the system.
R_{tot}^{series}	Reliability of the system equipped with components in series.
$R_{tot}^{paral.}$	Reliability of the system equipped with components in parallel.
T	Time duration.

1. INTRODUCTION

Due to the technical, economic, and environmental advantages of the photovoltaic (PV) systems, the presence of them has grown significantly in recent years. According to the international renewable energy agencies report in 2019, a year-on-year growth rate of the installed PV systems is 20% from 2017 to 2018 [1]. PV systems are operated in two modes: Grid-connected mode, and stand-alone one. Since the electrification on remote areas involves various difficulties and high construction costs, the stand-alone PV systems can be a good alternative for supplying energy in such areas. In addition, stand-alone PV systems can be utilized as a backup energy system for critical places [2]. However, the uncertain nature of the PV systems alongside the sudden failures may have evil effects on their optimal performance. Therefore, the reliability and availability of the PV systems must be evaluated precisely to guarantee the profitability of them during the specific operation time.

In recent years, several studies have focused on the reliability analysis of the PV systems. Authors in [3] have demonstrated that the reliability indices of the grid-connected PV systems have enhanced using the advanced components with high efficiency and availability. The effect of regular maintenance of the PV systems on their energy yields has been investigated in [4]. Authors have utilized the fault tree method for the probability analysis of the large-scale grid-connected PV systems' reliability in [5]. Likewise, the hybrid fault tree model has been used in [6] to assess the performance of the PV systems dynamically. Due to the vital role of the small power electronic components lifetime on the reliability of the PV systems, ref [7] has analyzed how their lifetime can affect on the reliability indices. Failures in the PV systems cause to increase the energy loss in such units. Therefore, it is necessary to estimate the failure rate of components in such plants carefully. Authors have reached this aim in [8]. An analytical approach based on the fault tree model has been utilized in [9] to investigate how reliability of each component of the grid-connected PV systems changes the overall system's availability. Colli has applied the failure mode and effect analysis (FMEA) approach to verify the PV system's sub-components' reliability in [10]. Authors in [11] have designed the transformerless inverters for the grid-connected PV systems to increase their reliability. Likewise, the reliability of the inverter in the PV systems has been improved using the battery system in [12]. Dynamic Bayesian network (DBN) framework has been utilized in [13] to evaluate the reliability of the PV arrays considering the intermittent faults. Based on the FIDES Guide standard, the precise failure rates of the PV systems components have been specified in [14]. Then, the stability and reliability of the system have been evaluated using the Monte Carlo simulation (MCS) method. Authors in [15] have presented the Markov reward model (MRM) method to compute the reliability and performance metrics of the grid-connected PV systems such as energy not supplied and availability. Jamshidpour et al. have identified that the utilization of the real-time FPGA-based switch failure diagnosis alongside the fault-tolerant converter leads to an increase in the PV systems' reliability in [16]. The reliability of the grid-connected PV system has been computed in [17] using the state enumeration approach. In addition, in [17], the effect of the ambient conditions on the failure rate of the components has been considered. Due to this fact that the inverters utilized in the PV systems are responsible for the majority of the failures, authors in [18] have proposed a new methodology to improve their reliability by decomposing to subsystems. The sequential Mcs is utilized in [19] to evaluate the reliability of the grid-connected PV systems considering the weather conditions and component aging. Authors in [20] have proved that the sizing of the PV modules affects the optimal lifetime and reliability of the inverters. They have shown that oversized arrangement of the PV modules decreases the inverters' reliability dramatically. Shenoy et al. have demonstrated the efficiency of using the differential power processing method for increasing the reliability of the grid-connected PV systems in [21]. Authors in [22] have applied the reliability block diagram to measure the reliability and availability of the grid-connected PV systems. The markovian approach has been used in [23] to evaluate the reliability of the stand-alone PV systems. However, an approximation has been made to model the different transition states of the batteries. Finally, Zhang et al. have reviewed the existing methodology for the calculation of the reliability in the PV systems in [24].

The importance of the stand-alone PV systems for the remote areas to supply energy and utilization of them as a backup system for the critical territory like military bases is undeniable. Thus, it is essential to evaluate the reliability of such systems accurately. As shown above, most studies examined the reliability of the grid-connected PV systems and in-depth analysis of the enhancement of PV system components' reliability. Also, a few research studies on the evaluation of the stand-alone PV systems have been done using the approximations. On the other hand, the uncertain nature of the PV systems due to the solar irradiance alongside the aging issue and ambient conditions such as temperature and humidity affects the reliability of the stand-alone systems. Thus, the impact of the mentioned factors must be seen in the process of reliability analysis during a specific time. To fulfill this gap, this paper proposes the stochastic reliability assessment for the stand-alone PV systems. In this paper, different scenarios for the solar irradiance are generated based on the historical data. Then, the fast forward scenario reduction approach is implemented to reduce the number of scenarios to an acceptable amount. Finally, in the last part, the reliability of the system is assessed using the MCS method considering the effect of ambient conditions on the failure rate of the different components. The main contributions of the paper are set up as follows:

- The precise stochastic reliability calculation is performed for the stand-alone PV systems using the MCS method, considering all up and down states of the system without any assumptions.
- The fast forward scenario reduction is utilized to reduce the number of generated scenarios to the acceptable amount.
- The impact of the ambient conditions such as temperature and humidity on the failure rate of the PV system' components is considered during the reliability calculation procedure.

The organization of the paper is as follows: section 2 involves four subsections. In the first subsection, concept of the reliability is clarified. the next subsection describes the effect of the ambient conditions on the failure rate of the components. Subsection C explains the stand-alone PV system's components and the last subsection is devoted to the description of the uncertainty modeling. Section 3 presents the proposed approach for the assessment of the system's reliability metrics. The next section demonstrates the results obtained from the proposed approach, and finally, the last part finalizes the paper.

2. RELIABILITY FORMULATION OF THE STAND-ALONE PV SYSTEM

This section contains four subsections in which the concept of the system's reliability, effect of ambient conditions on the failure rate of the different components, the modeling of the stand-alone PV system's components, and the way of scenario generation and reduction are discussed.

A. Concept of the reliability

The particular system' reliability is defined as a probability of the successful working of that system during a specific time. Moreover, unreliability of the system demonstrates the probability of unsuccessful working of the system within a given time. According to the failure density function $f(t)$, the reliability and unreliability of the system is formulated as follows [22]:

$$R_{syst}(t) = \int_{t}^{\infty} f(t) d\tau \tag{1}$$

$$F_{syst}(t) = \int_{-\infty}^{t} f(t) d\tau \tag{2}$$

The concept of the mean time to failure (MTTF) for each component of the PV system is expressed as an expected time of working prosperously. This concept is formulated as follows [22]:

$$MTTR_{\theta} = \int_{0}^{\infty} R(t) d\tau \tag{3}$$

Besides the MTTF, the concept of the mean time to repair (MTTR) is utilized in the reliability analysis problems to consider the expected repair time of the components as well. Finally, based on the defined MTTR and MTTF, the availability and unavailability of the system or each component of that are characterized as follows:

$$Ava_{\theta} = \frac{MTTF}{MTTF + MTTR} \tag{4}$$

$$Uva_{\theta} = \frac{MTTR}{MTTF + MTTR} \tag{5}$$

Each component of the stand-alone PV system involves various subassemblies with the specific failure rate. Indeed, each component contains devices which are arranged in series and parallel. Therefore, reliability of the component depends on its subassemblies configuration. For the system which consist of

N_{series} components in series, the total reliability is computed as follows:

$$R_{tot}^{series}(t) = \prod_{i}^{N_{series}} R_i(t) \quad (6)$$

In addition, reliability for the system with $N_{parallel}$ parallel components is computed as follows:

$$R_{tot}^{paral.}(t) = 1 - \prod_{j}^{N_{parallel}} (1 - R_j(t)) \quad (7)$$

Finally, reliability for the system that involves N_{series} components connected in series and $N_{parallel}$ parallel components is calculated using the equation 8 [25].

$$R_{tot}(t) = \left[1 - \prod_{j=1}^{N_{parallel}} [1 - (R_{i,j})^{N_{series}}]\right] \quad (8)$$

In order to assess the performance of the stand-alone PV systems, average expected energy not supplied of the system ($EENS$) is utilized as follows:

$$EENS_{syst} = \frac{\sum_{t=1} ENS_t}{\overline{N}} \quad (9)$$

B. The effect of weather temperature and humidity on the failure rate

As mentioned, the stand-alone PV systems consist of different components. Each one also involves different devices which are sensitive to the ambient conditions, especially weather temperature and humidity. Indeed, ambient conditions affect the optimal performance of such devices, and the failure rate of them is changed. Arrhenius model [26], has been utilized in this paper to consider the weather temperature effect on the failure rate of each component as follows:

$$\lambda = \lambda_\circ \times Exp(-[\frac{E_a}{K}(\frac{1}{T_{temp}} - \frac{1}{T_{temp_0}})]) \quad (10)$$

The humidity of the weather is also known as another critical factor in the reliability analysis. The failure rate of the component increases in case of a high amount for the humidity. The effect of weather's humidity on the failure rate of the component is modeled as follows [27]:

$$\lambda = \lambda_0 \times (\frac{HP}{HP^\circ})^c \quad (11)$$

It should be mentioned that the amount of the c is 2.7.

C. Stand-alone PV systems' components

C.1. PV module

PV module consists of different subassemblies such as PV cells, front glass, encapsulate, solar bond, and junction box. The failure of the PV module occurs in case of failure of each subassembly. Indeed, a series configuration is considered for the PV module, and the failure rate of that equals to the sum of the failure rates of the subassemblies. Moreover, the output power of the PV module is dependent on the global solar irradiation at a particular area. In this paper, global solar irradiation is assumed as uncertain parameter which affects on the output power of the PV system. In the next subsection, the process of scenario generation has been discussed in more details. Therefore, based on the global solar irradiation at each particular time, the output power of the k^{th} PV module is computed as follows [28]:

$$P_{module,k}^{Exp}(w) = \begin{cases} P_{module,k}^{nom.} & G_a(w) \geq G_{STD.} \\ P_{module,k}^{nom.} \times \frac{G_a}{G_{STD.}} & G_{Crt.} \leq G_a(w) \leq G_{STD.} \\ P_{module,k}^{nom.} \times \frac{G_a^2}{G_{STD.}G_{Crt.}} & 0 \leq G_a(w) \leq G_{Crt.} \end{cases} \quad (12)$$

Where, $G_{STD.}$ and $G_{Crt.}$ refer to the solar irradiation in the standard environment and certain irradiation point which set usually as 1000 (W/M^2) and 150 (W/M^2) respectively. The aging effect of the PV module on its output power per year of operation is considered as follows [29]:

$$P_{module,k}^{Real}(w) = P_{module,k}^{Exp}(w) \times [1 - (yr - 1)m] \; \forall yr = 1, 2, ..., \overline{N} \quad (13)$$

Finally, the total output power of the PV array is equal to the sum of the output power of the PV modules.

C.2. Battery

Battery bank plays an essential role in increasing the availability of the stand-alone PV systems during the night hours. For the critical areas, the battery bank is designed in a way that supports the energy during the three no-sun shines days. Moreover, the design of the battery bank is dependent on other factors, such as the required amount of energy during the night hours. Since the utilized battery in this system involves chemical materials, the failure rate of that relies on the ambient temperature and humidity. However, one of the crucial factors that reduces the number of life cycles of the battery is the depth of discharging (DOD). The DOD leads to reduce the life cycles of the battery and consequently increases the failure rate of it. In ref [30], life cycle data per different DOD levels has been provided for the lithium-ion battery and the relationship between them has been fitted using the power-law distribution as follows:

$$Cycle_b^{life} = 1783.8 \times (DOD_b)^{-1.4832} \quad (14)$$

Indeed, the ambient conditions, DOD, and a number of consecutive no-sunshine days are the main parameters that influence on the failure rate of the battery. Also, the selected configuration of the battery bank determines its total reliability in the stand-alone PV systems. The operation constraints of the battery are systemized as follows [31]:

$$P_{b,ch}^{min} \leq P_{b,ch,t} \leq P_{b,ch}^{max} \quad (15)$$

$$P_{b,dis}^{min} \leq P_{b,dis,t} \leq P_{b,dis}^{max} \quad (16)$$

$$SoC_{b,t} - SoC_{b,t-1} = (\eta_b^{ch} P_{b,ch,t} - P_{b,dis,t}/\eta_b^{dis}) \times \Delta t \quad (17)$$

$$SoC_b^{min} \leq SoC_{b,t} \leq SoC_b^{max} \quad (18)$$

$$SoC_{b,t=0} = SoC_b^{Initial} \quad (19)$$

$$P_{b,ch,t} \times P_{b,dis,t} = 0 \quad (20)$$

Equations 15 and 16 illustrate the allowable amount for the charging and discharging of the battery at each particular time. The next constraint demonstrates the energy level of the battery within each time. The allowable range for the energy level variation of the battery has been restricted using equation 18. Equation 19 refers to the initial status of the battery. Finally, the last equation implies that the simultaneous charging and discharging of the battery within a given time is invalid.

C.3. Inverter

An inverter is known as an important component in the stand-alone PV system that failure of it may fail the system. Inverter is composed of power electronic devices such as IGBT module, DC-link Cap, Microcontroller, and DC/AC contactors. The failure at each subassembly leads to the failure of the inverter. So, the failure rate of the inverter equals to the sum of the failure rates of its subassemblies. Also, ambient conditions have an impact on the failure rate of the inverter.

C.4. Other components

Other components of the stand-alone PV systems involve control charger, fuse, DC connector, and solar cables. In this paper, solar cables are considered to be ideal, but the failure and repair rates of the other components have been taken into account during the reliability assessment of the system.

D. Scenario generation and reduction methods

In this paper, the global solar irradiation is assumed to be uncertain parameter. The normal distribution function models the probability density function of the irradiation. MCS is selected to generate the different scenarios for the irradiation at each particular time. Then, the number of the generated scenarios has been reduced to the acceptable range using the fast forward scenario reduction approach based on the following steps [32]:

- Step 0:

Computation of the cost function is done for each pair of the scenarios in the initial set as follows:

$$\Gamma(w,w') = \|v(w) - v(w')\| \tag{21}$$

- Step 1:

The first scenario of the target set is specified using the equation 22 as follows:

$$w_1 = \arg \mathrm{Min}_{w\in\Phi} \sum_{w'=1, w'\neq w} p(w')\Gamma(w,w') \tag{22}$$

- Step l:

In this step, the l^{th} scenario from the initial set is transferred to the target set based on the following equations:

$$w_l = \arg \mathrm{Min}_{w\in\Phi^{l-1}} \sum_{w'\in\Phi^{l-1}} p(w')\Gamma^l(w,w') \tag{23}$$

$$\Gamma^l(w,w') = \mathrm{Min}[\Gamma^{l-1}(w,w'), \Gamma^{l-1}(w,w_{l-1})] \ \forall w,w' \in \Phi^{l-1} \tag{24}$$

As seen from equation 24, the cost function at each iteration is renewed. This step is iterated $\xi_w - 1$ times.

- Final step

This step determines the probability of the selected scenarios in the target set. Indeed, the probability of the non-selected scenarios in the non-target set Φ^- is added to the probability of the selected scenarios. This can be done using the following equations.

$$p_w + \sum_{w'\in X(w)} p(w') = p_w^{\bullet} \tag{25}$$

$$X(w) = (w' \in \Phi^- | w = x(w')), \ x(w') \in \arg \mathrm{Min}_{w^{\bullet\bullet}\in\Phi^+} \Gamma(w^{\bullet\bullet}, w') \tag{26}$$

As seen, after the accomplishment of the scenario reduction approach, the number of the selected scenarios has reduced to the specific amount, and the probability of each one has been renewed.

3. SOLUTION METHODOLOGY

In this section, the process of reliability evaluation of the stand-alone PV system is explained. Different methods are available to calculate the reliability metrics of the system in the literature. In this paper, the MCS approach is chosen to assess the reliability of the stand-alone PV system due to its computational efficiency. The reliability calculation of the stand-alone PV system is not the same as the grid-connected one. In the grid-connected PV system, the failure of the system occurs in case of failure of each subsystem like PV array, battery bank, or inverter. Whereas, in the stand-alone PV system, energy supply may be continued despite the failure of the PV arrays throughout the battery bank. Thus, different up states of the system must be considered in this type of the PV system in order to obtain accurate reliability indices. It should be mentioned that the up state of the PV system at the time t indicates that the PV system is able to supply the power requirement of the area completely without any interruption at that time. However, the down state of the PV system emphasizes that the PV system fails to provide the whole power requirement of the area at time t. Indeed, the following constraint should be satisfied once the system stands on the up state.

$$\sum_{k=1}^{N_{module}} P_{module,k}^{Real}(w,t) + \sum_{b=1}^{N_b} [P_{b,dis,t} - P_{b,ch,t}] \geq P_t^{load} \tag{27}$$

The following steps describe how the MCS method determines the up and down states of the system.

- Initial step

In this step, according to the planning results of the stand-alone PV system, and the optimal arrangement of the PV arrays and battery bank, failure rate of each subsystem is determined. Then, the reference time for calculation of the reliability (N_{run}) is identified and the count set to 0. ($\delta = 0$)

- Step 1

Update counter: $\delta = \delta + 1$

- Step 2

In this part, periods of time in which the component is up and down are calculated for each one in the stand-alone PV systems. To this end, uniformly random numbers in the [0 1] interval (r_1, r_2) is generated for them. Finally, up and down duration of θ^{th} component are computed as follows:

$$T_{Up}^{\theta} = -MTTF_{\theta} \times Ln(r_1) \tag{28}$$

$$T_{Down}^{\theta} = -MTTR_{\theta} \times Ln(r_2) \tag{29}$$

$$T_{tot}^{\theta} = T_{tot}^{\theta} + T_{Up}^{\theta} + T_{Down}^{\theta} \tag{30}$$

This step continues until constraint 31 is satisfied for each component of the system.

$$T_{tot}^{\theta} \geq N_{run} \; \forall \theta \quad (31)$$

- Step 3

This step specifies the state of the PV system. This is done based on the up and down states of each component in the previous step and the configuration of the system. It should be noticed that the system may be in the up state despite the failure of one of the PV arrays or battery bank. Whereas, the system fails when the failure occurs for both of them simultaneously within a specific time.

- Step 4

According to the up and down states of the system and global solar irradiation, the output power of the PV arrays, the energy level of the battery, and the system's power supply are determined for each time of the analysis using equations 12, 15-20.

- Step 5

Reliability metrics for the stand-alone PV system are computed according to the results obtained in the previous step.

- Step 6

The MCS approach is terminated when the iteration counter becomes large enough.

Flowchart of the stochastic reliability evaluation of the stand-alone PV system has been illustrated in Fig. 1.

As seen in Fig. 1, the up and down states of the system have been shown in box C of the flowchart. Box C implies that the PV-system can stand in up state at each time despite the failure of one of the PV arrays or battery bank once the equation 27 is satisfied.

4. SIMULATION AND RESULTS

In this section, the proposed mechanism for evaluation of the stand-alone PV system's reliability is implemented into the case study to verify its efficiency. The suggested case study involves 684 PV modules arranged in six PV strings, battery bank with 16 battery packs, and each pack consists of six batteries connected in series, one control charger, 7 fuses, one DC connector, and one inverter. The total energy must be supplied by the case study during the 24 hours is 500 (Kwh). It should be mentioned that, the number of components of the selected case study has been specified through the simulation in the PVsyst software [33]. In addition, the number of components for the selected case study can be found in [9]. The nominal power of the PV module model ND-210E1F of SHARP product is 210 W. the schematic of the case study has been shown in Fig. 2.

The number of reduced scenarios for the global solar irradiation is 20. Table 1 presents the failure and repair rates of the stand-alone PV system's components.

In addition, the reference temperature and humidity for the stand-alone PV system are considered to be 25°C and 65%. All simulations have been done under the 64-bit 7 using 2.5GHz Core i5 CPU system using MATLAB software.

Table 2 specifies the reliability of the stand-alone PV system's components separately per different years of operation.

As depicted from Table 2, the reliability of the components decreases in case of increasing the years of operation. However,

Table 1. Failure and repair rates of the stand-alone PV system

Component	Failure rate $failure.year^{-1}$	Repair rate $year^{-1}$
PV module	0.0280	0.0677
Battery	0.1129	0.0057
Inverter	0.3529	0.0833
Fuse	0.0027	0.0208
DC connector	0.0017	0.0208
Charge controller	0.0564	0.0161

Table 2. Reliability evaluation of each component per years of operation

Component	Years of operation					
	1	5	10	15	20	25
PV string	97.24	86.92	75.55	65.67	57.08	49.62
Battery	89.32	56.66	32.33	18.38	10.45	5.94
Inverter	70.26	17.12	2.93	0.51	0.008	0.001
Fuse	99.73	98.64	97.30	95.97	94.66	93.37
DC connector	99.82	99.13	98.26	97.14	96.56	95.71
Charge controller	94.51	75.42	56.88	42.90	32.36	24.41

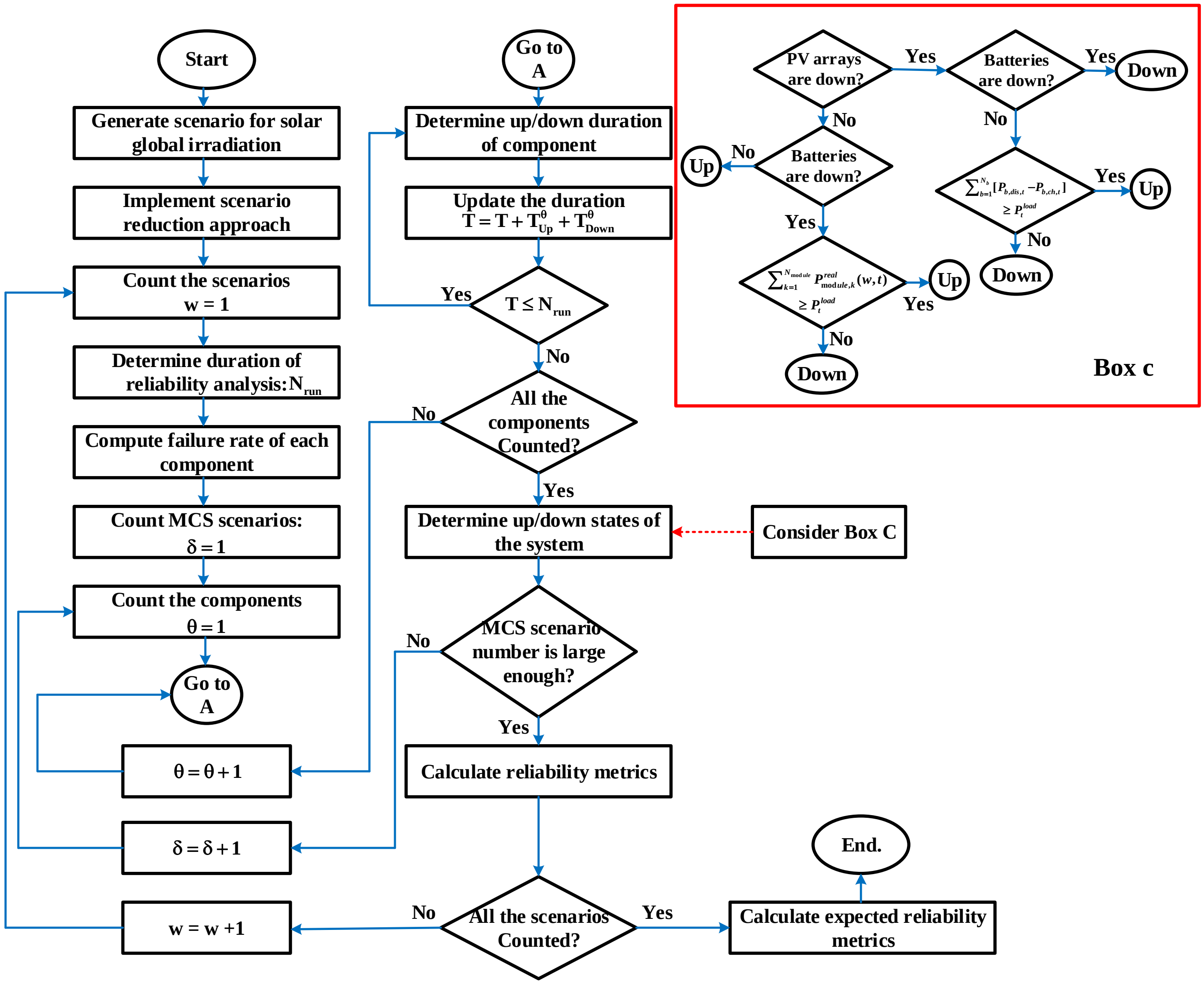

Fig. 1. Flowchart of the proposed approach for stochastic reliability evaluation of stand-alone PV system

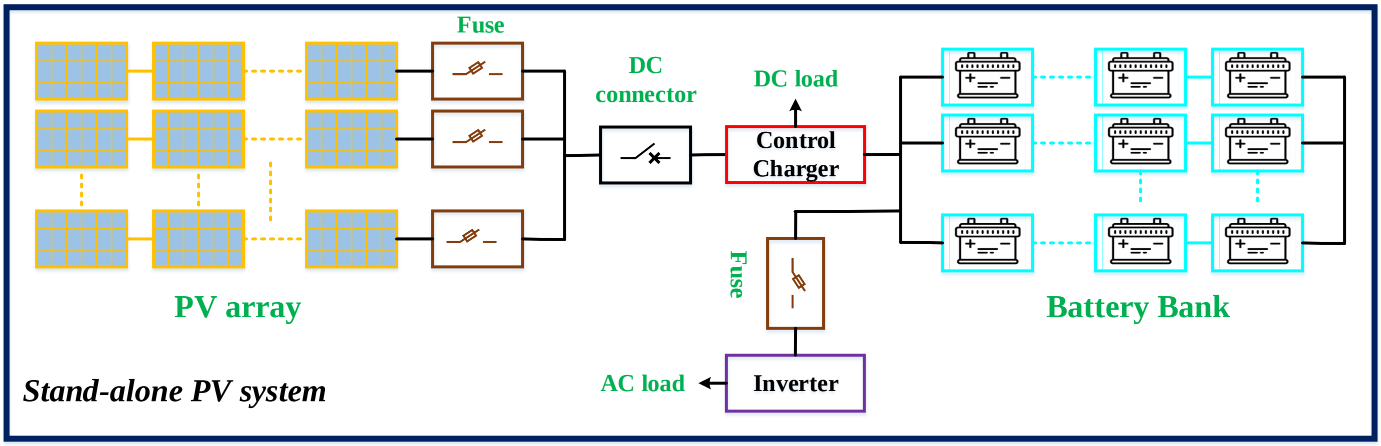

Fig. 2. The schematic of the case study

the rate of decrease is not the same for all components. From table 2, it can be concluded that the inverter and battery are two vulnerable components in the stand-alone PV systems in comparison with other ones. The mentioned components involve power electronic devices and chemical material, which lead to an increase in the failure rate of them. Thus, the product technology of them must be enhanced in order to be more reliable in the future.

Table 3 clarifies the expected availability of the stand-alone PV system and the average EENS during each years-of-operation, respectively.

Table 3. Expected availability and average EENS of the PV system

Years of operation	Availability (%)	EENS *Kwh*
1	99.90	130.484
5	99.86	141.18
10	99.79	174.14
15	99.37	191.48
20	98.96	241.95
25	98.74	375.81

As expected from Table 3, once the years of operation of the PV system increases, the availability of the system decreases. However, it is seen that the rate of the reduction is low and can be acceptable for the stand-alone PV system. In addition, Table 3 presents the average EENS for each duration of the operation. It is observed that the amount of the average EENS in comparison with the total supplied energy is low. Thus, based on the system availability and amount of the average EENS, it can be concluded that the optimal design of the stand-alone PV system can be utilized as a primary system for the critical areas.

Fig. 3 compares the expected availability of the system alongside the amount of the EENS per different temperature of the ambient for the 25 years of operation.

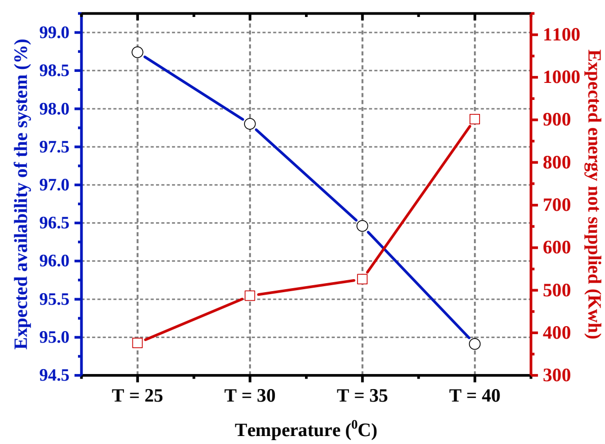

Fig. 3. The expected availability and EENS amount per different ambient temperature

Fig. 3 displays the availability of the system for different ambient temperatures. Ambient temperature as a crucial factor changes the failure rate of the components. When ambient temperature increases in the territory where the PV system has been located, the availability of the system to support the load decreases. Consequently, the EENS rises. Findings can be concluded from Fig. 3 per different years of the operation.

The humidity of the ambient is the other relative factor with the weather conditions of the location that influences the availability of the PV systems. Fig. 4 demonstrates the effect of the humidity on the reliability metrics of the suggested stand-alone PV system.

As proved in Fig. 4, ambient humidity causes a reduction in the expected availability of the system. This can be true for each duration of the operation. Moreover, the average of the EENS increases by the growth of the humidity percentage in the location of the stand-alone PV system. The results obtained from Fig. 3 and Fig. 4 revealed that the ambient conditions have a significant effect on the reliability of the PV system. It is

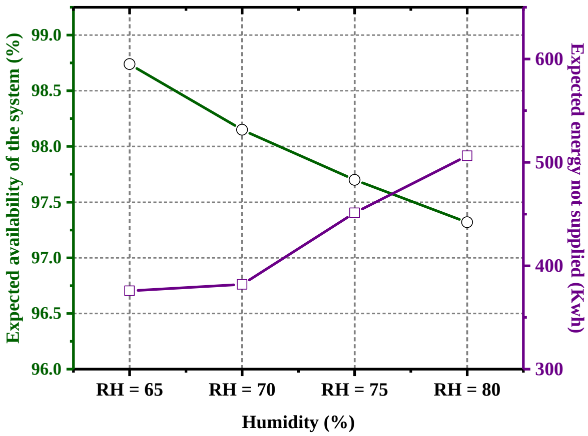

Fig. 4. The expected availability and EENS amount per different ambient humidity

noteworthy to mentioned that the effect of the high temperature on the availability and optimal performance of the system is more destructive than the high humidity.

Therefore the reliability of the stand-alone PV systems planned for the critical areas must be evaluated considering the ambient conditions in parallel with other functional factors such as considering all up/down states of the system without any approximation and uncertainty of the irradiation.

5. CONCLUSION

The accurate availability analysis of the stand-alone PV system for the sensitive places which must reliably supply the load is an essential problem. This paper was managed to propose the new method for the stochastic reliability calculation of the stand-alone PV system considering all up and down states without any approximation. Different scenarios were generated to consider the uncertainty of the global solar irradiation on the process of the reliability calculation. Then, the fast forward scenario reduction approach was utilized to reduce the number of scenarios and improve the simulation execution time. In addition, the impact of the ambient conditions such as temperature and humidity on the failure rate of the components, and PV modules' aging issue was taken into account in the proposed approach. These considerations led to an increase in the accuracy of the reliability calculation for the stand-alone PV systems. Our findings would seem to suggest that the optimal stand-alone PV system can be utilized as main energy system for the critical areas. The worst availability for the system during the 25 years of the operation is 98.74% (Table 3). Moreover, it was hypothesized that the increase in the ambient temperature resulted in a decrease in the availability of the system. (Fig. 3). A similar finding is also true for the humidity of the location (Fig. 4). However, the effect of the temperature on the reliability metrics of the system is more significant. To sum up, this paper provided the novel framework for a stochastic reliability evaluation of the stand-alone PV system considering the uncertainty of the global solar irradiation and effect of the ambient conditions on the failure rate of the components. However, further work needs to be carried out to investigate the uncertain impact of the load side on the reliability assessment of the stand-alone PV systems.

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