Reliability Evaluation of a Solar Photovoltaic System with and without Battery Storage

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Sanajaoba Sarangthem
Indian Institute of Technology Roorkee

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S. Sanajaoba Singh
Electrical Engineering Department
Indian Institute of Technology Roorkee
Roorkee-247667, Uttarakhand, India
sanajaoba88@gmail.com

Eugene Fernandez
Electrical Engineering Department
Indian Institute of Technology Roorkee
Roorkee-247667, Uttarakhand, India
eugenefdz@gmail.com

***Abstract*—Solar energy is considered as one of the major renewable energy sources and electricity generated from photovoltaic system involves zero green house gas emission and zero dependence on fossil fuel. However, the use of solar energy suffers from the challenge of ensuring steady flow of electric power particularly during the periods of low solar radiation. This has caused system designers to look into the reliability aspects of solar photovoltaic systems. One way of minimizing the impact of irregular power supply is by the inclusion of a storage unit so that the surplus energy generated during period of high solar radiation can be stored and utilized later during periods when solar radiation is low or absent. But, storage systems using batteries are an expensive proposition. It is of interest to system design engineers to examine just how much is gained in terms of reliability of power delivery at the cost of hardware failure of panel for solar PV systems operated with and without battery storage. The present paper attempts to investigate the changes in system reliability of a solar photovoltaic system under the cases of operation with and without adequate battery storage. Reliability estimation through Loss of load probability index is carried out using Monte Carlo Technique.**

Keywords—solar photovoltaic; battery storage; reliability evaluation; loss of load probability; Monte Carlo simulation

I. INTRODUCTION

The rapidly increasing energy demand and the concerns over environmental degradation resulted from use of conventional energy sources have opened the options for exploring more alternative sources for energy production. Solar energy is considered as the major renewable energy source and electricity generated through photovoltaic system involves zero greenhouse gas emission and zero dependence on fossil fuel. Declining production cost of photovoltaic modules coupled with economic incentives offered by governmental organizations will further increase the future installed capacity of solar power. However, the inherent uncertainty and viability associated with system components and input solar radiation pose serious challenges in designing such photovoltaic system. One way of nullifying the impact of intermittency is the inclusion of storage unit so that the surplus energy generated during periods of high solar insolation can be stored and utilized in later time. The reliability assessment of renewable energy based power system without or with energy storage need to be addressed differently from conventional power system since they are considered as variable capacity generation systems.

The reported techniques in literature for reliability assessment can be broadly grouped under two categories: (i) analytical techniques (ii) Monte Carlo simulation. Analytical techniques model the system with mathematical equations and evaluate the desired reliability indices through direct numerical solution [1]. It fails to simulate the actual behaviors of the system which are stochastic in nature. This is overcome by Monte Carlo simulation by treating the problems as a series of real experiments and simulating the random behavior of system components [2]. Reliability evaluation of renewable energy based power system was started in 1980s. In [3], authors introduced new reliability concepts and terminology applicable to PV technology and applications. These new concepts accounts for the variability of input solar energy as well as unique characteristics of the PV array. Many researchers have made various contributions towards renewable energy sources modeling for reliability assessment [4] and [5]. Simulation based methods are adopted in [4] and [6] whereas analytical techniques are used by researchers in literatures found in [7] and [8].

Loss of power supply probability technique is used in [9] for designing stand-alone photovoltaic systems. In [10], chronological simulation technique is used for estimating the loss of load probability of stand-alone photovoltaic systems based on synthetic radiation sequences. A closed-form solution approach is developed in [11] for evaluation of the loss of power supply probability of stand-alone photovoltaic systems with battery storage. Reliability evaluation of renewable energy sources based systems is carried out in [12] using universal generating function. A novel approach for reliability assessment using probabilistic storage model is reported in [13] for an autonomous PV-wind-storage system. However, there are only very few literatures which model the hardware failure of the solar photovoltaic panels.

In view of this, the current work develops a model for photovoltaic system taking into account variable behavior of solar resource and the outages due to hardware failure of panel. The developed model is applied for evaluating the reliability of a remote photovoltaic system identified with loss of load probability (LOLP) reliability index through Monte Carlo simulation. In the first case, a simple photovoltaic

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system without any storage is considered. A comparison is drawn between the calculated values of LOLP reliability index with photovoltaic output considering only variation in solar radiation and other considering both variation in solar radiation and hardware status of photovoltaic modules. Different ratings of photovoltaic such as 30kW, 40kW, 50kW and 60kW are used in order to account for the diversity in the number of photovoltaic modules. In the second case, battery storage is introduced into the previous system and numbers of battery strings are varied for each of the PV rating in order to achieve a LOLP value of 0.0001 while assuming battery and photovoltaic modules as components which is always available. With the numbers of battery strings obtained corresponding to LOLP value of 0.0001, each of the system is subjected to hardware availability of photovoltaic modules and variation in values of reliability index calculated are examined.

II. MODELING PV SYSTEM

A. Available solar power

The power output from a photovoltaic cell is determined by the quantity of solar radiation at a particular site. Many locations around the world seldom have recorded solar radiation data. Hence, generation of synthetic hourly solar radiation data becomes necessary for PV system reliability studies. HOMER simulation program [14] is used to generate synthetic hourly solar radiation from monthly average values available at a given location. The program synthesizes hourly solar radiation data based on Graham algorithm [15] and required only the latitude and monthly averages. The hourly output of the PV array is calculated using the following formula.

$$P^t{}_{pv} = f_{pv} Y_{pv}\left(\frac{I_T}{I_S}\right) \tag{1}$$

where

f_{pv} = PV derating factor.

Y_{pv} = PV array capacity.

I_T = global solar radiation incident on the PV array.

I_S = 1 kW/m^2.

The PV derating factor is a scaling factor (typically less than or equal to 100%) applied to the PV array output to account for losses incurred due to higher ambient temperatures, different operating voltages, and soiling of the panels.

B. Capacity levels due to hardware failure of PV

Photovoltaic modules consist of packaged, connected assembly of PV cells which are often considered as the most reliable elements in PV systems. Nevertheless, the modules can also fail or degrade in their long-term lifecycle. Hardware failure of photovoltaic modules results in different capacity states of PV system. In PV system, failure of some PV strings only decreases the PV output and does not lead to failure of the whole PV system. Several PV modules fail independent of one another and hence the hardware failure events can be represented by a random variable and is assumed to follow a Binomial distribution [16]. Various capacity states due to hardware failure of the PV system and corresponding probabilities can be represented by the following probability distribution:

$$C_{pv} = \{P_{pv}(i),\ F_{pv}(i);\ i = 0\ to\ N_{pv}\} \tag{2}$$

where $P_{pv}(i)$ is the capacity state when i modules are operating out of N_{pv} total modules and is given by $P_{pv}(i) = \frac{i \times p_m}{N_{pv}}$; p_m is the maximum power available from the PV modules.

The probabilities corresponding to different capacity states for a set of identical modules are given by

$$F_{pv}(i) = \binom{N_{pv}}{i}(1-q_{pv})^i\, q_{pv}{}^{N_{pv}-i} \tag{3}$$

where q_{pv} = unavailability.

C. Actual hourly available power

The following steps describe the procedure for calculation of actual hourly available power from PV taking into account the capacity states due to hardware failure.

1) Generate hourly output power from (1) using the hourly variation in solar radiation.
2) Model the PV modules operating states using Binomial distribution given in (3).
3) Generate a random number between [0, U]; U= upper limit on the probability of capacity state.
4) Check if random number < probabilities of residing in capacity state i. chosen randomly from model developed in step 2.
5) If yes, calculate $P^t{}_{pv-actual} = \frac{P^t{}_{pv} \times P_{pv}(i)}{P(N_{pv})}$
6) Else $P^t{}_{pv-actual} = P^t{}_{pv}$

III. MODELING BATTERY STORAGE

The kW power flow through the battery is given by

$$P^t{}_{batt} = P^t{}_{pv-actual} - Load^t / \eta_{con} \tag{4}$$

where

$Load^t$ = Load during t^{th} time unit, kW.

η_{con} = Converter efficiency.

A positive value of (4) signifies battery charging mode and a negative value indicates the discharging mode of battery. The charging and discharging operation of the battery changes the battery state of charge (*SOC*) accordingly and can be calculated as

$$SOC^{t+1} = SOC^{t}\left[1-\frac{\sigma}{24}\right]+\frac{P^{t}{}_{battery}\times l(t)\times \eta_{batt}}{E_{batt}} \tag{5}$$

where η_{batt} is battery charging efficiency in charging operation and discharging efficiency in discharging operation, σ is the self discharge rate of battery, $l(t)$ is the length of t^{th} time unit and E_{batt} is the energy rating of battery storage.

Further, the battery charging and discharging operation is constrained by following equation.

$$P^{t}{}_{batt,c\max} \leq P^{t}{}_{batt} \leq P^{t}{}_{batt,d\max} \tag{6}$$

where

$P^{t}{}_{batt,c\max} = (SOC_{\max} - SOC^{t})\times E_{batt}$; maximum battery charge power.

$P^{t}{}_{batt,d\max} = (SOC^{t} - SOC_{\min})\times E_{batt}$; maximum battery discharge power.

IV. MONTE CARLO SIMULATION

Monte Carlo method (MCS) is a widely used class of simulation techniques which works with random numbers for solving problems such as uncertainty analysis, optimization, and reliability based design etc [17]. This method evaluates iteratively the behavior of physical systems and mathematical model (deterministic) using set of random numbers as inputs. The use of random numbers characterizes MCS as non-deterministic and comes under the category of stochastic calculations. MCS can also be categorized as a sampling method because of random generation of inputs from probability distributions in order to simulate the process of sampling from an actual population. In the present case, Monte Carlo simulation is utilized to evaluate LOLP values at different ratings of photovoltaic only and photovoltaic-battery combination.

A. *Assumptions made for simulation*

1) Total duration of time series taken as 1 year is discretized with each time unit equal to 1 hour.
2) Same year has been sampled many times equal to the total number of iterations.
3) Load demand and generated power remain constant during each hour simulated.
4) Each state representing load demand and generation is unique and will occur only once in total duration of time series for small discretization.
5) Each state representing load demand, generation is sampled by randomly choosing an integer uniformly distributed in [1, 8760].

B. *Simulation procedure*

1) Read hourly generation and load state (X_i); i =1 to 8760, initialize sample size (N), C=0.
2) Randomly select X_j sample with size *N*, where $X_j \in X_i$; $j=1$
3) Classify X_j as $X_{failure}$ and $X_{success}$. $X_{failure}$ is identified when system load level is greater than total generation while $X_{success}$ is identified when system load is equal to or less than total generation.
4) If $X_j = X_{failure}$ then $C = C+1$.
5) Repeat steps 3 to 4 till $j = N$.
6) Calculate $LOLP = \frac{C}{N}$
7) Repeat steps 2 to 6 until acceptable value of $LOLP$ or stopping criteria is reached.

V. DESCRIPTION OF STUDY AREA AND SYSTEM COMPONENTS

A. *Location*

The study area is located at Almora district of Uttarakhand, India having a total population of 1437 with 267 households. This geographical location is identified with latitude of 29038''21'N and longitude of 79029''56'E having a height of 1576 meters from mean sea level.

B. *Solar resource*

The region lying between 300N to 300S latitude are best suitable for solar energy utilization and the part of India in between 80N to 320N are the best suitable for solar energy utilization. The solar radiation data is taken from [18] and the study area has annual average solar radiation of 4.67 kWh/m2/day. Solar radiation profile spanning over a year is shown in fig.1. HOMER synthetically generates hourly solar radiation data based on monthly averages and latitude of the location using Graham algorithm.

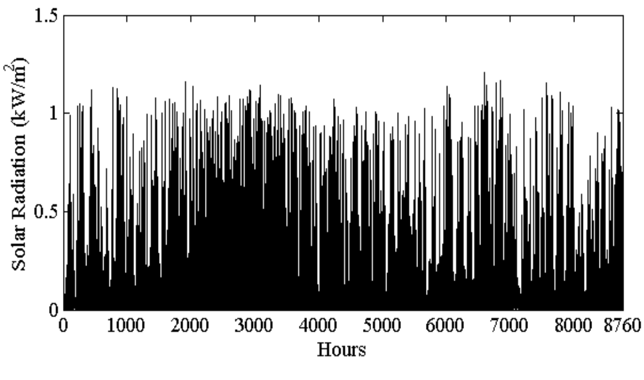

Fig. 1. Solar radiation profile of study area.

C. Load profile

The system hourly load profile is given in fig.2 with energy consumption of 47 kWh/day and 8.9 kW peak. The load profile is synthetic and obtained using HOMER software from the load data reported in the literature [19].

D. PV modules

PV modules selected is a 36-cell polycrystalline (PV-MF100EC4) rated at 100 Wp [20]. Different numbers of PV modules can be connected in series in order to give higher ratings say 300 PV modules connected in series to generate 30kWp and similarly other higher ratings can also be achieved.

E. Battery storage

Battery model Surette 6CS25P is considered for the study. Technical specifications of the battery are given in table I. Higher energy capacity is achieved by series connection of batteries to form battery string with each string consisting of 4 batteries and capable of producing 28 kWh of electricity.

F. Converter

Systems consisting of both AC and DC components require a converter. An inverter converts DC electricity to AC electricity and the efficiency at which the conversion takes place is assumed constant and taken as 90% with a life time of 15 years. A 10kW converter capable of supporting the peak demand is considered in the study.

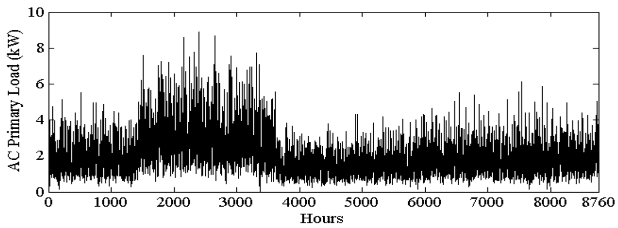

Fig. 2. Load profile of the study area

TABLE I. TECHNICAL SPECIFICATION OF SURRETTE 6CS25P BATTERY

Nominal capacity	1156Ah (6.94kWh)
Nominal voltage	6V
Round trip efficiency	80%
Minimum state of charge	40%
Float life	12years
Maximum charge rate	1A/Ah
Maximum charge current	41A
Lifetime throughput	9645kWh

VI. RESULTS AND DISCUSSION

In the first case, the proposed methodology is applied to a standalone photovoltaic system without any storage device as in fig. 3. Different photovoltaic ratings of 30kW, 40kW, 50kW and 60kW are considered in order to investigate the impact of hardware availability and unavailability of photovoltaic modules on the system reliability. Reliability analysis is carried out by evaluating LOLP reliability index through Monte Carlo simulation. LOLP is calculated first by considering only the hourly variation in solar radiation and second by considering both the variation in solar radiation and hardware status of the photovoltaic modules. Fig.4 depicts the difference in LOLP values calculated for different photovoltaic ratings. Examination of the fig.4 reveals that considering hardware status results in higher values of LOLP as compared to the system without considering hardware status. Hardware failure of the solar modules results in different output capacity levels thereby reducing the overall available solar power. Hence, when the actual hourly available generated photovoltaic power is combined with system hourly load data, reduced level of available solar power due to hardware failure results in higher values of LOLP evaluated. Therefore, there is a strong need to consider the hardware status of photovoltaic modules for reliability analysis otherwise assumption of photovoltaic modules as always available unit may give inaccurate results.

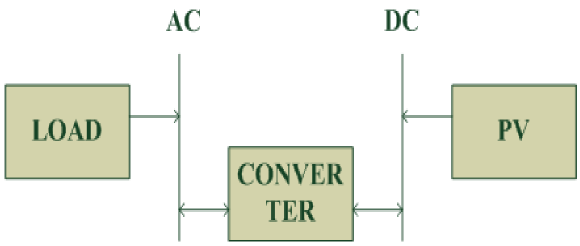

Fig. 3. Configuration of a standalone PV system

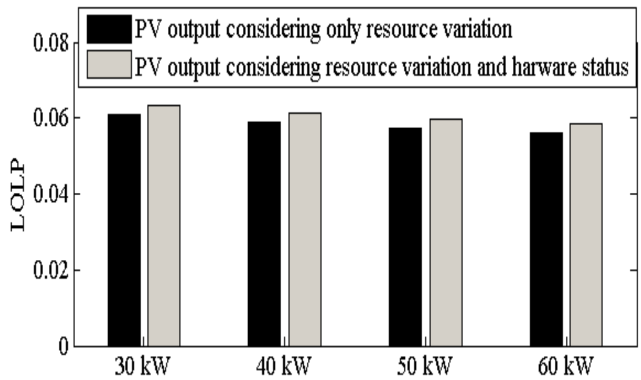

Fig. 4. Comparison of LOLP values between PV system considering only resource variation and other considering both resource variation and hardware status of PV modules

In the second case, battery system is utilized as energy back up unit as shown in fig.5 and the number of battery strings is searched to achieve a fairly lower value of LOLP say 0.0001 for each of the photovoltaic ratings as in [19] without considering the hardware status of the PV. Corresponding to LOLP value of 0.0001, the required number of battery strings for each of the photovoltaic ratings is given in table II.

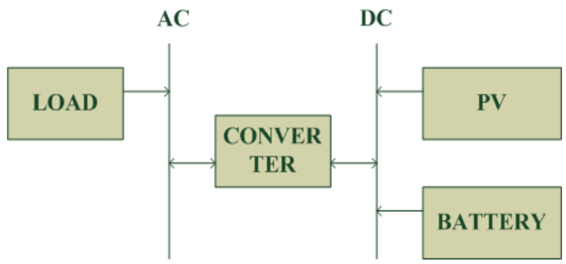

Fig. 5. Configuration of a standalone PV system with battery

TABLE II. NUMBER OF BATTERY STRING REQUIRED TO ACHIEVE LOLP=0.0001

Sl. No.	PV ratings	No. of battery strings	Battery Capacity
1.	30kW	9	252kWh
2.	40kW	7	196kWh
3.	50kW	6	168kWh
4.	60kW	5	140kWh

As seen from table II, 9 number of battery strings is required by 30kW photovoltaic system, similarly 7, 6 and 5 numbers of battery strings is required respectively by 40kW, 50kW and 60kW photovoltaic system. Each of the photovoltaic-battery system is subjected to capacity outages due to hardware failure of photovoltaic modules in order to investigate the impact of hardware status of the system PV component on the system reliability. While incorporating battery storage in the system, certain aspects need to taken into consideration such as battery capacity, the battery state of charge (SOC) and coordination operating strategy between system and energy storage. The power flow through battery in each time interval is determined according to (2) through coordination operating strategy and actual hourly photovoltaic generation. Fig.6 depicts the kW power flow through the battery for each of the photovoltaic-battery combination. A positive value indicates battery charging operation and negative value indicates battery discharging operation. The charge and discharge operation accordingly change the battery state of charge (SOC) and is updated through (3). The variation of percentage state of charge (SOC) for each of the photovoltaic-battery combination is shown in fig.7. The power flow through the battery is constrained by the maximum battery charge and discharge power which are functions of permissible maximum and minimum battery SOC respectively and battery SOC at that instant of time.

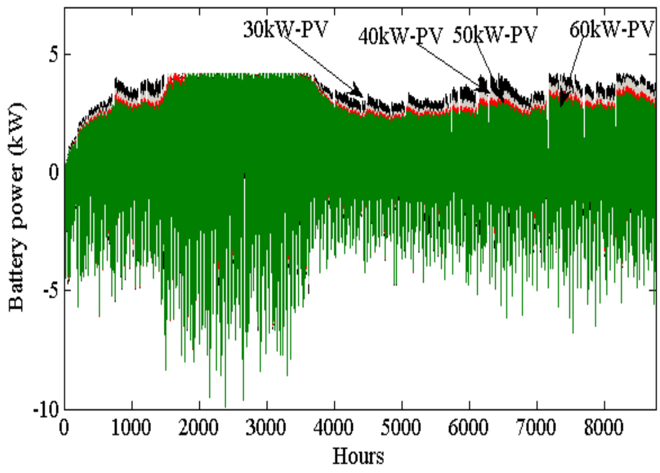

Fig. 6. Variation of power flow through battery for different rating of PV incorporating hardware status of PV

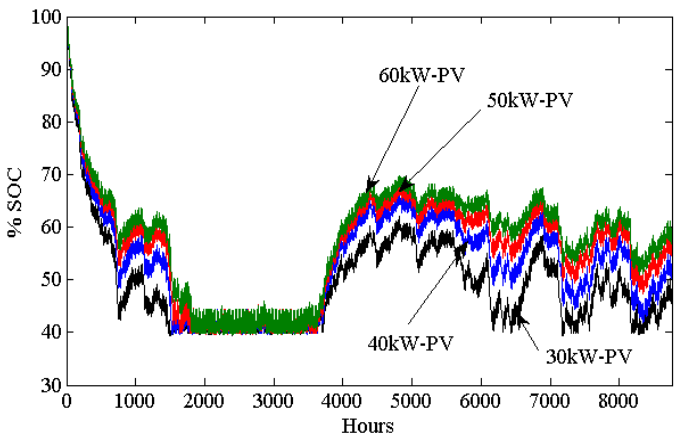

Fig. 7. Variation of % SOC of battery for different rating of PV incorporating hardware status of PV

The variation in the values of LOLP evaluated for each of the photovoltaic-battery combination without and with considering hardware status of photovoltaic module is shown in fig.8. It is observed from the fig.8 that there is a significant increase in values of LOLP obtained when hardware status of the PV component are considered. Hence, the system which was considered fairly reliable with LOLP value of 0.0001 may not give accurate measure of the system reliability when hardware status of PV component is considered. The incorporation of outages due to hardware failure of photovoltaic modules is much in addition to considering resource variation for accurate reliability assessment of such system. The unrealistic assumptions of photovoltaic modules as 100% reliable in reliability analysis may give inaccurate or misleading results.

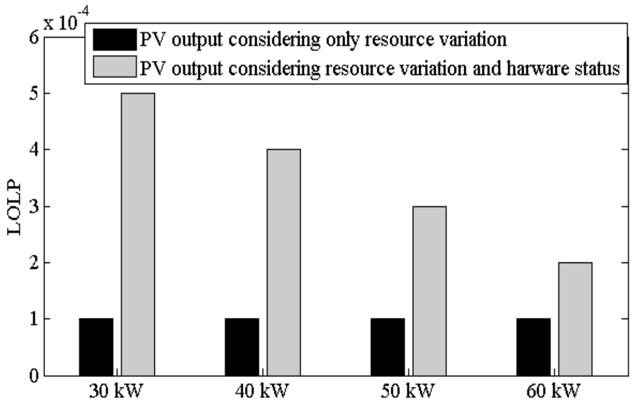

Fig. 8. Comparison of LOLP values between PV-battery system without considering hardware status and other considering hardware status of PV

VII. CONCLUSIONS

This paper presented a new methodology to model the PV component of a stand-alone photovoltaic system with storage batteries for reliability analysis. The developed model takes into account the outages due to hardware failure of photovoltaic modules as well as the intermittent characteristics of the solar resources. The proposed methodology is applied to a remote photovoltaic system taking the solar resource and load profile of a case study area located at Almora district of Uttarakhand, India. Reliability analysis is carried out through evaluation of loss of load probability using Monte Carlo simulation. Simulation results show significant deviation in the values of reliability index evaluated when hardware status of the system component is considered compare to systems without considering hardware status. Hence, neglecting hardware status while modeling system component of such system may not give a true measure of the system reliability.

APPENDIX

Numerical values of the constant used in the simulation.

$\sigma = 0.2\%/day$, $q_{pv} = 0.04$, $\eta_{batt} = 75\%$ (charging),

$\eta_{batt} = 100\%$ (discharging), $SOC_{\max} = 100\%$

$SOC_{\min} = 40\%$, $\eta_{con} = 90\%$

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