Method for Evaluating Battery Size Based on Loss of Load Probability Concept for a Remote PV System

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***Abstract*—Solar photovoltaic power is one of the potential renewable energy generation technologies which have recently received considerable attention globally. However, the stochastic nature of these energy sources makes the power output difficult to predict and control exactly and hence energy storage device is expected to coordinate with such energy sources to maintain system reliability. This paper presents a realistic evaluation model of photovoltaic power and battery storage which can be used in Monte Carlo simulation. The highly intermittent nature of solar radiation, charge/discharge constraints of battery storage and operating coordination between energy storage and system are incorporated while modeling. The developed models are applied for calculating battery size of photovoltaic system based on reliability criteria such as Loss of load probability (LOLP) for a remote case study area. Finally, the system performance is assessed by increasing the peak demand of the study area.**

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

I. INTRODUCTION

The hike in electric energy associated with fossil and nuclear fuels and an increased public concern over potential environmental impacts of conventional energy utilization has created an increased attention for development and exploitation of alternative sources like wind and solar energy. Nowadays, there has been an increasing trend in promoting the use of these energy sources by governmental policies providing financial support in different forms and adopting various rules for penalizing conventional based energy generation facilities that emit green house gases. However, in order to improve performance, accurately predict their output and integrate them with other conventional energy sources, research and development work in solar and wind energy technologies keep on continuing. In this regard, techniques based on probabilistic approaches continue to be developed to access their performance as standalone or grid connected system. A probabilistic battery state model is developed in [1] applicable to a renewable energy based system for reliability evaluation using analytical technique. In [2] battery status for following time segment is calculated based on expected value of charge/discharge power flowing through battery during previous time segment.

In this paper, optimum number of batteries is calculated based on reliability criteria such as Loss of load probability (*LOLP*). Different sized PV systems such as 30kW, 40kW, 50kW and 60kW are chosen and the number of battery strings required to satisfy a specified *LOLP* value of 0.0001 is calculated. A Monte Carlo simulation procedure is used to evaluate the conventional *LOLP* index by varying the number of battery strings corresponding to each PV systems.

LOLP is the overall probability that the available generation capacity is exceeded by the system load level. A *LOLP* value of 0 means the load will be always satisfied and a value of 1 means the load will never be supplied. The system load will be satisfied when the generated power by the PV array is sufficient and battery storage energy is not depleted. When the power generated by PV array is greater than system load, the surplus energy is stored in the batteries. Further, in this paper the impact of increase in peak demand on system performance for each of the` the PV systems considered is analysed.

II. MODELING PV SYSTEM

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 [3] 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 [4] and required only the latitude and monthly averages. The configuration of a solar photovoltaic system with battery storage is shown in fig.1. The hourly output of the PV array is calculated using the following formula.

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

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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.

III. MODELING BATTERY STORAGE

The kW power flow through the battery is given by

$$P^t{}_{batt} = P^t{}_{pv} - Load^t / \eta_{con} \qquad (2)$$

where

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

η_{con} = Converter efficiency.

A positive value of eqn. (2) 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 [5] and can be calculated as

$$SOC^{t+1} = SOC^t \left[1 - \frac{\sigma}{24}\right] + \frac{P^t{}_{battery} \times l(t) \times \eta_{batt}}{E_{batt}} \qquad (3)$$

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.

$$P^t{}_{batt,c\max} \le P^t{}_{batt} \le P^t{}_{batt,d\max} \qquad (4)$$

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.

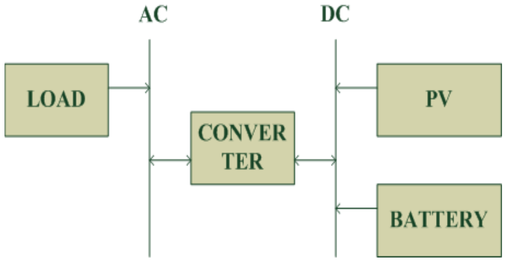


Fig. 1. Configuration of a stand-alone PV system with battery

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 [6]. This method evaluates iteratively the behaviour 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 photovoltaic and battery combination for finding the corresponding battery size satisfying a certain specified reliability criteria.

A. Assumption 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 values of $LOLP$ or stopping criteria is reached.

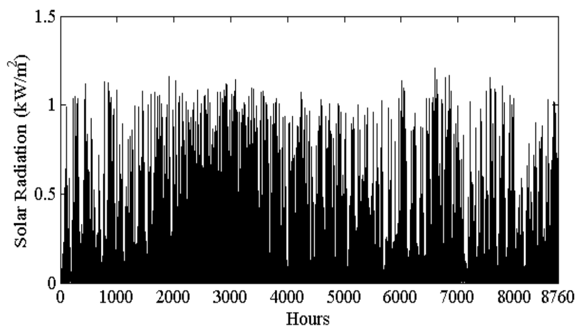


Fig. 2. Solar radiation profile of the study area.

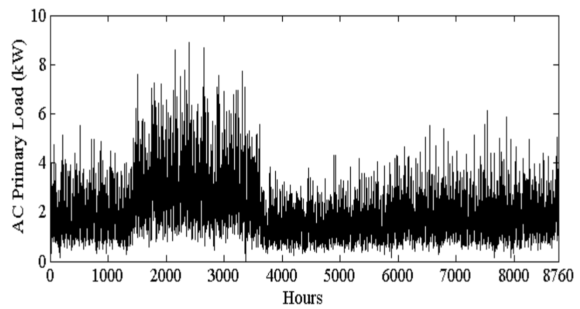


Fig.3. Load profile of the study area.

V. DESCRIPTION OF STUDY AREA AND SYSTE 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 $29^0 38''21'$N and longitude of $79^0 29''56'$E having a height of 1576 meters from mean sea level.

B. Solar Resource

The region lying between 30^0N to 30^0S latitude are best suitable for solar energy utilization and the part of India in between 8^0N to 32^0N are the best suitable for solar energy utilization. The solar radiation data is taken from [7] and the study area has annual average solar radiation of 4.67 kWh/m^2/day. Solar radiation profile spanning over a year is shown in fig.2. HOMER synthetically generates hourly solar radiation data based on monthly averages and latitude of the location using Graham algorithm

C. Load Profile

The system hourly load profile is given in fig.3 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 [8].

D. PV Modules

PV modules selected is a 36-cell polycrystalline (PV-MF100EC4) rated at 100 Wp [9]. 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 1. 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.

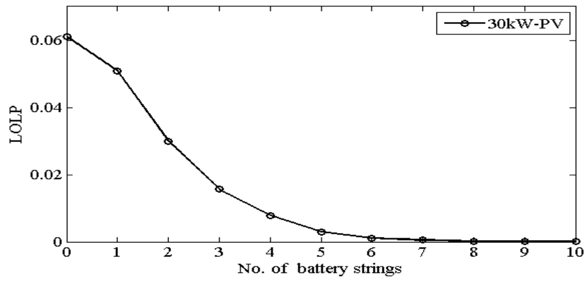
TABLE I. TECHNICAL SPECIFICATIONS OF SURRETTE 6CS25P BATTERY

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

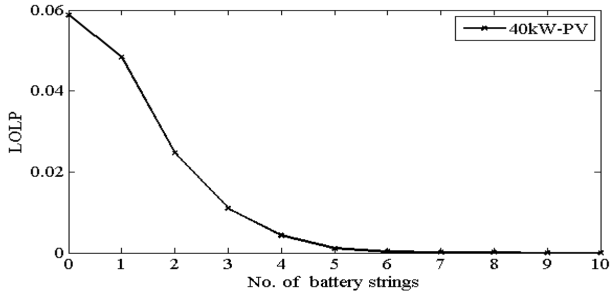
VI. RESULTS AND DISCUSSION

The simulation studies have been carried out on a remote photovoltaic system with battery storage for a case study area located at Almora district of Uttarakhand, India. The number of battery strings is varied from 1 to 10 for each of the photovoltaic ratings. The photovoltaic ratings considered are

30kW, 40kW, 50kW and 60 kW. Each battery string consists of 4 batteries with each battery rated at 6V, 1156 Ah (6.94kWh). Loss of load probability (*LOLP*) is calculated corresponding to number of battery string starting from 0 to 10. Number of battery string equal to 0 indicates system without any battery backup. The plot of *LOLP* values as a function of number of battery strings are given in figs.4(a), 4(b), 4(c) and 4 (d) corresponding to 30kW, 40kW, 50kW and 60kW PV ratings respectively. Analysis of figures reveals that *LOLP* values are reduced when the number of battery strings is increased and same trend is observed for each of the PV rating considered. It is also observed from fig.5 that the higher rating of PV lowers the *LOLP* values obtained at different number of battery strings. However, *LOLP* value settles to zero at different number of battery strings corresponding to different ratings of PV. Table 2 gives the number of battery strings required to achieve *LOLP* value equal to 0.0001 for different PV ratings.



(a)



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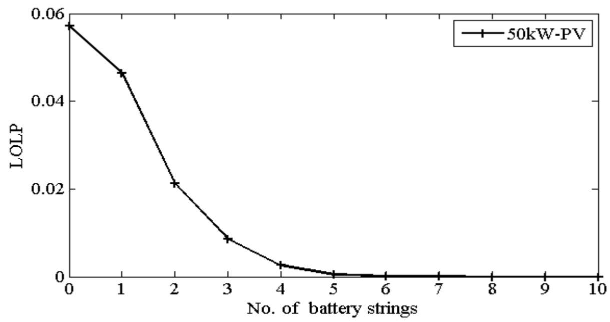
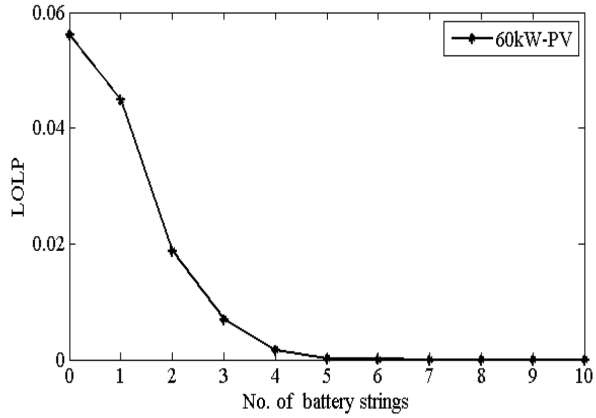


(c)



(d)

Fig.4. Variation of LOLP values as a function of number of battery strings for different PV ratings.

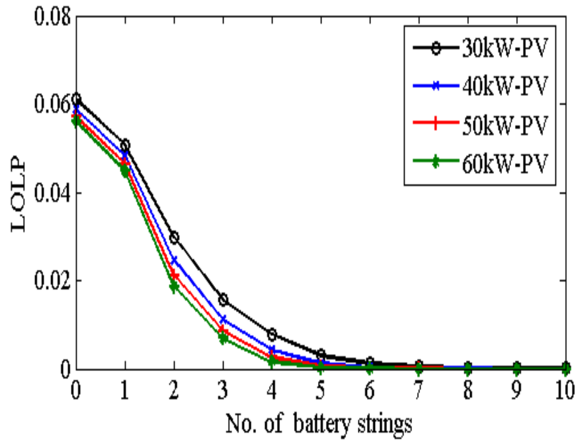


Fig.5. Combined plot of LOLP values as a function of number of battery strings for different PV ratings.

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

Sl. No.	PV ratings	No. of battery strings
1.	30kW	9
2.	40kW	7
3.	50kW	6
4.	60kW	5

Hence, it is clear from table1 that different photovoltaic ratings requires different number of battery strings so as to achieve a specified level of reliability identified by *LOLP* value of 0.0001 in our case. The proposed methodology thus, provides a way of estimating battery storage size in terms of number of strings of battery required by different sized photovoltaic systems.

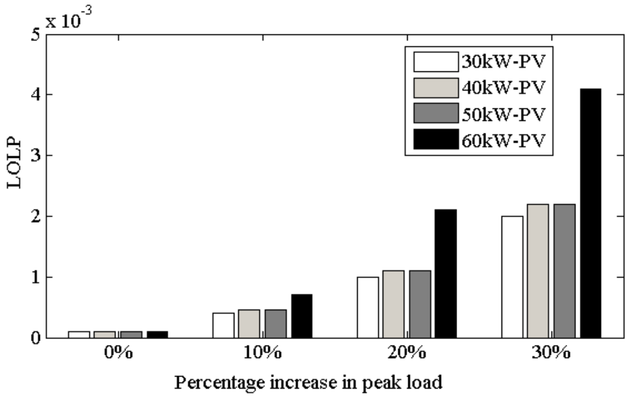


Fig. 6. Variation of LOLP with load growth.

The obtained different photovoltaic-battery combinations are further simulated for various cases of increase in peak load such 10%, 20% and 30% increase in peak load while maintaining the same load shape. Fig.6 compares the increase in loss of load probability with increase in peak load for all photovoltaic-battery combinations. System reliability degrades with increase in load as observed from increase in *LOLP* values evaluated at each of the photovoltaic-battery combination as in fig.6. It is also evident from fig.6 that size of storage capacity has a significant impact on system reliability as higher capacity PV of 60kW with 5 number of battery strings encounter higher level of loss of load while compare to others photovoltaic-battery combinations where they encounter more or less similar level of loss of load. The reasons for such behavior are:

1) Surplus energy generated during higher solar insolation is not fully utilized for storage due to state of charge (*SOC*) constraints.

2) Same amount of required battery discharge power during zero insolation results in different state of charge (*SOC*) value for each PV-battery combination. Higher value of *SOC* in 30kW PV- 9 strings battery and lower value in 60kW PV-5 strings battery.

3) Lower capacity battery corresponding with higher PV rating results in higher loss of load due to minimum *SOC* constraints compared to higher capacity battery and lower PV rating combination

VII. CONCLUSIONS

This paper has developed a realistic evaluation model of photovoltaic power and battery storage taking into account the highly sporadic nature of solar radiation, charge/discharge constraints of battery storage and operating coordination between energy storage and system. The developed model is suitable for used in Monte Carlo simulation. The developed models are applied for estimating battery size of different sized photovoltaic system based on reliability criteria such as Loss of load probability (LOLP) for a remote case study area located in Almora district of Uttarakhand, India. It is observed that different sized PV system demands different battery storage capacity in order to achieve a specified level of reliability. Further, the system performance is simulated for various cases of increasing peak demand of the study area. It is observed that the system reliability degrades with increase in peak demand and is influenced greatly by the size of the storage capacity.

APPENDIX

Numerical values of the constant used in the simulation.

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

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

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

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