Effect of Different Solar Irradiance Parameters on Reliability Evaluation of the Grid

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Abstract. Large-Scale volatility photovoltaic grid-connected which will have a profound impact on the reliability of the system. A new method based on maximum likelihood estimation is presented in this paper in which probabilistic distribution of solar irradiance is calculated on the premise of solar irradiance beta distribution, according to volatility and intermittent characteristics of photovoltaic, and simulated the actual solar irradiance which affecting power output of photovoltaic based on Monte Carlo method, then, Established a photovoltaic probability output model which can reflect the randomness output of photovoltaic; and use of the partitioning method, the reliability assessment of an interconnected generation system with photovoltaic connected with IEEE-RTS79 system is performed by Monte Carlo simulation; The results show that there have a contribution on reliability evaluation of the grid when connected on determined location and under a certain load level; also the example show the influence of different parameters of solar irradiation on system reliability indicators and the result show different parameters of beta distribution have a great impact on grid reliability indicators.

1. Introduction

With the increasing demand for electricity, traditional petrochemical energy is facing a crisis of exhaustion, the world energy situation is undergoing an unprecedented profound revolution, and how to maintain the sustainable development of the power industry is the main problem facing at present. Solar photovoltaic has the characteristics of renewability, non pollution and long life, the development and utilization of solar energy can be used as an important means to alleviate the energy crisis, improve the power supply structure and reduce environmental pollution.

Different from the traditional power supply, the large-scale parallel network of pv units has positive significance in terms of energy conservation and emission reduction and improvement of power structure, however, due to the low energy density and poor stability of the solar energy, the power of the photovoltaic unit has the characteristics of randomness, intermittency and volatility. The large-scale parallel network of pv units faces greater uncertainty in the abundance of interconnected power generation systems. Reliability as an important "vital sign" of power system, how to evaluate
the impact of solar power grid on the reliability of power grid has become a real focus. At present, some scholars have carried out relevant research on the grid connected problems of photovoltaic units. Solar irradiance is affected by weather and other factors, which causes the intermittence and fluctuation of photovoltaic unit output, so the real interconnection capacity must lower than the maximum interconnection capacity, literature [1-4] has evaluated the combined confidence capacity of photovoltaic power station from the aspects of weather, load fluctuation and uncertainty of the output of photovoltaic units; Because the energy storage system can smooth the volatility of new energy, enhance the stability of the connected power generation system, therefore, the combination of renewable energy and energy storage systems such as photovoltaic units has the application prospect [5-6]; In addition, how to properly allocate the proportion of several new energy sources to the combined power generation system with a variety of new energy sources, making it the largest contribution to the grid index and the hotspot issue of the present study[7-9]; In order to make more rational use of solar energy and improve the efficiency of photovoltaic units, literature [10-12] studied how to achieve the maximum power point tracking method of photovoltaic units; Considering the impact of large-scale photovoltaic grid connected to the grid, it may affect the safe operation of the grid, and the literature [13-14] has studied the limit capacity of the combined network.

This article simulate the solar irradiance satisfying the beta distribution based on the Monte Carlo method, according to the output model of PV unit, the probabilistic model of PV unit output is formed; then connect photovoltaic units to the grid in different areas of the IEEE - RTS79 system and use Monte Carlo sampling method to send transmission system component, form the system state, to assess the influence of pv unit grid reliability index of power grids, and show the influence of different parameters of solar irradiation on system reliability indicators, the simulation results provide a positive reference for the grid connected conditions of PV units.

2. Probability Distribution of Photovoltaic Unit Output

2.1. Probability density distribution of solar irradiance
There are many distributions of simulated solar irradiance, but the Berta distribution is the most widely used [15], the probability density function is:

\[ f(E) = \frac{\Gamma(\lambda + \mu)}{\Gamma(\lambda)\Gamma(\mu)} \left( \frac{E}{E_m} \right)^{\lambda-1} \left( 1 - \frac{E}{E_m} \right)^{\mu-1} \]  

(1)

In the formula, \( E_m \) is the maximum value of the solar irradiance, \( \lambda \) and \( \mu \) represent the two shape parameters of beta distribution.

Integrating equation (1) for the probability cumulative distribution function of solar irradiance \( E \) is shown as (2):

\[ F(E) = \frac{\Gamma(\lambda + \mu)}{\Gamma(\lambda)\Gamma(\mu)} \int_{0}^{E} \left( 1 - \frac{t}{E_m} \right)^{\mu-1} dt \]  

(2)

For inversion calculation of formula (2), the intensity function expression of the actual solar irradiance \( E \) simulated by computer is:

\[ E = E_m \ast F^{-1}(E) \]  

(3)

After the solar irradiance is produced, the output power of the PV unit is calculated according to the formula (4) PV output model:

\[ P_{o} = E S \eta \]  

(4)

In the formula, \( S \) is the total area of solar cell array, \( \eta \) is the photoelectric conversion efficiency.
Photovoltaic power generation system generally provides active power to the grid, so this paper simplifies the pv unit to active power supply to the grid.

2.2. Solve the beta distribution parameters according to maximum likelihood method

The key to simulate actual solar irradiance using Monte Carlo method is to determine the two shape parameters of beta distribution. Literature [17] have been proposed using maximum likelihood method to calculate the shape parameter and size parameter of probability distribution of wind speed. Based on the same idea, the two shape parameters of beta distribution can also be calculated by maximum likelihood method. The basic idea of maximum likelihood method is to determine the general method of unknown parameters according to the method of probability theory. When some numerical value is chosen as the estimated value of the parameter, make observations appear most likely, so that the maximum likelihood problem of the unknown parameter $\lambda$ and $\mu$ can be reduced to the maximum value problem The maximum problem of the likelihood function.

According to formula (1) the logarithmic likelihood function of the probability density function of solar irradiance is shown as equation (5):

$$L(\lambda, \mu) = \sum_{i=1}^{N} \ln f(E_i)$$

Order:

$$F_1 = \frac{\partial L(\lambda, \mu)}{\partial \lambda} = 0$$

$$F_2 = \frac{\partial L(\lambda, \mu)}{\partial \mu} = 0$$

The corresponding equations can be obtained by using Newton Ralph Xun method to solve formula (6) and (7):

$$\begin{bmatrix} F_1(\lambda, \mu) \\ F_2(\lambda, \mu) \end{bmatrix} \begin{bmatrix} \frac{\partial F_1(\lambda, \mu)}{\partial \lambda} & \frac{\partial F_1(\lambda, \mu)}{\partial \mu} \\ \frac{\partial F_2(\lambda, \mu)}{\partial \lambda} & \frac{\partial F_2(\lambda, \mu)}{\partial \mu} \end{bmatrix} \begin{bmatrix} \Delta \lambda \\ \Delta \mu \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

(8)

According to the modified equation (8), select the appropriate initial value, iterate to satisfy the convergence condition, and end the iteration, and obtain the two shape parameters $\lambda$ and $\mu$ of the beta distribution.

2.3. The Monte Carlo sampling of the photovoltaic unit’s output

The output power of PV unit mainly depends on the intensity of solar irradiance. However, the uncertainty of solar irradiance varies with weather factors and the diurnal environment, resulting in the fluctuation and intermittence of PV output. From the formula (3), we can simulate the actual intensity of solar irradiance by computer, and the reliability index obtained by the grid connected with the output of single photovoltaic unit generated by the computer has great randomness. Therefore, for the reliability assessment of the power grid with pv unit, a large number of sampling is needed to calculate the reliability index of the overall power grid. Assuming the solar irradiance is divided into N intervals, the solar irradiance of the $i$ distribution interval is $E_i \sim E_{i+1}$, the probability of solar irradiance in this interval can be calculated by equation (9):

$$p_i = \frac{M_{(i)}}{M} \quad (i = 1, 2, \cdots, N)$$

(9)
In the formula, \( M_i \) is the total number of solar irradiance produced by sampling, \( M_{\text{all}(i)} \) is the number of solar irradiance, when the number of sampling is large enough, the probability of the \( i \) interval is assumed to be true. The distribution interval of solar irradiance produced by simulation is shown as table 1.

The solar irradiance is divided into \( N \) probability intervals, the location of the random number \( R \) generated by the computer in figure 1 shows the position of the solar radiation generated by equation (3), when the random number generated is enough, the overall reliability index of the simulated photovoltaic unit connected to the grid is close to the reliability index of the real photovoltaic unit connected to the grid.

Figure 1. Extracting solar irradiance interval

The steps of the probability distribution interval of PV unit output are as follows:

a. The distribution function of the intensity distribution of solar radiation in table 1 forms the function of discrete distribution \( D(x) \).

\[
D(x) = \sum_{j=1}^{l} p_i
\]

b. Taking a random number \( R \) which uniformly distributed in the \([0, 1]\) interval, and when the random number satisfies equation (11) (as shown in figure 1), the solar irradiance is in the interval \( i \).

\[
\sum_{j=1}^{i-1} p_j < R \leq \sum_{j=1}^{i} p_j \quad (i=1,2,\cdots,N)
\]

c. After determining the solar irradiance range \( i \) from formula (11), and calculate the output of PV unit according to formula (4). Assuming that the intensity of the solar irradiance is \( E_i \sim E_{i+1} \) at this point, and determining the range of the output of the pv system in the \( i \) interval is \( P_{\text{all}(i)} \sim P_{\text{all}(i+1)} \), using formula (12) approximate processing, geting the average output value \( \overline{P}_{\text{all}(i)} \) of the PV unit, and calculating the reliability index \( \text{LOLP}_i \) and \( \text{EDNS}_i \) of the \( i \) system state of the pv unit.

\[
\overline{P}_{\text{all}(i)} = \frac{P_{\text{all}(i)} + P_{\text{all}(i+1)}}{2}
\]
Table 1. Solar irradiance distribution information table

| distribution interval of radiation intensity (x) | radiation intensity / (W/m²) | probability |
|-----------------------------------------------|-----------------------------|-------------|
| 1 0~100                                      | 0.115404                    |             |
| 2 100~170                                    | 0.05105                     |             |
| 3 170~240                                    | 0.050032                    |             |
| 4 240~310                                    | 0.048642                    |             |
| 5 310~380                                    | 0.047536                    |             |
| 6 380~450                                    | 0.0476                      |             |
| 7 450~520                                    | 0.047142                    |             |
| 8 520~590                                    | 0.04663                     |             |
| 9 590~660                                    | 0.046736                    |             |
| 10 660~730                                   | 0.047394                    |             |
| 11 730~800                                   | 0.04719                     |             |
| 12 800~870                                   | 0.046872                    |             |
| 13 870~940                                   | 0.046948                    |             |
| 14 940~1000                                  | 0.048436                    |             |

3. Reliability Evaluation of Photovoltaic Unit Connecte to the Grid

3.1. Optimal DC power flow load shedding model

The health of the components is closely related to the safe operation of the power system, due to one or more components running out of power in the actual power system, resulting in the power grid tidal current changes, such as node voltage limit, overload of power flow or bus isolation and so on. In order to ensure the safe and stable operation of power grid, it is necessary to take some measures to eliminate the hidden dangers of power grid. When active power capacity of the power grid generator is insufficient, it is necessary to cut a certain amount of load at the receiving end of the grid. The commonly used load curtailment methods include average load shedding method, the nearest cutting load method and the optimal load shedding method. In this paper, we use the optimal dc power flow algorithm to calculate the optimal load shedding of PV units connected to grid.

\[
\min \sum_{i=ND} C_i \\
T(S) = A(S)(PG + \bar{P}_j - PD + C) \sum_{i=NG} PG_i + \bar{P}_{s(i)} - \sum_{i=ND} PD_i + \sum_{i=ND} C_i = 0 \\
0 \leq \bar{P}_{s(i)} \leq \bar{P}_{s(i)}^{\max} \\
PG_j^{\min} \leq PG_j \leq PG_j^{\max} \quad (i \in NG) \\
0 \leq C_i \leq PD_j \quad (i \in ND) \\
T_k(S) \leq T_k^{\max} \quad (k \in L)
\]

In the formula, \( T(S) \), \( PG \), \( \bar{P}_j \) and \( PD \) refers to active power flow vector, generator capacity, PV unit access capacity and bus load of system outage state. \( A(S) \) is the relation matrix between active power flow and injection power in outage state \( S \). \( C \) is the Load reduction vector variable; \( \bar{P}_{s(i)} \), \( PG \), \( PD \), \( C \) and \( T_k(S) \) are respectively the elements of \( \bar{P}_j \), \( PG \), \( PD \), \( C \) and \( T(S) \). \( NG \), \( ND \) and \( L \) are respectively the system generator bus, load bus and branch set.

The goal of the model is to minimize the total load reduction of the system under the condition of power balance, DC current equation and conventional generator, pv unit and line current.
3.2. Calculation of reliability index of the photovoltaic unit connected to the grid

On the basis of determining the output power of PV unit, to evaluate the reliability index of generation and transmission system, it is necessary to sample the system components of generator, transmission line, transformer and so on through Monte Carlo method to determine the system fault set, through the power flow analysis, calculate the overall reliability index of the power grid under all fault sets and analyze the influence of the PV unit output on the reliability index of the power grid. The evaluation steps are as follows:

(1) Selection of system fault set
   a. produce the random number of the i system state uniformly distributed in n [0,1] intervals(suppose the power system is abstracted into a system with n components).
   b. Suppose that the failure probability of the j equipment is \( P_j \), determine whether \( R_j \leq P_j \). If it is established, the equipment fails \( S_j = 0 \); otherwise the equipment will run normally \( S_j = 1 \).
   c. Determine whether the sampling end conditions, if the sampling is completed; Otherwise, turn the steps a, until the sampling is over.
   d. All system fault sets \( S = \{S_1, S_2, \ldots, S_j, \ldots S_n \} \), which \( S_i = [S_{i1}, S_{i2}, \ldots, S_{ij}, \ldots S_{in}] \) is the state vector of a system.

(2) Reliability calculation of power grid

There are many indicators to describe the reliability of power grid, including power shortage expectation (EDNS), power shortage probability (LOLP), power shortage time expectation (LOLE), and electricity shortage expectation (EENS) and so on. In this paper, the reliability index of generation and transmission system with grid connected photovoltaic units is evaluated by using two indexes of LOLP and EDNS as the representative, the expressions are as follows:

\[
LOLP = \sum_{i=1}^{M} LOLP_i
\]

\[
EDNS = \sum_{i=1}^{M} EDNS_i
\]

In the formula, \( LOLP \) and \( EDNS \) is load shedding probability and load shedding for the whole system, \( M \) is total number of system states, \( LOLP_i \) and \( EDNS_i \) is the load shedding probability and load shedding of the i system, When the i system state is unloaded, the value of \( LOLP_i \) and \( EDNS_i \) is zero.

3.3. Reliability evaluation process of the photovoltaic unit connected to the grid

The reliability evaluation steps of the photovoltaic unit connected to the grid are as follows.

A. read the failure probability of generator, transmission line, transformer and basic parameters of photovoltaic unit;
B. form the probability distribution range of PV unit output according to formula (9);
C. set the initial sampling times \( k = 1 \) and the total sampling times of the system \( M \);
D. generates a random number, simulate the solar irradiance by using formula (3), and determine the output of PV unit according to formula (12);
E. form system fault set;
F. calculate photovoltaic unit connected to the grid, based on the optimal DC power flow model, and calculate the reliability index of the a single system state;
G. determines whether the sampling times reaches \( M \); if it reaches, the sampling ends and the step h; otherwise, \( k = k + 1 \), step d;
H. calculate the overall reliability index of power grid according to formula (15) and (16).
4. Example Analysis
Take the IEEE—RTS79 standard test system shown in Figure 2 as an example, the system consists of 24 buses, 17 load nodes, 33 transmission lines, 5 transformers, 32 generators, and 1 camera; the total installed capacity is 3405MW, and the annual peak load value is 2850MW. The other calculation parameters in this paper refer to literature [18], the maximum intensity of solar irradiation intensity $E_m$, the total area of the battery $S$ and the efficiency of the photoelectric conversion $\eta$ were respectively 11000W/m², 0.6667m² and 15%.

According to the regional constraints, the test system is divided into two sub-regions A1 and A2, among the voltage levels of A1 and A2 regions is respectively 138kV and 230kV. The capacity of A1 generation in sub region is insufficient, and the capacity of A2 generation in sub region is more abundant, regional A2 needs to provide power support for regional A1 to ensure the power supply reliability of the whole system. The power supply is supported by 5 contact transformers between A1 and A2, and the maximum power transmission constraint is 1200MVA.

![Figure 2. IEEE-RTS79 system single line figure](image)

4.1. The reliability indicators change with the different locations of the photovoltaic units
The contribution of photovoltaic units connected to grid to the reliability index of the power grid is closely related to the location of the PV unit. In this example, 4 locations are selected in the A1 region, and 3 locations are selected in the A2 region to access the PV unit. The changes of the reliability index of the grid are shown in table 2:

| access to different locations | LOLP  | EDNS (MW) |
|------------------------------|-------|-----------|
| 1                            | 0.0584| 9.48      |
| 3                            | 0.0616| 9.04      |
| 6                            | 0.0641| 10.78     |
| 10                           | 0.0705| 13.38     |
| 13                           | 0.0665| 10.96     |
| 15                           | 0.0601| 9.87      |
| 18                           | 0.0647| 10.51     |
| no access to PV unit         | 0.0887| 14.20     |

As shown in Table 2, the reliability index of power grid is improved compared with the unconnected pv unit of the grid, however, the contribution of different access points to grid reliability is different, the contribution of pv units to the reliability index of the power grid is obvious in the area of insufficient abundance. From the example, it is more important to connect the PV unit with the 3
node to the reliability index of the power grid, this is because the IEEE - RTS79 system is a weak link system, the A1 and A2 regions provide power support only through 5 contact transformer, and node 3 is in the insufficient area of adequacy A1, lack of power support, moreover, the load of node 3 is larger, If the contact transformer out of operation, it may cause the load shedding of the power grid. Therefore, if the PV unit is connected to the 3 node, it can effectively make up for the lack of power support of the node, and has a great contribution to the reliability level enhancement of power grid.

4.2. The influence of beta distribution parameters on reliability indexes
Solar irradiance satisfies beta distribution, Different beta distribution shape parameters have different effects on the reliability of power grid, fig. 3 shows the change of the reliability index of the power grid with the shape parameters of the beta distribution when the pv unit is connected to node 1. 

![Figure 3. The relationship between beta distribution parameters and reliability indices](image)

It can be seen from Figure 3 that the reliability level of the power grid increases with $\mu$ increase and decreases with $\lambda$ increase. This is because the larger the beta distribution parameter $\mu$, the smaller it is, the greater the solar irradiance. The capacity of PV units will also increase, which will contribute to the improvement of the reliability level of power grid.

5. Conclusion
The grid connected photovoltaic unit with randomness and volatility has further increased the complexity of the system operation. In this paper, Monte Carlo method is used to evaluate the impact of grid connected photovoltaic units on the reliability index of power grid, and the following conclusions are drawn:

1) In this paper, Monte Carlo method is used to simulate the actual solar irradiance, and the distribution probability interval of the pv unit is formed, and the randomness of the output of the photovoltaic unit is taken into account reasonably.

2) Grid connected photovoltaic system changes the operation mode of power grid, and increases the generation capacity of the system. The example shows that the reliability of the power grid can be improved by connecting the PV unit with a certain capacity in the power grid

3) Propose a method for solving the beta distribution parameters using maximum likelihood method, give the influence rules of different beta distribution parameters $\lambda$ and $\mu$ on the reliability index of power grid, the reliability level increases with $\mu$ increasing and decreases with $\lambda$ increasing, the influence of the two on the reliability index EDNS shows the opposite rule.

4) Grid connected photovoltaic units can improve the reliability level of power grid, the contribution of PV units in different locations to the reliability index of power grid is different, it can
greatly enhance the reliability index of power grid in area with high load access photovoltaic units, and this provides a reference for future pv unit access location.

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