The Impact of Different Solar Tracker Systems on Reliability of Photovoltaic Farms

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Among different renewable resources technologies associated with solar energies, photovoltaic (PV) systems have grown significantly. The produced power of a PV system is proportional to the solar radiation and so due to the variation in the solar radiation during the day and a year, the generated power of the PV farms changes too. Due to the rotational motion of the earth around itself during a day and also the transitional motion of the earth around the sun during the year, the amount and angle of sunlight on PV panels' surface change. For enhanced amount of solar radiation on PV panels, the solar tracker can be used to place the solar panels perpendicular to the sun's rays. Two kinds of solar tracker systems including single-axis and double-axis trackers can be used in PV farms. In this paper impact of solar trackers on PV farms' reliability is evaluated. For this purpose, a multi-state reliability model is constructed for PV farms where failure of composed elements and change in solar radiation intensity are considered. For determining the optimal states number and associated probabilities of this model, the XB index and fuzzy c-means clustering method are implemented. The suggested reliability model is applied for the adequacy assessment of power networks containing large-capacity PV farms. Besides, the impact of solar trackers on reliability indices of power networks integrated with PV farms is investigated.

keywords: *Photovoltaic farm, Solar radiation, Reliability, Fuzzy c-means clustering, XB index.*

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NOMENCLATURE

Parameters

A Availability
J_m Objective function in fuzzy c-means clustering technique
v_k Output of PV unit
z Zenith angle
u_{ik} Fuzzy degree between v_k and i^{th} cluster
P_i Probability of i^{th} state
a Azimuth angle
γ Tilt angle
c Number of clusters
n Number of output data

Abbreviation

PV Photovoltaic
AC Alternating current
COPT capacity outage probability table
EENS Expected Energy Not Supplied
DC Direct current
IEEE-RTS IEEE Reliability Test System
MPPT Maximum power point tracker
LOLE Loss Of Load Expectation
RBTS Roy Billinton Test System
XB Xie & Beni

1. INTRODUCTION

The environmental impacts of fossil fuels have led environmental organizations to impose restrictions on the use of these fuels which have resulted in the growth of the use of the renewable energy sources and alternatives to these fuels. Among different renewable resources, solar energy as an abundant and available resource is utilized to produce electric energy in power networks. Solar energy can be converted to electricity using different technologies including photovoltaic (PV) systems and concentrating solar thermal power plants such as linear concentrating systems and so on [1]. Among different technologies of solar power plants, PV systems due to the cheaper price and easier construction have grown a lot in the electricity industry and large-scale PV farms such as Bhadla Solar farm with 1365 MW capacity in India, Yanchi solar PV station with 1 GW capacity in China, Kurnool solar park with 1 GW capacity in India, Longyangxia farm with 850 MW capacity in China, Villanueva solar farm with 754 MW capacity in Mexico and Kamuthi solar farm with 648 MW capacity in India are installed around the world [2]. Produced power of PV farms is proportional to the magnitude of sunlight and its angle on the surface of PV panels. Due to the rotational motion of the earth around itself during the day and also the transitional motion of the earth around the sun during the year, the magnitude and the angle of sunlight on PV panels' surface change. For the enhanced amount of solar radiation on PV panels, the solar tracker systems can be used to place solar panels at a perpendicular angle on the sun's rays. Two kinds of solar tracker systems including single-axis and double-axis trackers can be used in PV farms. In this paper impact of solar trackers on PV farms' reliability is investigated. Due to the significant penetration level of PV farms in power networks, many researches have been performed to study these farms and their impacts on different aspects of power networks. In [3], a reliability assessment of large-scale PV systems integrated into the distribution network is performed. Time-varying failure rate related to conventional power elements considering the aging period is modeled, in the research. Then, the failure of PV components, change of solar radiation and PV arrays degradation are considered to model the PV systems. In [4], a scientific-based probabilistic model based on Markov chains is proposed for calculating the reliability indices of PV panels. In the paper, to improve the operation and maintenance activities and optimize the stocks of spare parts, the failure rates of elements are determined based on statistical data. Besides, an algorithm is proposed to calculate the maximum number of interruptions and the maximum duration of an interruption for a PV power plant. Paper [5] studies the reliability of a standalone micro-grid including a PV system and energy storage device. Models of PV systems, energy storage devices, micro-turbine and comprehensive loads with time-varying elements are determined, in the research. Besides, optimal load shedding and the Monte Carlo method are implemented for reliability studies of understudied micro-grid. The important reliability indices considering PV integration in the microgrid are calculated. Paper [6] evaluates the reliability of PV power networks considering variable factors, aging of elements, variable solar radiation and weather conditions by Monte Carlo approach. The research proposes a probability model related to the output of PV arrays by analyzing the impact of element failures. In [7], a reliability model of PV system considering time-varying failure rates is developed. In this paper, based on various weather conditions and detailed architecture of PV system, variable failure rates of PV elements are determined. In [8], an approach dependent on time is proposed for evaluating the capacity benefit of wind and PV units. In this paper, wind turbine, PV system and electricity load have been modeled with variable clusters dependent on time and the correlation between these data sets is considered for determining the capacity benefit of wind and PV systems. Paper [9] proposes a method containing design and experiment for optimizing the reliability of inverters used in PV systems. In this paper, several inverters are designed for calculating associated reliability. Besides, important parameters affected reliability is determined. Paper [10] suggests a systematic way for studying the reliability of large-scale PV farms connected to the power grid taking into account the variation of output failure rates of main elements dependent on weather conditions. In the research, the effect of PV module failure, and also inverters and capacitors failures are considered and using the state enumeration method, the reliability of PV units is studied. In [11], stochastic reliability investigation of stand-alone PV systems is performed. In this paper, for considering the uncertainty nature of the global solar irradiation on the produced power of PV system, stochastic modelling is proposed. Besides, for reducing the number of generated scenarios, fast forward scenario reduction method is used. Moreover, the impact of environmental conditions including humidity and temperature on the hazard rate of PV system components is evaluated. Paper [12] proposes an optimal risk-constrained peer-to-peer energy trading approach used in smartgrids containing PV systems. In this paper, for increasing the profitability of consumers and reducing the dependency of microgrid on main grid, demand response program based on the price is suggested. Besides, for modelling the uncertainty nature of generated power of PV systems, deep learning method is used to forecast the output of PV units. In [13], economic and technical energy management in a smart home containing PV panels and electric vehicles is performed. In this paper, a novel multi-objective technique is proposed to manage the energy of smart home at different seasons. In the smart home, the rooftop PV panel is applied to supply part of the demand during the day. The uncertainties associated to solar irradiance, state of charge, and availability of electric vehicles are considered in the paper. Paper [14] proposes evolutionary computing approach for optimal reliability studying of grid-connected PV units. In this paper, a multi-objective problem is solved to determine optimal site and design of PV panels for achievement of optimal reliability. The current paper studies reliability of grid-connected PV systems, probabilities of different states, availabilities of generation buses, the generated capacities of the system considering different failure states, and the frequency and mean duration of generation failure states. In [15], an analytical method is proposed to assess time-varying reliability of PV systems. This paper suggests a discrete convolution-based technique to evaluate the reliability of grid-connected PV unit considering variable availability of composed components of PV arrays. Besides, the impact of variation in solar irradiance and environment temperature on reliability of PV arrays is studied. Paper [16] determines spinning reserve required in a power system containing wind and solar generation units. In this paper, a multi-state reliability model considering both failure of composed components and variation in the generated power is developed for wind and PV units. To determine appropriate value of spinning reserve, unit commitment risk of the system is computed. In [17], reliability assessment of a renewable energy-based microgrid including wind units, stream-type tidal turbines and PV systems is performed. To calculate reliability indices of microgrid, dependency of failure rate of composed components of renewable generation units on wind velocity, tidal stream speed, solar irradiance and ambient temperature is considered. In this research, Monte Carlo simulation method is used to calculate reliability indices of the microgrid. In Table 1, the summary of literature review performed in the paper is illustrated.

It is deduced from literature review performed in this section that reliability evaluation of large-scale PV units considering the impact of different solar tracker systems is not studied. Considering that little research has been devoted on this topic, in the current paper, the impact of different solar radiation systems on the reliability of power networks containing PV farms is studied. Thus, the paper's contributions are as follows:

- Developing reliability model of large-scale PV units. The effect of elements failures and variation of generated power caused by changes in solar radiation are considered in the model.
- Reducing states number in the generated power data of the PV systems using the XB index and fuzzy c-means clustering approach.
- Investigating solar trackers' effect on produced power of PV units.
- Investigating the impact of different solar tracker systems on the reliability of PV farms.
- Comparison between different solar tracker systems according to reliability improvement of PV unit.

Thus, the organization of the current research is: the second part contains PV farms, composed components and the impact of solar tracker on produced power of PV farms. The third part develops a reliability model of PV units. The fourth part proposes a technique for evaluating the reliability of power networks containing PV units with large capacities. The fifth section is about numerical results related to the adequacy assessment of two reliability test systems integrated with large-scale PV farms. The sixth part concludes the paper.

2. PV SYSTEMS

In this part, the structure and main elements of PV units are introduced. Besides, the effect of different tracker systems on produced power of PV units is studied. According to sun tracker systems operation, three groups of PV farms including PV farms with fixed panels, PV farms equipped with single-axis trackers and PV farms equipped with double-axis trackers exist.

A. The Structure of the PV Farms

A PV cell is a p-n junction that converts solar radiation to DC electric power. The voltage and the current produced by a solar cell are small and to enhance them, a PV panel contains several PV cells with series or parallel connections. Produced power of PV panels is determined by the voltage-current characteristic of them. To generate maximal output in PV arrays, a maximal power point tracker (MPPT) system tracks the operating points with maximal power. The tracker system is usually a DC-DC converter. The output of PV panels is DC and for converting this DC power to the AC form, an inverter is used. Besides, the main grid is AC, and for transferring the generated power of PV system to the grid, the inverter can be used. In Fig. 1, the topology and elements of a typical PV farm composed of several PV arrays connected to the inverter are presented. As can be seen in the figure, an array is composed of several panels [18].

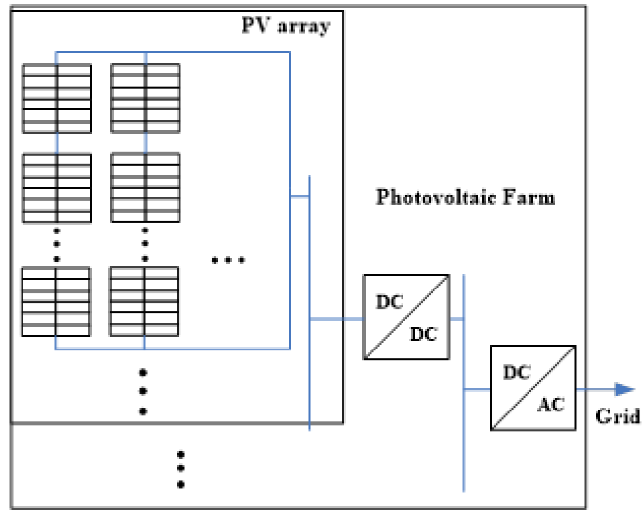

Fig. 1. Topology of a typical PV farm.

B. The Effect of Sun Tracker System on the Output of PV Farms

Generated power of a PV unit depends on solar radiation intensity in panels. It is dependent on the magnitude and the angle of the sunlight on the surface of the panels. Due to the rotational motion of the earth around itself during the day and also the transitional motion of the earth around the sun during the year, the magnitude and the angle of sunlight on PV panels' surface change. For enhancing solar radiation intensity on PV panels, the solar tracker systems can be used to place the solar panels perpendicular to the sun's rays. The solar tracker systems can be classified on the basis of control system, drivers, tracking strategy and degree of freedom of movement [19]. On the basis of control system, two tracker systems including closed and open loop tracking systems are available. On the basis of driving system, two trackers including passive and active solar tracking systems are available. Degree of freedom is number of directions that PV panel movement is occurred. On the basis of degree of freedom, single-axis and double-axis tracker systems are developed. In solar power plants, there are other solar tracker systems such as polar-aligned and tilted trackers that can be used in PV or concentrated solar power plants. In this paper, due to the performance and ease of use, single-axis and double-axis solar trackers are studied. These two kinds of solar tracker systems can be used in PV farms. In the PV farms equipped with the single-axis tracker, during the day, the sun's position in the sky relative to the earth changes the east-west direction, the tracker system also moves the panels to follow the sun. However, in addition to east-west direction of sun's position change, its position changes with the earth's transition around sun in a north-south direction. Thus, a single-axis tracker system cannot place the surface of the panel perpendicular to the sunlight all time of the year. For this purpose, double-axis tracker devices with ability of moving panels in east-west and north-south directions can be used to place the surface of panels perpendicular to the sunlight. Thus, output of PV farms equipped with dual-axis trackers is expected to be higher than PV farms equipped with single-axis solar trackers. In PV units equipped to the double-axis tracker, when the device is not in appropriate alignment with the sun, different illumination is received by sensors. Thus, a differential signal is created that can be used by a microprocessor or a

Table 1. Literature review summary

References	Description	Drawback
[3],[7],[10],[14,15]	Reliability assessment of large-scale PV system considering variable failure rate and change of solar radiation is performed.	The impact of different solar tracker systems is not considered.
[4]	Reliability indices of PV panels are computed by Markov chains.	The impact of different solar tracker systems is not considered.
[5,6]	Reliability evaluation of PV systems is performed by Monte Carlo method.	In reliability assessment by numerical methods, the volume of calculations is large.
[8]	The capacity benefit of PV systems and wind units is determined considering the variation in output of renewable generation units.	Reliability indices of PV units is not calculated.
[9]	Reliability assessment of different inverters used in PV systems is performed.	The impact of other PV system components on reliability performance is not considered.
[11]	Reliability of stand-alone PV units is studied by scenario generation method.	Reliability evaluation of large-scale PV unit is not performed.
[12]	optimal risk-constrained peer-to-peer energy trading approach used in smartgrids containing PV systems is performed.	Reliability evaluation of PV unit in generation level is not performed.
[13]	Economic and technical energy management in a smart home containing PV panels and electric vehicles is performed.	Reliability of large-scale PV farm is not performed.
[16]	Spinning reserve of power systems containing wind and PV units is determined considering unit commitment risk.	The impact of different solar tracker systems on reliability indices is not considered.
[17]	Reliability assessment of a renewable energy-based microgrid including wind units, stream-type tidal turbines and PV systems is performed.	Reliability evaluation of large-scale PV systems considering tracker effect is not performed.

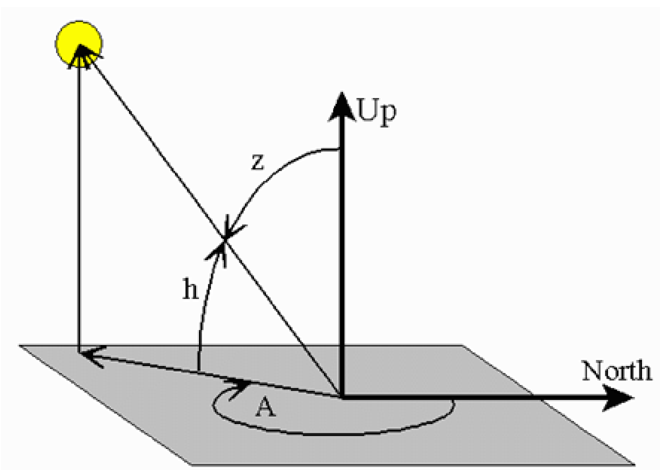

Fig. 2. Sun position in the sky.

comparator for determining the proper movement in the suitable direction. The motors receive required signal for moving accordingly. The process is stopped, when the sensors receive similar illumination. In this state, the PV panels are normally aligned with the sunlight [19]. In practice, solar tracker systems optimize the orientation of solar panels to maximize sunlight exposure. It is not always possible to achieve a perpendicular position. The goal is to adjust the panel tilt and azimuth angles to maximize the incident sunlight on the panels, but it may not always result in a perfectly perpendicular alignment.

Sun position in the sky can be presented by two angles, zenith and azimuth as can be seen in Fig. 2. The azimuth angle is measured clockwise from north to the point associated with the image of the sun on Earth and the zenith angle is measured as the angle between the vertical line and line drawn from sun to desired point. The elevation angle is the angle between the line drawn from the sun to desired point and the horizon (90-zenith angle) [20].

Longitude and latitude quantities are used to determine the position of a point such as the location of the installed panels on the ground. Latitude indicates the position of the desired region in the direction between the North Pole and Antarctica

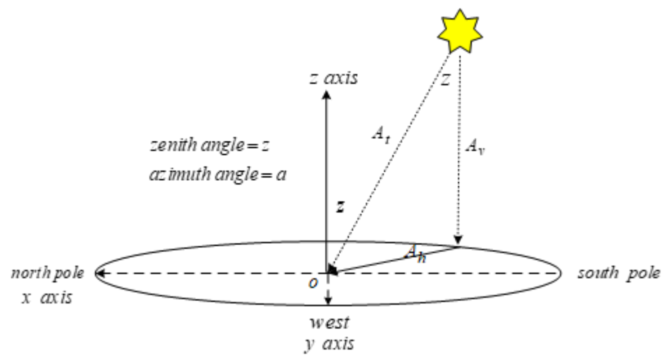

Fig. 3. The presentation of the sunlight at the desired point o.

and longitude shows the position of the region in the east to the west direction. For determining radiation amount in panels, it is assumed the sun shines at point o at the zenith angle of Z as presented in Fig. 3

The effective sun radiation on a panel installed with a tilt angle γ to the south can be calculated as (1). For this purpose, a new coordinate system with the vectors u, w and y is defined and the conversion between the vectors from the old coordinate to the new coordinate as presented in Fig. 4 is performed [20].

$$A_w = -cos(z)A_t sin(\gamma) - sin(z)A_t cos(\gamma)cos(a) \quad (1)$$

$$A_y = sin(z)A_t sin(a)$$

$$A_u = sin(z)A_t sin(\gamma)cos(a) - cos(z)A_t cos(\gamma)$$

The effective sun radiation on a fixed panel installed with a tilt angle γ to the south can be calculated as [20]:

$$A_{fixedpanel} = A_u = \quad (2)$$

$$sin(z)A_t sin(\gamma)cos(a) - cos(z)A_t cos(\gamma)$$

The effective sun radiation on a panel installed with a tilt angle γ to the south equipped with single-axis sun tracker is calculated as [20]:

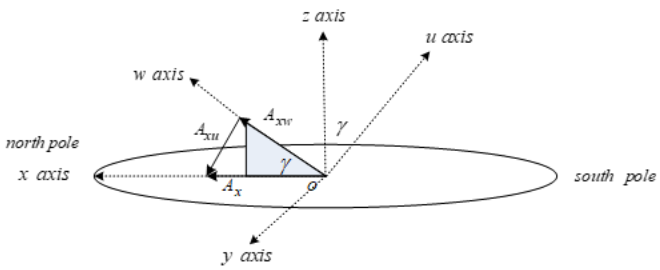

Fig. 4. The new coordinate system to determine the radiation on the panel.

$$A_{singleaxis} = \sqrt{A_y^2 + A_u^2} = \tag{3}$$

$$A_t\sqrt{(sin(z)sin(a))^2 - (sin(z)sin(\gamma)cos(a) - cos(z)cos(\gamma))^2}$$

The effective sun radiation on a panel with double-axis sun tracker is calculated as [20]:

$$A_{doubleaxis} = A_t \tag{4}$$

Thus, based on the solar radiation data, zenith and azimuth angle associated with the sun's position in the sky and tilt angle of panels in the fixed panel and panel with single-axis sun tracker, the radiation received by panels is determined.

3. RELIABILITY MODELLING OF THE PV FARMS

Power network reliability is about power network ability for supplying required demand according to associated standards that categorizes two aspects including security and adequacy [21]. In adequacy assessment of power network sufficient facilities in generation, transmission and distribution parts must be established to supply required demands. In power network security, response of power network to different disturbances, such as outages of generating units is studied. Reliability studies of power systems are done in main parts including generation units, transmission networks and distribution sections. For investigating analytical adequacy of power networks containing PV units with large capacity, a reliability model with several states must be constructed that considers elements failure and variable output caused by variable solar radiation. Paper [22] presents failure of PV unit elements including PV panels, DC/DC converters and inverters can be neglected in reliability presentation of PV units. In [22], effect of sun tracker system on reliability presentation of PV farms is not considered. To calculate the reliability indices of power system, generated power is compared with the load. The risk state is occurred when generated power is less than the required load. Thus, if the generated power of the system increases, the curtailed load decreases, and reliability of the power system improves. Sun tracker systems increase the produced power of PV systems. Thus, these systems affect reliability performance of power systems including PV farms. For this purpose, this paper studies the impact of different sun tracker systems on reliability performance of electric network containing PV farms.

A sun tracker system consists of optic sensors, control system, main structure and motors. Elements failure fails sun tracker device which must be considered in reliability presentation of

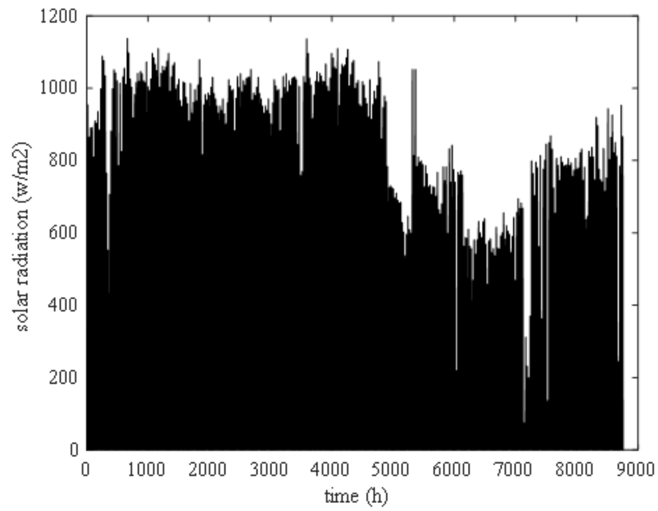

Fig. 5. Hourly solar radiation received by the panels with double-axis tracker.

PV unit. Hourly solar radiation data in Kish Island in 2017 measured by a spherical sensor is presented in Fig. 5. In this sensor, the maximum measured components of the solar radiation are recorded and so, the solar radiation data recorded by this sensor is equal to the solar radiation received by the panels equipped with the double-axis trackers. According to sun zenith and azimuth angles and the hourly solar radiation data, the hourly radiation received by stationary panels and panels with single-axis radiation are calculated according to the relations (2), (3) and (4) and presented in Fig. 6 and 7, respectively. In Fig. 8, the solar radiation received by a fixed panel, a panel with single-axis sun tracker and a panel with double-axis sun tracker during a day are presented. The generated power of PV unit depends on the solar irradiance. Because of variation in the solar irradiance, the generated power of PV units varies over time. To consider the uncertainty nature of PV unit arisen from variation in solar irradiance, different probability density functions including Weibull, beta, lognormal, logistics and gamma functions can be used [23]. In this paper, to model uncertainty nature of PV units, i.e. to consider the variation in PV unit generated power, multi-state reliability model of them is developed. Due to the wide variation of PV system output, the reliability model has more than two states.

Output of PV unit is obtained by multiplying solar radiation data by number of panels, panels' surface and efficiency of PV system. Thus, wide change in solar radiation makes output of PV units varies a lot. To develop a reliability presentation with several states for PV units, states of output data must be decreased through a suitable clustering method. In this paper for determining optimal number of clusters related to reliability presentation of PV units, XB index that considers distance among initial and decreased states in numerator and minimal distance between two clusters in denominator is obtained as [24]:

$$XB = \frac{J_m(v, U)}{min_{i \neq j}(\left|v_j - v_i\right|^2) \times n} \tag{5}$$

Where, $J_m(v, U)$ is the objective function of clustering method that must be minimized, v_i and v_j are the centers of two clusters i and j. In this appearance, fuzzy c-means clustering technique is applied for determining capacities and corresponding probabili-

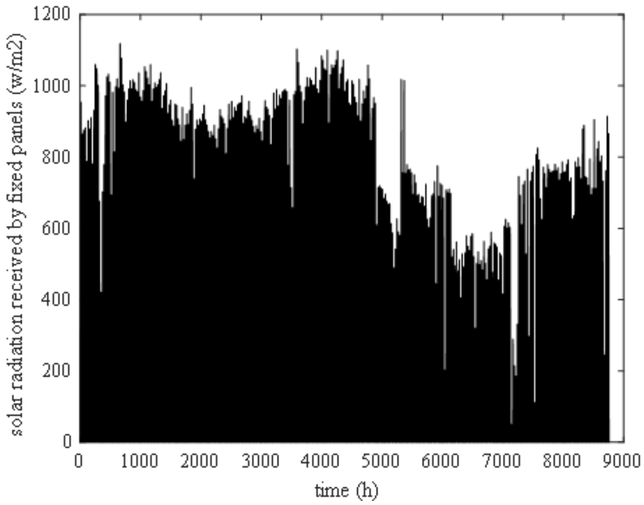

Fig. 6. The hourly solar radiation received by the fixed panels.

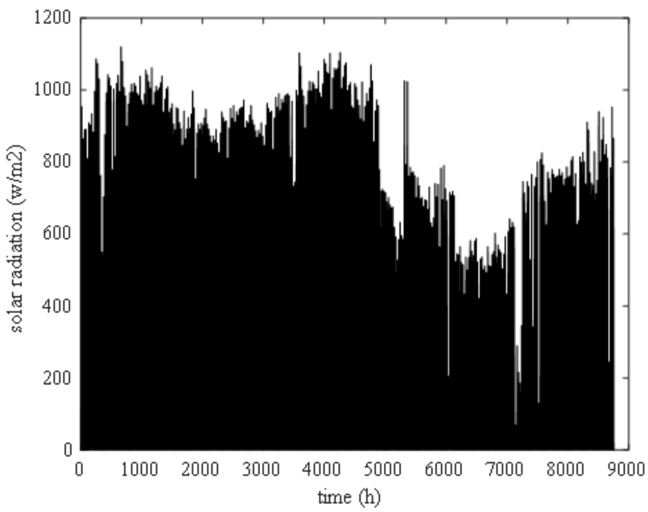

Fig. 7. Hourly solar radiation in panels with single-axis tracker.

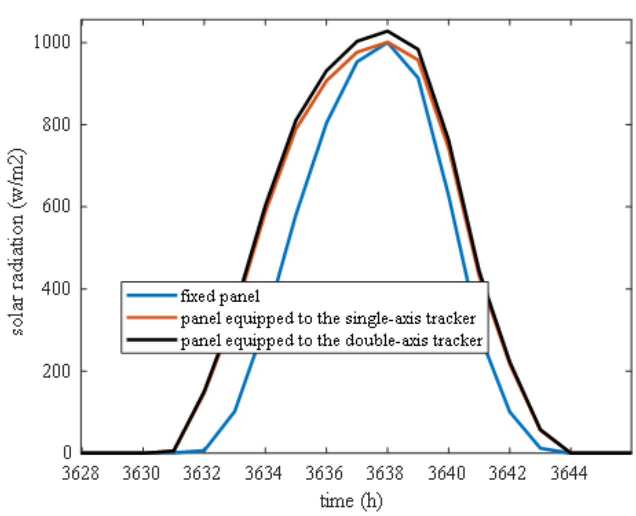

Fig. 8. The solar radiation received by three types of the panels.

ties of the reduced clusters. Objective function related to fuzzy c-means clustering approach is determined as [25-26]:

$$J = \sum_{i=1}^{c} \sum_{k=1}^{n} u_{i,k}^{m} \left| y_k - z_i \right| \tag{6}$$

Where, y_k is output of PV unit corresponding to time k, z_i is center of ith cluster, c is number of decreased states or clusters, n is number of output data, m is a real number presents fuzzification (it is greater than 1), u_{ik} presents fuzzy degree between y_k and ith cluster. In this method, for reducing number of states in reliability presentation of PV unit, XB index is obtained. Optimal number of decreased power data is determined when XB index is minimal. By fuzzy c-means clustering method, capacities and probabilities associated with these clusters are determined. Based on this method, the probability of cluster i can be calculated as [25]:

$$P_i = \sum_{k=1}^{n} u_{ik} \tag{7}$$

In the current research, for considering impact of failure of sun tracker system on reliability presentation of PV units, Monte Carlo method is proposed. In PV farms with single-axis solar trackers, failure of sun tracker system causes the power plant to operate as a PV farm with fixed panels. To consider the effect of sun tracker failure, at each hour, MATLAB software produces a random number. If produced number is in [0,A] (A is availability of the sun tracker system), the sun tracker system is up and output of PV system is obtained according to PV unit equipped with single-axis panel. If the generated number is in [A,1], the sun tracker system is down and the output of PV system is obtained according to PV system with fixed panel. Simulation is performed for several hundred years and, reliability presentation of PV unit equipped with the single-axis sun tracker system is determined through fuzzy c-means clustering method. To develop reliability presentation of PV farms equipped with the double-axis sun tracker system, the same procedure through Monte Carlo method is followed for investigating effect of sun tracker device failure on solar radiation intensity in panels.

• If the east-to-west and north-to-south sun trackers are failed, solar radiation intensity in panel is equal to the solar radiation received by a fixed panel.

• If the north-to-south sun tracker fails, solar radiation intensity in panel is equal to solar radiation intensity in panel equipped with single-axis sun tracker with tilt angle related to previous hour. Variation in north-to-south position of the sun is very slow, and the time required for repair of the sun tracker system is short and so, this failure is neglected in reliability presentation of PV farms.

• If east-west sun tracker fails, solar radiation intensity in panel is equal to solar radiation intensity in fixed panel with tilt angle equal to latitude minus sun declination angle.

4. ADEQUACY ASSESSMENT OF POWER NETWORKS INTEGRATED WITH PV UNITS WITH LARGE CAPACITY

To analytically assess reliability of power networks integrated with PV units with large capacity in adequacy level, as shown in Fig. 9, all generation units and the system load connect to common bus and it is neglected from the transmission network.

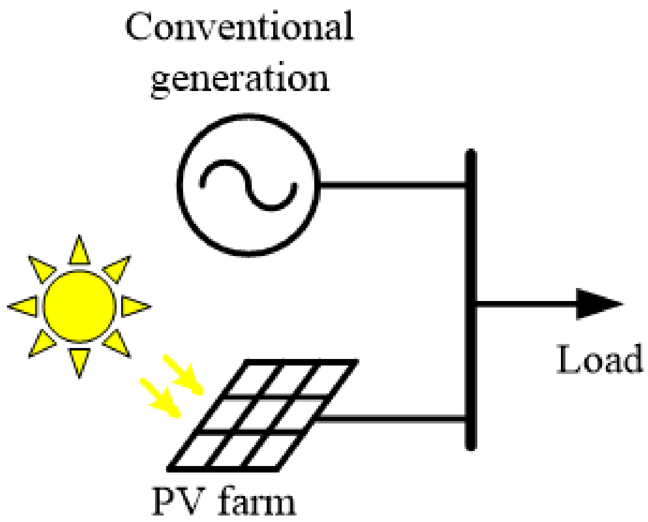

Fig. 9. Adequacy study of power system containing PV units.

For determining adequacy indices of power networks containing PV units with large capacity, a table named capacity outage probability table (COPT) composed of possible powers and related probabilities, is obtained for each conventional power plant. These generation units are presented with two states including up (with rated capacity) and down (with zero generation power) states. COPT of PV units is obtained as explained in previous section and by combining all COPTs, total COPT of generation network is achieved. With convolving generation system model, i.e., total COPT and load model, the important reliability indices in the adequacy level including loss of load expectation (LOLE) and expected energy not supplied (EENS) can be obtained. The LOLE is the average time of specific period that the load is curtailed. To calculate this index, for each state of COPT, the time of load curtailment is computed. The LOLE is computed by summing the time of load curtailment weighted by the probability of each state. The EENS is the average value of curtailed energy during the specific period. To calculate this index, for each state of COPT, the value of interrupted energy is determined. The EENS is computed by summing the value of curtailed energy weighted by the probability of associated state.

5. NUMERICAL RESULTS

Reliability presentation of understudied PV farms in three modes including stationary panels, panels with single-axis sun tracker and panels with double-axis tracker is developed, in this part. Then, adequacy assessment of Roy Billinton Test System (RBTS) and IEEE Reliability Test System (IEEE-RTS) integrated with PV units is performed. Besides, effect of different sun tracker systems on reliability indices related to power networks containing PV units is investigated. In this paper, the simulations are carried out in MATLAB software.

A. Reliability Presentation of Different PV Units

A 30MW PV unit composed of 100000 PV panels is considered to be installed in Kish Island. In this paper, due to the latitude of Kish Island, the tilt angle of the panels in the PV farms with fixed panels equipped with the single-axis tracker is considered to be 26.5o. The availability of different sun tracker systems including the single-axis sun tracker system, east-west and north-south

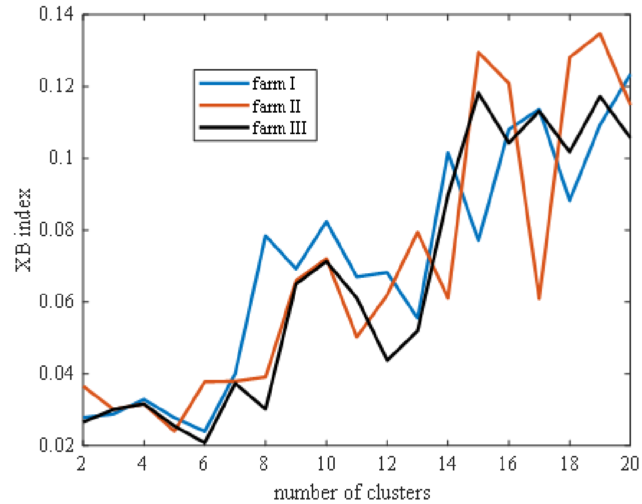

Fig. 10. XB index considering cluster number.

Table 2. The capacities and probabilities of the clusters associated with different PV farms

Case I	Capacity (MW)	25.6	29.8	11.5	0.1	19.0	5.3
	Probability	0.0651	0.0515	0.0719	0.6392	0.0851	0.0872
Case II	Capacity (MW)	7.0	0.2	23.1	29.9	15.1	
	Probability	0.1084	0.5854	0.1134	0.0946	0.0983	
Case III	Capacity (MW)	30.0	0.2	14.0	6.6	20.5	26.0
	Probability	0.0790	0.5784	0.0799	0.0996	0.0784	0.0847

sun tracker systems (parts of double-axis sun tracker device) is 0.98. The area of each panel is considered to be 2m2 and the efficiency of the PV farm including the efficiency of the PV panels, the converters and the wires is considered to be 16.67%. In this part three farms are considered as below:

Farm I is the 30MW PV farm including fixed panels, farm II is the 30MW PV farm including panels with single-axis sun tracker and farm III is the 30MW PV farm including the panels equipped with the double-axis sun tracker. According to proposed approach performed by Monte Carlo simulation method in 100 years, the XB index associated with different PV farms is obtained. It is presented in Fig. 10. The figure presents 6, 5 and 6 clusters can optimally model the PV farms with fixed panels, PV units with single-axis tracker and PV units with double-axis tracker, respectively. By applying fuzzy c-means clustering method, capacities and associated probabilities of farms are determined. Table 2 presents the results.

B. Adequacy Assessment of RBTS

The RBTS is small reliability test system containing 240MW installed capacity. The characteristic of generation power plants of the RBTS is given in [26]. For studying the effect of different PV farms on adequacy indices of RBTS, five case studies are evaluated: in cases I to III, PV farms I to III are respectively integrated into RBTS, case IV is original RBTS and case V is RBTS integrated with a 30MW conventional power plant with the availability of 0.98. Load duration curve is a straight line extending from one hundred to sixty percent of peak demand. Loss of load expectation and expected energy not supplied for these five cases are obtained. Figs. 11 and 12 present the results.

The figures present that the integration of new generation

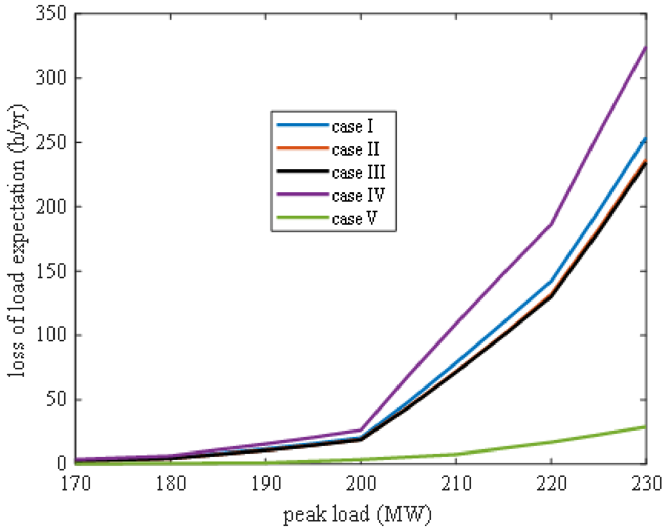

Fig. 11. LOLE at different peak demand.

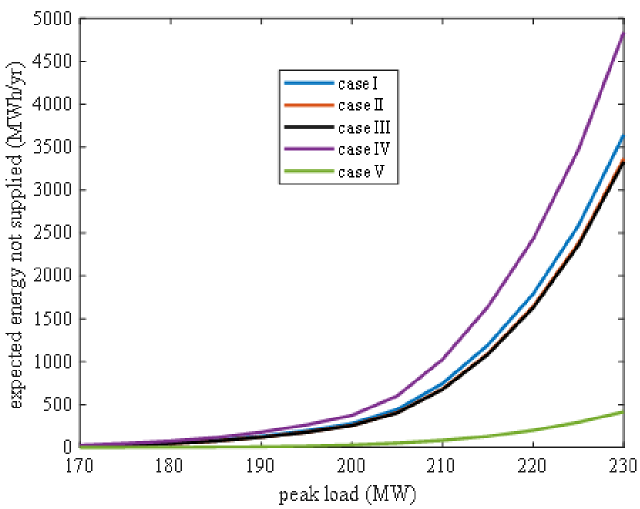

Fig. 12. EENS at different peak demand.

units makes reliability indices improve. However, conventional power plant integration can improve reliability indices of power networks more than PV Units integration with the same size. Among different PV farms, the farms equipped with the double-axis sun tracker system enhance reliability of power network more than PV farms with fixed panels and PV farms with single-axis trackers. However, the difference between the reliability indices in the PV farm with double-axis tracker and PV farm equipped with single-axis sun tracker system is not significant.

C. Adequacy assessment of IEEE-RTS

IEEE-RTS is a large network with 3405MW installed capacity. Characteristics of the generation units of this system are explained in [27]. For investigating impact of different PV farms on adequacy indices of IEEE-RTS, five case studies are assessed: in cases I to III, PV farms I to III are respectively integrated into IEEE-RTS, case study IV is original IEEE-RTS and case study V is IEEE-RTS integrated with a 30MW conventional power plant with the availability of 0.98. Load duration curve is a straight line extending from one hundred to sixty percent of peak demand that is assumed to be 2850MW. LOLE and EENS for these five case studies are calculated. Table 3 presents the results. The table presents integration new power plants results reliability indices enhance. However, integration conventional generation units can improve reliability indices of power networks more than PV unit integration with the same size. Because uncertain nature of PV units makes produced power of PV unit less than rated output most time. It has arisen from change in solar radiation. Among different PV farms, the farms equipped with the double-axis sun tracker system enhance reliability of power network more than PV farms with fixed panels and PV farms with single-axis trackers. However, the difference between the reliability indices in the PV unit with double-axis tracker and PV farm with single-axis sun tracker system is not significant.

Table 3. The reliability indices of different cases

Cases	LOLE (h/yr)	EENS (MWh/yr)
1	109.0122	16329
2	108.0033	16159
3	107.8289	16130
4	112.9085	16984
5	94.7670	13944

As can be seen in Table 3, at peak load of 2850 MW, the LOLE of original IEEE-RTS is 112.9085 hours per year. When, the PV farm with no tracker system is integrated into the power system, the LOLE decreases by 3.45%. while, when PV farm equipped with single-axis and double-axis tracker systems are integrated into the power system, the LOLE decreases by 4.34% and 4.50%, respectively. However, integration of conventional unit decreases the LOLE by 16.07%. Thus, uncertainty nature of PV farms arisen from variation in solar irradiance makes the impact of PV farm on reliability indices to be less than conventional plant with the same capacity. In this study, the capacity of PV farm comparing to the peak load of power system is 10.5%. Thus, the impact of PV farm on reliability indices is not significant.

D. Comparison between proposed method and Monte Carlo approach

In this part, to satisfy the results obtained by proposed method, a comparison with Monte Carlo simulation approach used in [5-6] for reliability evaluation of large-scale PV systems is done. For this purpose, at each hour, random numbers (between 0 and 1) are produced for all components of different PV systems. If the produced number is between zero and availability of component, the related component is perfect. But, if the produced number is between availability of component and 1, the related component is failed. Thus, according to the states of PV system components, and according to solar radiation data at each hour, hourly output power of various types of PV units is determined. Besides, by producing random numbers for generation units of RBTS and IEEE-RTS, the generated power of the test systems at each hour is specified. To compute the reliability indices, at each hour the generated power is compared with the demand. Thus, during each year, the hours that the load curtailment is occurred and the value of this curtailed load are determined. LOLE is the sum of hours that load curtailment is occurred at them, and the EENS is the sum of curtailed load at that year. By repeating the Monte Carlo simulation for several years, the average values of LOLE

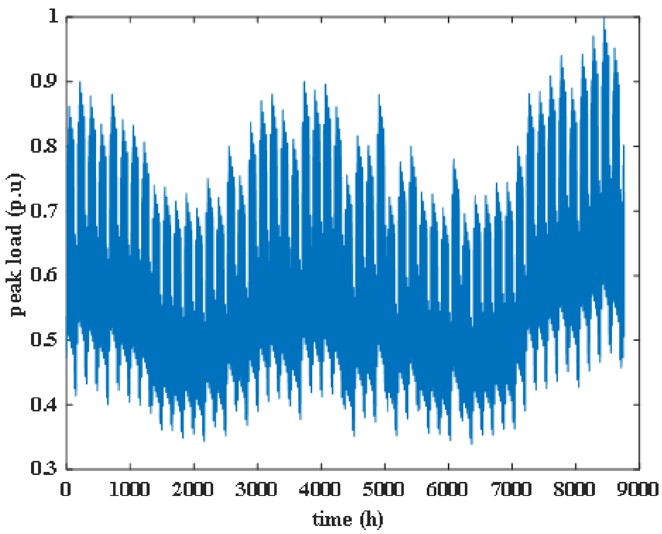

Fig. 13. Hourly per unit peak load.

Table 4. . Comparison between LOLE (h/yr) obtained by proposed method and Monte Carlo approach for RBTS

Cases	Proposed method	Monte Carlo method	Error%
1	20.4472	20.0012	2.18
2	19.0907	18.6650	2.23
3	18.8661	18.2014	3.52
4	26.3562	25.9611	1.50
5	3.5026	3.4210	2.33

and EENS are obtained. The hourly per unit peak load used in the simulation is illustrated in Fig. 13.

In this stage, reliability evaluation of RBTS for five mentioned cases at peak load of 200 MW is performed by Monte Carlo simulation approach during 1000 years, and the reliability indices including LOLE and EENS are calculated. The comparison between the results calculated by Monte Carlo simulation approach and the results obtained by proposed method of the paper is illustrated in tables 4 and 5. As can be seen in the tables, the errors between the results obtained by two methods are low, and so, the accuracy and the effectiveness of the proposed method is satisfied.

In this part, reliability analysis of IEEE-RTS for five mentioned cases through Monte Carlo simulation method is performed. The peak load is assumed to be 2850 MW. By repeating the Monte Carlo simulation approach for 100 years, the reliability indices are calculated and illustrated in Tables 6 and 7. It is deduced from these tables that the error between proposed method and Monte Carlo simulation approach is low.

Table 5. Comparison between EENS (MWh/yr) obtained by proposed method and Monte Carlo approach for RBTS

Cases	Proposed method	Monte Carlo method	Error%
1	280.74	273.22	2.68
2	259.03	255.28	1.45
3	256.32	250.63	2.22
4	375.05	368.21	1.82
5	31.27	30.21	3.39

Table 6. Comparison between LOLE (h/yr) obtained by proposed method and Monte Carlo approach for IEEE-RTS

Cases	Proposed method	Monte Carlo method	Error%
1	109.0122	104.0025	4.60
2	108.0033	104.8565	2.91
3	107.8289	102.2554	5.17
4	112.9085	108.2997	4.08
5	94.7670	91.9514	2.97

Table 7. Comparison between EENS (MWh/yr) obtained by proposed method and Monte Carlo approach for IEEE-RTS

Cases	Proposed method	Monte Carlo method	Error%
1	16329	15598	4.48
2	16159	15425	4.54
3	16130	15478	4.04
4	16984	16201	4.61
5	13944	13462	3.46

6. CONCLUSION

In this paper, different PV farms including PV farms with fixed panels, PV farms with the single-axis tracker and PV farms with the double-axis tracker, based on reliability criteria are compared. In this regard, a reliability presentation with several states is suggested for these PV units. Besides, changes in output power caused by change of solar radiation intensity and failure of elements especially failure of sun tracker device is considered in the model. The sun's position in sky is presented by azimuth and zenith angles and the relations of solar radiation received by different PV farms are determined. For considering effect of sun tracker device on reliability model of PV units, Monte Carlo simulation approach is proposed and based on the historical data reliability presentation of different PV units can be obtained. In this paper, for decreasing states of output power data, XB index is obtained and fuzzy c-means clustering method is implemented. Resulted reliability presentation of PV units is utilized for assessing reliability of power networks including large-capacity PV units. Besides, effect of different solar trackers on the reliability indices is evaluated. In this paper, adequacy studies of RBTS and IEEE-RTS incorporating large-capacity PV farms with different types of sun tracker systems are performed. Numerical results present that integration of PV units makes reliability indices enhance. However, PV farms enhance reliability indices of power networks less than same-sized conventional power plants. It has arisen from the uncertain nature of PV farms that makes their output power of the change. Among different PV farms, the farms equipped with the double-axis sun tracker system enhance reliability of power network more than

PV farms with fixed panels and PV farms with single-axis trackers. However, the difference between the reliability indices in PV units with double-axis trackers and PV farms equipped with single-axis sun tracker systems is not significant. It is deduced from numerical results of RBTS that at peak load of 200 MW, expected energy not supplied of original RBTS is 375.05 MWH per year. Addition of 30MW PV farm with fixed panel improves the reliability index by 25.15%, while PV farm equipped to single-axis and double-axis tracker improves the EENS by 30.93% and 31.66%, respectively. However, addition of conventional generation unit improves reliability index by 91.66%. Thus, variability of output power of PV farms causes the effectiveness of these renewable power plants on reliability improvement of power system to be about 34.54% of conventional generation units with the same size. To satisfy the accuracy of the proposed technique in reliability assessment of PV systems, a comparison with Monte Carlo simulation approach is performed, in the paper. It is concluded from this comparison that the results obtained by proposed analytical method are almost the same.

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