Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Reliability Evaluation of Solar Power Plants Equipped with parabolic Trough Reflectors

Amir Ghaedi[a,*], Reza Sedaghati[b], Mehrdad Mahmoudian[c]

[a]Department of Electrical Engineering, Dariun Branch, Islamic Azad University, Dariun, Iran.,
[b]Department of Electrical Engineering, Beyza Branch, Islamic Azad University, Beyza, Iran.,
[c]Department of Electrical and Electronic Engineering, Shiraz University of Technology, Shiraz, Iran.

ARTICLE INFO

Article Type:

Research Article

Received:13.05.2023
Accepted:22.10.2023

Keywords:
Linear parabolic trough reflectors
Reliability
Fuzzy c-means clustering (FCM) technique
Adequacy
Solar power plants

ABSTRACT

Due to the challenges of fossil fuels, renewable resources such as wind, solar and ocean are applied for electric power production. Among different kinds of renewable resources, the potential of solar energy is significant in Iran. The electricity cost produced by parabolic trough collectors is low. Accordingly, this paper aims to study the reliability performance of this plant. To this end, a multi-state reliability model considering both failures of composed components and variation of produced power caused by variation of sun irradiance is developed for solar power plants with parabolic trough collectors. To reduce the number of power states of the model, the fuzzy c-means clustering method and XB index are applied. The obtained reliability model of solar plants is utilized for analytical reliability analysis of electric networks. Numerical outcomes of adequacy analysis of RBTS and IEEE-RTS results integration of parabolic trough collectors improve reliability indices of the system. However, due to the variation of sun irradiance results in the variation of plant output, improvement of reliability indices caused by parabolic trough collector is less than traditional plants. Besides, by comparing the outcomes obtained by the proposed work and Monte Carlo method, the accuracy of the suggested method is approved.

1. Introduction

Nowadays, the amount of renewable resources in power networks for the generation of electric power has increased. Due to the availability and high density of solar energy, different types of solar power plants, such as photovoltaic farms, heliostat-based power plants, linear parabolic

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[*] Corresponding Author Email:amir.ghaedi@miau.ac.ir

Cite this article: Ghaedi, A., Sedaghati, R., & Mahmoudian, M. (2023). Reliability Evaluation of Solar Power Plants Equipped with parabolic Trough Reflectors. Journal of Solar Energy Research, 8(3), 1635-1650. doi: 10.22059/jser.2023.359179.1305

DOI: 10.22059/jser.2023.359179.1305 DOR: 20.1001.1.25883097.2023.8.3.6.6

collectors, parabolic dishes, and linear Fresnel collectors, are installed all over the world. Large-scale solar power plants are installed for a variety of reasons, including the availability and high density of solar energy, as well as their clean environment, sustainability, and low cost. Both photovoltaic and solar thermal power plants have been used to generate electricity so far. The photovoltaic system uses the p-n junctions for converting sun radiation into electric power. Sun's radiation is concentrated in thermal solar generation units by a lot of big mirrors, which causes the receivers to get hot. The thermodynamic cycle can be driven by a working fluid by using the high temperature of receivers. Vapor is created by the working fluid being transformed. When the vapor runs through the turbine, electricity is generated. This paper evaluates the reliability of linear parabolic collectors, which are one type of solar thermal power plant among others, including heliostat-based power plants, linear parabolic collectors, parabolic dishes, and linear Fresnel collectors. Due to the significance of linear parabolic collectors, numerous researches are done for examining effects of these renewable resources on various facets of electric network. It was modeled by Kannaiyan et al. [1] that using a Fresnel reflector with water as the working fluid and a parabolic trough collector with Thermion oil. To determine the system's transfer-function at both continuous and discontinuous domains at rated conditions, the step test approach was used in this paper. Next, a controller built on the continuous proportional integral approach is suggested, which includes controls for static feed-forward or predictive function. A novel approach to designing a solar parabolic trough collector fitted with another reflector was put forth in paper written by Shajan and Baiju [2]. In this study, a software program for optical simulation is developed to create a homogeneous solar flux distribution in medium-temperature parabolic solar plant. This software produces the highest power on central receiver in concentrated solar power plant. Efficiency of parabolic solar unit fitted by capillary heat pipe was thoroughly examined by Boukhalfa et al. [3]. This study examines the effects of various factors, such as solar radiation and parabolic trough collector's inclination, on the system's overall performance. Additionally, a comparison between experimental and theoretical results is done. According to the knowledge of the authors, reliability of parabolic solar generation units has not been studied. In this section, newly published papers that examined the reliability performance of other renewable units such as wind, photovoltaic, run of the river, reservoir kind, stream kind tidal units, ocean thermal energy conversion systems, and wave generators are reviewed. This is because the uncertainty inherent in renewable resources results from change in produced power of them. Produced electric power from renewable units varies due to variations in wind velocity, sun radiation, water stream rate, tidal level, tidal stream velocity, temperature of ocean surface, and wave height and period. Ghaedi et al. [4] performed a several-state wind farm reliability presentation which was created using several wind turbines outfitted with doubly-fed induction generators. Influence of failure of assembled devices such as turbine, gear-box, doubly-fed induction generator, power electronic converter, cable, and transformer is considered when determining reliability presentation of these farms. It is also important to consider variations in produced electric power of wind turbines caused by variations in wind velocity. The analytical approach is applied to determine adequacy indices of electric networks containing wind farms with large installed capacity through multi-state reliability model of wind farms. Ghaedi et al. [5] performed an adequate assessment of electric network, including sizable photovoltaic units. This study develops a reliability model for photovoltaic systems that takes into account failure of the system's parts, such as solar cells, a maximum power point tracking system, inverters, transformers, and cables, as well as variations in generated power due to changes in solar radiation. Numerical simulation indicates that hazard rate of the photovoltaic farm's assembled parts is low, and as a result, it has little bearing on the adequacy evaluation of the photovoltaic farms. Khalilzadeh et al. [6] proposed a several-state reliability presentation of run of the river units. This model takes into account both component failure and variation in the power they produce. Because of variations in water flow rate, producing electric power of run of the river units varies. So, using clustering technique, number of states in reliability presentation of them is decreased. Adequacy analyses of electric network, including tidal units of reservoir kind, were carried out by Mirzadeh et al. [7]. In this study, it was assumed that the tidal plant generates electricity in an ebb state to increase the plant's output of energy. The reliability presentation created for these tidal units takes into account the failure of the plant's assembled parts, such as the sluices, turbines, generators, transformers, and cable, as well as variations in the power the plant generates due to changes in tidal height. Additionally, influence of change in level of tides on hazard rate of assembled elements is looked into. Mirzadeh et al. [8] performed reliability modeling of stream-kind tidal units considering influence of hazard rate of assembled elements and change in electric produced power them. This paper examines three various kinds of generator technologies nowadays applied in tidal units including doubly-fed asynchronous generator, synchronous generator with exciter winding, and synchronous generator without exciter winding. Based on closed-loop technology mentioned by Nasiriani et al. [9], it developed a reliability model for ocean thermal power plants. In these units, deep water is used as a cold source to change the working fluid's vapor state back to a liquid and the water at the ocean's surface serves as a heat source to turn the liquid back into a liquid. Ammonia is used as the working fluid in systems for converting ocean thermal energy because of its low boiling point. This study examines hazards of ocean thermal unit's combined elements, including pipes, supporting systems, pumps, heat exchangers, turbines, transformers, and cables. The presentation linked to hazard of assembled elements and the presentation linked to the change in plant's generated power is what led to the development of the ocean thermal energy conversion system's complete reliability model. Ghaedi and Gorginpour [10] performed a reliability method for studying a composite electric network that includes wave energy conversion systems. In this research, a reliability presentation for a sea wave slot-coned generator is developed. This generator is one of many wave energy extraction technologies, such as wave dragon, pelamis, tapchan, limpet, oyster, Archimedes wave swing, oscillating water column, and so on. The contingency analysis approach is used to determine the reliability indices of composite electric network made up of production units and transmission lines.

Ghaedi et al. [11] proposed the impact of various solar tracker systems on the reliability performance of photovoltaic farms is analyzed. In this research, fixed panel solar plants, photovoltaic plants equipped with single-axis tracker systems and photovoltaic farms equipped with double-axis tracker systems are studied. In the framework presented by Ghaedi et al. [12], a well-being approach of the electric network including central receiver power plants is studied. In this research, a multi-state reliability model suitable for operation studies of heliostat power plants is developed. Ghaedi et al. [13] studied the effect of vanadium redox batteries on the reliability of power systems integrated with current kind tidal power plants. In this study, a multi-state reliability model is developed for a set composed of stream-type tidal turbines and vanadium redox battery to consider failure of composed components and variation of produced power. Ghaedi et al. [14] studied the impact of variation in renewable resources including wind velocity, tidal current speed and sun irradiance on the reliability performance of a renewable energy-based microgrid. In this paper, the microgrid is composed of wind turbines, stream-type tidal turbine and photovoltaic systems. Ghaedi et al. [15] analyzed reliability performance of the electric network including wind units equipped with the permanent magnet synchronous generator. In this study, the impact of variation in the wind velocity on the hazard rate of composed components of wind units is investigated. In Ghaedi and Gorginpour [16], a spinning reserve required in the power system containing wind and solar power plants to satisfy the risk criteria was determined. In this paper, a multi-state reliability model considering failure of composed components and variation of produced power is developed for both wind turbines and solar power plants. Ghaedi and Gorginpour [17] determined the required spinning reserve in an electric network containing large-scale wave converters. The wave dragon as a commercial scale wave converter is studied in the paper to study the impact of wave energy conversion systems on the operation performance of the power system. In Ghaedi and Mirzadeh [18], reliability evaluation of electric network including barrage-type tidal power plant was performed. In this paper, the impact of variation in the tidal height on the hazard rate of main components of the barrage-type tidal power plant is studied. Ghaedi et al. [19] computed the required spinning reserve of an electric network containing ocean thermal energy conversion systems. To calculate the spinning reserve of the power system including ocean thermal energy conversion system, a multi-state reliability model is developed for these renewable power plants. In Mirzadeh et al. [20], reliability modeling of the stream-type tidal power plant was carried out. In this research, a multi-state reliability model is developed for this renewable unit considering both failures of composed components and variation of the produced power arising from variation of tidal current speed. Mirzadeh et al. [21] determined the required spinning reserve in an electric network containing barrage-type tidal power plant. To this end, reliability modeling of tidal barrage considering failure of composed components and variation of produced power arising from variation of tidal height is performed. In Ouagued et al. [22], magnesium-chlorine thermochemical cycle used to produce the hydrogen by solar parabolic trough collectors was studied. In this research, direct sun irradiance is estimated with tilted and tracking collectors in the Algerian desert. Bagheri et al. [23] improved the performance of solar still by external solar panels and cylindrical parabolic trough collectors for seawater desalination. In this research, two different setups including a simple solar still unit and a solar still unit composed of solar panels and cylindrical parabolic collector are compared. In formulations presented by Geete et al. [24], exergy analysis of parabolic solar collectors at different conditions was performed by PAPSC software. In this research, the performance of parabolic solar collectors with and without considering cone angle of sun is studied. Abdollahi Haghghi et al. [25] examined thermodynamic analysis of parabolic trough collectors used for power and heating production at the engineering faculty of Urmia University in Iran. In this research, the energetic and exegetic analysis of parabolic trough collectors with an organic Rankine cycle is carried out. Heidarnejad and Noorpoor [26], performed a thermodynamic and thermos-economic analysis of a multi-generation energy system utilizing solar and biomass sources. In this research, electricity, heating and cooling power are provided utilizing a Rankine cycle, a heater, a double effect absorption chiller, a liquefaction natural gas subsystem, a multi-effect desalination system, a parabolic trough collector and a combustion burner. Goel et al. [27] conducted dynamic modeling and controller design of a parabolic trough collector. In this research, an analytical dynamic model is developed for parabolic trough collector to derive the transfer function of parabolic trough solar collector system. In paper written by Guo et al. [28], modeling of solar field in direct steam generation parabolic trough collector was conducted based on the heat transfer mechanism and artificial neural network. In this research, the first four-layer neural network models the inlet pressure and outlet temperature of solar field, and then the second four-layer neural network analyzes the outlet temperature of solar field. Shabbir et al. [29], conducted feasibility study and design of concentrated solar power plants. In this research, a comprehensive study of four different concentrated solar power plant configurations is performed and a comparison between concentrated technologies and solar photovoltaic power plants is carried out. Waghmare et al [30], conducted numerical simulation of tracking modes of compound parabolic trough collector with tubular receiver. This study aims to analyze the amount of solar incident flux falls on the reflector of the compound parabolic collector by applying five different tracking modes.

Reliability modeling of solar power plants with parabolic trough collectors is not addressed in the previous research. Accordingly, the current paper studies reliability performance of these renewable resources so that the suitability of the electric network with these renewable units can be evaluated. Thus, the contributions of the paper are:

- Developing a multi-state reliability model for solar power plants equipped with parabolic trough collectors considering both failure of composed components and variation of the sun irradiance.
- Determining adequacy indices of electric networks including solar power plants equipped with parabolic trough collectors.

Organization of this paper is based on its purpose. The second section describes the operating principles of parabolic solar units and the parts that make them up. A reliability model is created for these renewable resources in the third section, taking into account both component failure and variations in the power they generate due to changes in solar radiation. The fourth section introduces the suggested method for determining the suitability of an electric network with a solar plant outfitted with a parabolic trough collector. The fifth section contains the numerical findings related to adequacy assessment of two reliability test networks, RBTS and IEE-RTS. Finally, the research summary is covered in last part.

2. Solar Power Plants Equipped with parabolic Trough Collectors

Due to the problems related to the fossil fuels such as greenhouse gas emissions causing global warming, climate change and ozone disruption, renewable resources are applied for electric power generation in the recent electric networks. Among different renewable resources including wind, solar and ocean, sun energy is a renewable resource that is utilized globally to generate electricity because it is readily available and has a high energy density. Two general solar power plants, including photovoltaic systems and concentrated power plants, are being developed to convert solar energy into electricity. Linear and point-focusing approaches are two of the methods available in concentrated power plants. In Fresnel trough and parabolic collectors, linear focusing is used. The solar towers and parabolic dishes, however, employ the point-focusing technique. Among various types of solar power plants, the cost of electricity produced by parabolic trough collectors is low. Besides, these plants produce very high temperatures which are suitable for steam generation. These renewable power plants can be easily integrated with thermal energy storage systems causing the operation of plants in periods of low sun irradiance such as cloudy days or during the night which was represented by Di Fraia et al. Accordingly, in the current paper, the reliability performance of parabolic trough collectors is studied. In Fig. 1, the general layout of a sun generation unit with a parabolic trough collector is shown. As can be seen in the Figure, parabolic trough mirrors reflect solar radiation and focus it on the pipes located at linear focal lengths of the mirrors. As a result of the concentrated solar radiation on these pipes, which contain mineral oils, the temperature of the oils can rise to 400^{0}C. The heat of the mineral oil is transferred via a heat exchanger to the working fluid, which is typically water. The working fluid is transformed into vapor, which can turn a turbine connected to a generator. As a result, the Rankine cycle generates electricity. The working fluid is changed from its vapor state to its liquid state in the condenser to finish the Rankine cycle. The Rankine cycle is then finished by pumping the working fluid into the boiler.

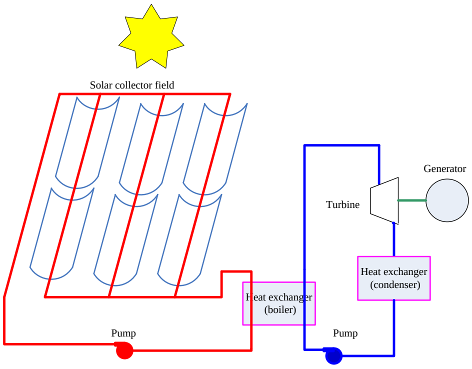

Figure 1. Assembled elements of sun generation unit equipped with parabolic trough collectors

Solar radiation is a determining factor in the amount of power produced by sun generation units with parabolic trough collectors. The renewable generation units produce the following amount of power [32–35]:

$$P_{PTC} = nSA\eta_{\cos}\eta_{clean}\eta_{mr}\eta_{i}\eta_{ra}\eta_{rt}\eta_{th-wf}\eta_{b}\eta_{tu}\eta_{g} \qquad (1)$$

Where, n is the number of parabolic mirrors, P_{PTC} is produced power of parabolic trough collector, S is sun irradiance, A is the area of parabolic mirror, and η_{cos} is cosine effect. Relying on kind of mirror collectors and their direction, the effect of the reflector, η_{clean} is the optical correction of the mirror due to dirt, η_{mr} is the reflection of the mirror, η_i is the reflection action function (part of the reflected light reflected by the receiving tube), η_{ra} received absorbance (part of the radiation received by the receiving tube) where η_{rt} is the permeability received (part of the electricity taken from the receiver tube and sent to working fluid), $\eta_{th\text{-}wf}$ is heat transfer of working fluid, η_b is boiler efficiency, η_{tu} is turbine efficiency, and η_g is generator efficiency. It can be determined the energy transfer to mass by Negahdari et al. [36]:

$$P_G = P_{PTC}\eta_{PEC}\eta_T \qquad (2)$$

Where, P_G is transmitted power to network, η_{PEC} is efficiency of power electronic converter and η_T is the efficiency of transformer.

3. Reliability Presentation of Sun Generation Units with Parabolic Trough Collectors

Čepin et al, [37] showed that the reliability was characterized in power system studies as the facilities' capacity to supply the necessary loads. Adequacy and security are two key factors that are examined for examining reliability of electric networks. The generation, transmission, and distribution subsystems, as well as other components of the power system, must all have sufficient facilities to meet the necessary loads for the power system to be deemed adequate. While the response of electric network to satisfy necessary demands is studied when disturbances occur in the power system as part of studies on its security. Two strategies, using analytical and numerical methods, are created for analyzing reliability performance of electric networks. The electric network reliability analysis numerical techniques are according to Monte Carlo simulation methodology. Reliability model of composed components must be established for the analytically based reliability analysis of electric network. Thus, a 2-state Markov presentation with healthy and broken states is taken into account for components of power system. Fig. 2 illustrates the 2-state reliability model of components. The Figure illustrates how components transfer from their healthy state to their broken state by failure rate that is the number of failures per defined study time. Besides, the model presents how the components return to their healthy state, which is represented as the repair rate which is the number of repairs in defined study time.

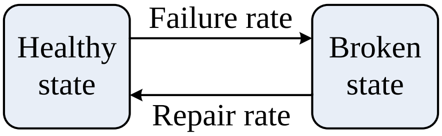

Figure 2. Markov model of components with two states

The Markov model shown in Figure 2 assumes that each component has a useful life and a constant failure rate during this time. The probability of both the Markov model's healthy and broken states can be computed as equations (3) and (4) as mentioned by Čepin et al, [37]:

$$P_{healthy-state}=\frac{rapair\ rate}{failure\ rate+repair\ rate} \quad (3)$$

$$P_{broken-state}=\frac{failure\ rate}{failure\ rate+repair\ rate} \quad (4)$$

The effect of component failure on overall plant failure must be assessed in order to establish the reliability model for solar power plants with parabolic trough collectors. Figure 1 illustrates this phenomenon. As can be seen in Fig. 1, parabolic mirrors fitted to the receiver tubes, the boiler, turbine, condenser, pumps, generator, and transformer are the main built-in parts of parabolic solar generation unit. Parabolic mirrors exist in solar power plants. Each parabolic mirror that fails results in reduction of produced power of the plant as much as the power of each mirror. However, the plant's operation is halted due to the failure of other parts, such as the boiler, turbine, condenser, pump, generator, and transformer. Figure 3 illustrates, from the perspective of reliability, how the failure of a plant's assembled elements affects failure of entire device. According to this Figure, failure of boiler, turbine, condenser, pumps, generator or transformer causes the failure of plant. Thus, these components are placed in series. However, failure of all parabolic mirrors fails in plant. Thus, parabolic mirrors are placed in parallel with each other, and their set is placed in series with other components.

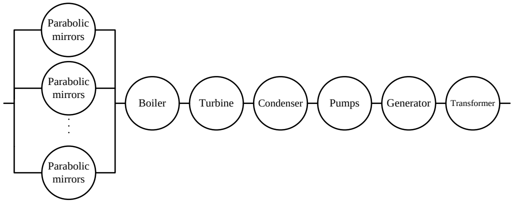

Figure 3. Impact of failure of composed components on overall hazard of plant

Reliability presentation of C-MW solar generation unit equipped *n* parabolic mirrors is shown in Figure 4. As can be seen in the Figure, failure of each parabolic mirror reduces the power of the plant as much as the power of related mirrors. While the failures in other components cause entire failure of the plant. In the Figure, λ_m and μ_m are the failure rate and repair rate of each parabolic mirror, respectively. In addition, λ_S and μ_S are respectively equal to the failure and repair rates of the system consisting of series connection of boiler, steam turbine, condenser, water pump, generator and transformer, respectively.

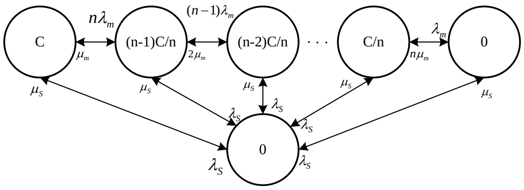

Figure 4. Reliability presentation of the solar generation plant considering failure of assembled elements

Hazard and repair rates of system composed of series connection of boiler, turbine, pumps, generator and transformer can be calculated as mentioned by Čepin et al, [37]:

$$\lambda_S=\sum_{i=1}^{5}\lambda_i \quad (5)$$

$$\mu_S=\frac{\sum_{i=1}^{5}\lambda_i}{\sum_{i=1}^{5}\frac{\lambda_i}{\mu_i}} \quad (6)$$

Where, λ_i and μ_i are the failure and repair rates of each element such as boiler, steam turbine, water pump, generator and transformer, respectively. The solar power plant is equipped with numerous parabolic mirrors, so the failure of each parabolic mirror has little effect on the electricity production of the plant. Therefore, the failure of parabolic mirrors is negligible in the solar power plant reliability model. Based on this theory, reliability presentation of a parabolic trough solar generation unit is shown in Figure 5. According to this reliability model, a two-state model with equivalent failure and repair rates is applied for reliability presentation of a solar power plant equipped with parabolic trough collectors to consider the failure of composed components.

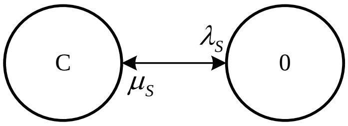

Figure 5. Reliability presentation of sun generation unit neglecting failure of parabolic mirrors

Hazard and repair rates of plants have the same amount of λ_S and μ_S. This section examines reliability presentation of plants along with influence of variations in solar radiation on electric network that the solar plant generates. The sun's radiation changes over time. In 2020, the variation of sun irradiance at each hour associated with Shiraz region of Iran is shown in Figure 6. As can be seen in the Figure, the solar radiation changes significantly. Solar radiation affects how much power a solar power plant can produce. The solar power plant's output varies greatly because of variations in solar radiation. As a result, reliability presentation of solar generation units fitted by parabolic trough collectors related to plant's generated power has several states. It is necessary to reduce the states of the solar power plant's reliability model to analytically evaluate it.

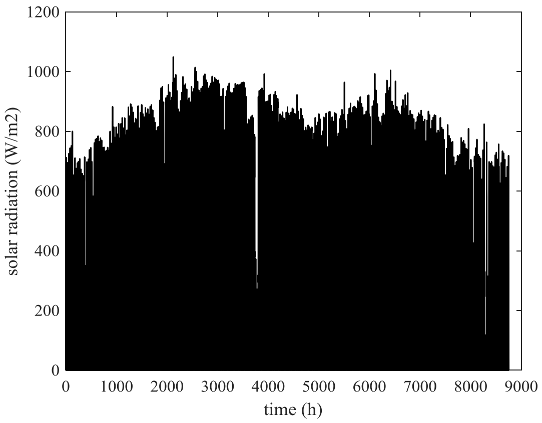

Figure 6. Hourly solar radiation in Shiraz region in 2020

In this paper, for decreasing states of reliability presentation of solar generation units equipped with parabolic trough collectors, fuzzy c-means (FCM) clustering methodology is suggested. According to this approach, for decreasing number of states of the presentation following cost function must be minimized as mentioned by Bezdeket al, [38]:

$$Z_m(U,PC)=\sum_{i=1}^{m}\sum_{k=1}^{n}U_{ik}^{f}\left|P_k-PC_k\right| \qquad (7)$$

Here, f, PC_k, U_{ik} are fuzzy factors, center of i^{th} cluster and fuzzy number between P_k and i^{th} cluster. In FCM, to determine suitable number of clusters, we calculate XB factor as mentioned by Bedecked al, [39]:

$$XB=\frac{of_m(U,PC)}{n\times\min_{i\neq j}[(PC_i-PC_j)^2]} \qquad (8)$$

In (8), $Z_m(U,PC)$ is the objective function of FCM method that reduces n data of generated power to m center associated with the generated power. When XB index is minimal, you can determine optimal number of clusters. Each data (for example data k^{th}) belongs to the center i^{th} by fuzzy number U_{ik}. The probability of each new state can be determined as mentioned by Bezdeket al, [38]:

$$P_i=\frac{\sum_{k=1}^{n}U_{ik}}{n} \qquad (9)$$

Comprehensive reliability presentation of solar production plants with parabolic trough collectors is created by combining reliability presentation of the plant related to hazard of composed elements and reliability presentation associated with changes in produced electric power. Figure 7 presents the reliability presentation of a solar power plant equipped with parabolic trough collectors. In this presentation, by clustering method the states related to change in electric produced power are reduced to h cluster with capacities $C1$, $C2$, … Ch. Besides, failure of plant causes the produced power of the plant to be transferred to zero-capacity states. Number of states in this reliability presentation is reduced by merging states with same capacity such as h states with zero capacity.

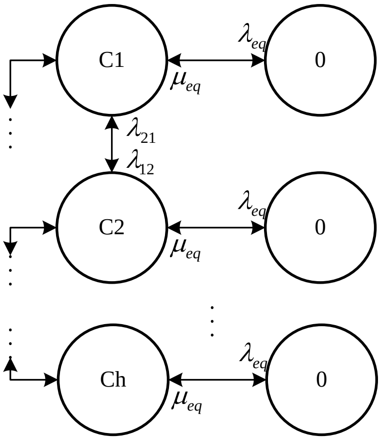

Figure 7. Comprehensive reliability presentation of solar production plant with parabolic trough collectors

4. Reliability Analysis of Electric Network Incorporating Sun Plants Equipped with Parabolic Trough Collectors

The method for reliability assessment of electric networks incorporating solar plants with parabolic trough collectors is introduced in this section. In this study, hierarchical level 1 is applied for reliability evaluation of the electric network, i.e. adequacy is performed at the generation level. As a result, the transmission network reliability is ignored. In other words, the transmission network is taken to be 100 percent trustworthy. All power plants and all loads are connected to a single bus, as shown in Figure 8, for assessing generation network's suitability. As can be seen in Figure 8, all power plants including renewable and traditional units are connected to a common bus and it is neglected from transmission network.

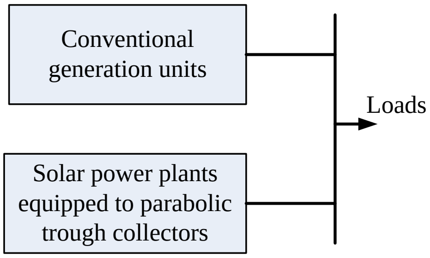

Figure 8. Reliability analysis of electric network incorporating sun power plants equipped with parabolic trough collectors

The generation model of every power plant, including parabolic solar units and conventional generation units, is established to assess the system's adequacy. Two states for the traditional generation units are shown. However, there are higher than 2 states in reliability presentation for solar units with parabolic trough collectors. A capacity-outage-probability-table (COPT) is constructed for each power plant according to the generation units' obtained reliability models. Each state's capacity and probability are computed using the COPT. The system reliability indices, such as average time of interruption (LOLE), average interrupted energy (EENS), maximum provided demand (PLCC), and increased maximum provided demand (IPLCC), are obtained by combining demand model with total COPT.

LOLE: average time during which production capacity is insufficient to support the required load, leading to load shedding.

EENS: the reduced energy during the understudied period.

PLCC: The maximum amount of peak load that the system is capable of supplying, assuming the reliability criterion EENS is met (for instance, EENS is below the permissible value).

IPLCC: The power system's PLCC can be raised if a new production unit is incorporated. PLCC has increased to meet the reliability criteria.

5. Numerical Results

The numerical outcomes for reliability analysis of Roy Billinton Test network (RBTS) and IEEE Reliability Test network (IEEE-RTS), which include solar power plants with parabolic trough collectors, are presented in this section. Billinton et al. [40] and Barrows, et al. [41] represented that RBTS and IEEE-RTS generation units have following Characteristics. Tables 1 and 2 present the Characteristics of RBTS and IEEE-RTS. In this paper, it is neglected from the failure of transmission and distribution networks to perform adequacy analysis of generation networks.

Table 1. Characteristics of RBTS [40]

Unit number	Cap. (MW)	Failure rate per year	Repair time
1	40	6	45 hrs
2	40	6	45 hrs
3	10	4	45 hrs
4	20	5	45 hrs
5	5	2	45 hrs
6	5	2	45 hrs
7	40	3	60 hrs
8	20	2.4	55 hrs
9	20	2.4	55 hrs
10	20	2.4	55 hrs
11	20	2.4	55 hrs

Table 2. The Characteristics of IEEE-RTS [41]

Unit number	Capacity (MW)	Failure rate (occ/yr)	Repair time (hrs)
1	50	4.42	20
2	50	4.42	20
3	50	4.42	20
4	50	4.42	20
5	50	4.42	20
6	50	4.42	20
7	12	2.98	60
8	12	2.98	60
9	12	2.98	60
10	12	2.98	60
11	12	2.98	60
12	155	9.13	40
13	100	7.30	50
14	100	7.30	50
15	100	7.30	50
16	197	9.22	50

17	197	9.22	50
18	197	9.22	50
19	20	19.47	50
20	20	19.47	50
21	76	4.47	40
22	76	4.47	40
23	20	9.13	50
24	20	9.13	50
25	76	4.47	40
26	76	4.47	40
27	155	9.13	40
28	155	9.13	40
29	350	7.62	100
30	400	7.96	150
31	400	7.96	150
32	155	9.13	40

At this point, a 30-MW solar power plant with 57143 parabolic trough collectors is being thought about. Each parabolic mirror has a 2.5 m^2 surface area. The east-west solar tracker system is equipped with mirrors. The solar power plant would produce 30 MW of power at 900 w/m^2 of solar radiation. Table 3 lists the traits of the solar power plant that has received the least attention [32–35].

Table 3. Characteristics of understudied sun unit equipped with parabolic trough collectors [32-35]

Parameter	Value
A	2.5 m2
n	57143
η_{cos}	0.93
η_{clean}	0.85
η_{mr}	0.94
η_{i}	0.99
η_{ra}	0.98
η_{rt}	0.98
$\eta_{th\text{-}wf}$	0.85
η_{b}	0.89
η_{tu}	0.45
η_{g}	0.97
η_{PEC}	0.98
η_{T}	0.98

Hourly produced electric power of the solar unit with parabolic trough collectors is calculated and shown in Figure 9. For computing the hourly produced power of the solar power plant equipped with parabolic trough collector, the hourly sun irradiance is multiplied by number of mirrors, area of each mirror and various efficiencies mentioned in equations (1) and (2).

Figure 10 displays the XB index, which was calculated to determine number of reduced states of produced electric power. In this Figure, the XB index is plotted versus number of reduced states of produced power associated with the solar power plant. The XB index is minimal for 4 clusters, as shown in the Figure. As a result, it is assumed that there are four clusters. We determine centers and their probabilities using FCM technique. Figure 11 displays the clustering results. In this Figure, the probabilities of different clusters, as well as their capacity of them are presented.

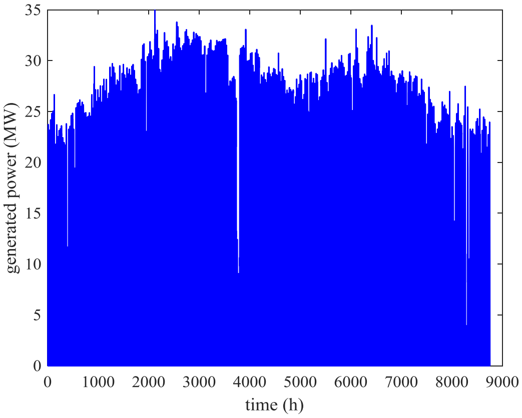

Figure 9. Hourly produced electric power of solar unit

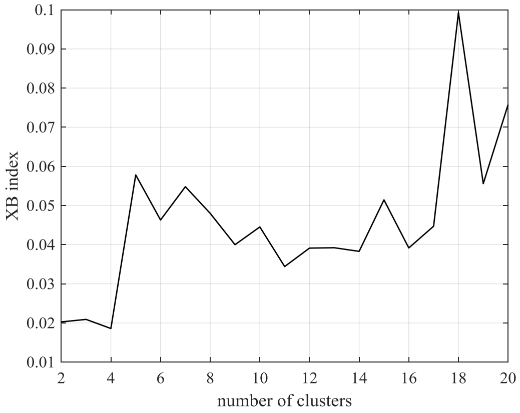

Figure 10. XB factor versus cluster number

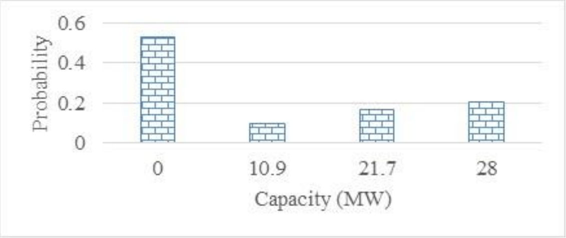

Figure 11. Clustering results

At this stage, the reliability model associated with the variation of produced power of the solar power plant equipped with parabolic trough collector presented in Fig. 11 is being studied for considering the effects of composed components failure. The understudied solar power plant's estimated annual failure and repair rates are 2 and 98, respectively. Thus, the understudied solar power plant would have 0.98 and 0.02 probability of being in healthy and broken states (availability and unavailability). Combining the plant's reliability model related to variations in the generated power and the reliability presentation related to hazard of assembled elements yields final reliability presentation of entire solar power plant under study. As a result, Figure 12 depicts comprehensive reliability presentation of parabolic solar unit under investigation.

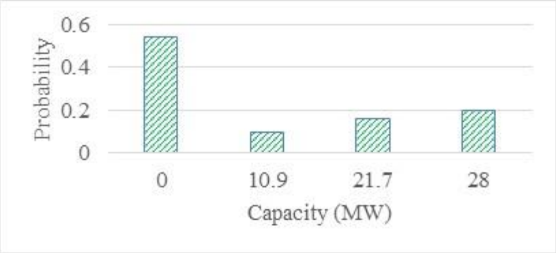

Figure 12. Comprehensive reliability presentation of understudied solar unit

To evaluate the suitability of RBTS and IEEE-RTS including solar power plants, the obtained several-state reliability presentation of the understudied solar unit is used. In the current study, a load duration curve is used to model the demand. In this study, the load duration curve is thought to be a straight line that goes from 100% to 60% of peak demand. Three cases are investigated when evaluating RBTS's reliability: case I is RBTS, case II is RBTS with 30-MW traditional generation plant and availability of 0.98, and case III is RBTS with an understudied 30 MW solar power plant equipped with parabolic trough collectors. The three aforementioned cases were evaluated for sufficiency in accordance with the suggested technique, and reliability indices, including LOLE and average interrupted energy taking peak load into account, were obtained and presented in Figures 13 and 14, respectively. It is concluded from Figure 13 that with increasing in the peak demand, the average time of interruption increases. Since a new power plant (traditional or solar power plant) is integrated to the electric network, the average time of interruption decreases. The decrease in the average time of interruption in the case of addition of traditional generation unit is more than the addition of solar power plants. It has arisen from the uncertain nature of solar power plants. Due to the variation in the sun irradiance, the produced power of solar power plant equipped with parabolic trough collectors is less than nominal capacity, while, in traditional power plants, if the plant is healthy, the rated capacity is produced. Similar results can be traced for average interrupted energy presented in Fig. 14.

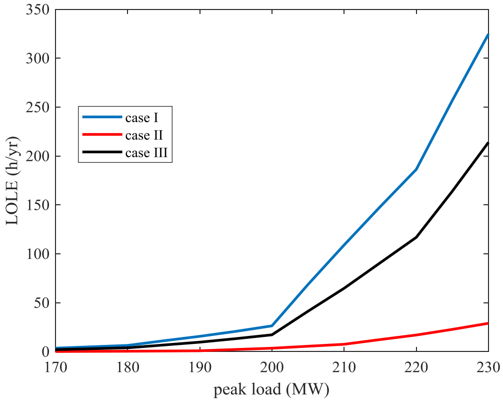

Figure 13. LOLE index versus peak demand for RBTS

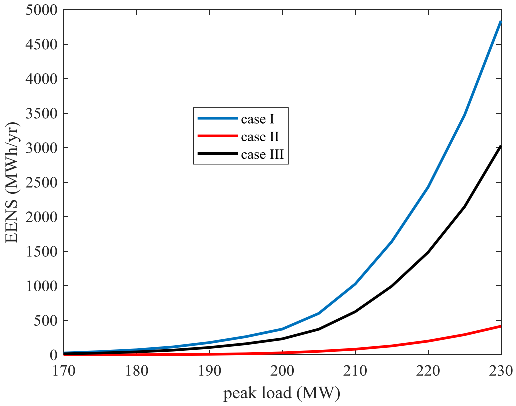

Figure 14. Average interrupted energy versus peak demand for RBTS

At this point, average interrupted energy is used as the reliability criterion to determine the system's PLCC. In Fig. 15, the PLCC for three cases is calculated considering three values of average interrupted energy, including 100, 200, and 300 MWh annually. Additionally, Fig. 16 calculates and displays the IPLCC of the system for Cases II and III, which add a conventional generation unit and a solar power plant to the initial RBTS. Figures 15 and 16 present that by achieving lower risks, limits the capability of the electric system for supplying the load result in less demand to be supplied by the system. In other words, at higher reliability criterion, the peak load-carrying capability of the system would be lower. Besides, the capability of the solar power plants equipped with parabolic trough collector for providing the load is less than the traditional units. It is arises from the uncertain nature of solar power plants. Due to the variation of sun irradiance, the produced power of parabolic trough collectors is less than the nominal capacity.

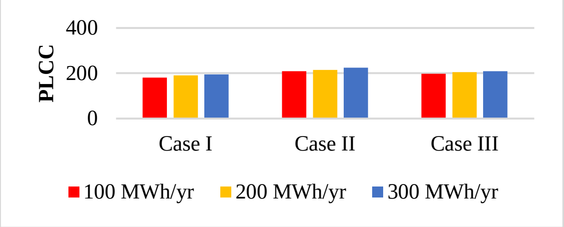

Figure 15. PLCC of the RBTS in three cases

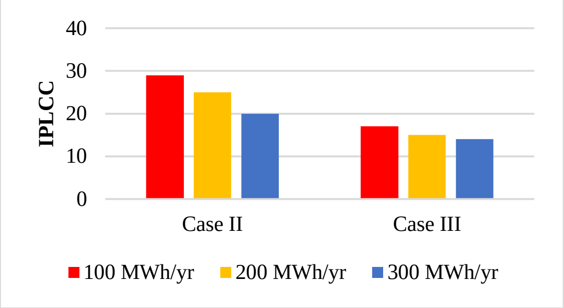

Figure 16. IPLCC of the RBTS in Cases II and III

In this stage, three cases are examined for evaluating the adequacy of IEEE-RTS: IEEE-RTS (case I), IEEE-RTS containing 30-MW traditional power plant with an unavailability of 0.02 (case II), and IEEE-RTS containing an understudied solar power plant (case III). The reliability indices, which take into account variations in demand, are obtained and shown in Figures 17 and 18. In Figure 17, average time of interruption and in Figure 18, average interrupted energy are depicted. As can be seen in the mentioned Figures, since the peak loads are increased, both reliability indices raise correspondingly. In other words, when the peak load increases, the reliability of the power network deteriorates. However, addition of new power plants to the electric network improves the reliability indices. Compared to the traditional power plants, the solar power plants equipped with parabolic trough collectors have less effect in improving the reliability indices of the power system. It is due to the variation of sun irradiance makes the produced power of solar power plants is less than nominal capacity in the most of time of plant operation. Additionally, we calculate PLCC and IPLCC for three reliability criteria and display them in Figures 19 and 20. These analyses lead to the conclusion that integration of new power plants into the electric network improves the reliability performance of power system in generation level. However, compared to the conventional power plants, the impact of solar power plants equipped with parabolic trough collectors with equal capacities on the generation system reliability improvement is less. It is because solar power plants equipped with parabolic trough collectors have an uncertain nature that results from variations of sun irradiance over time.

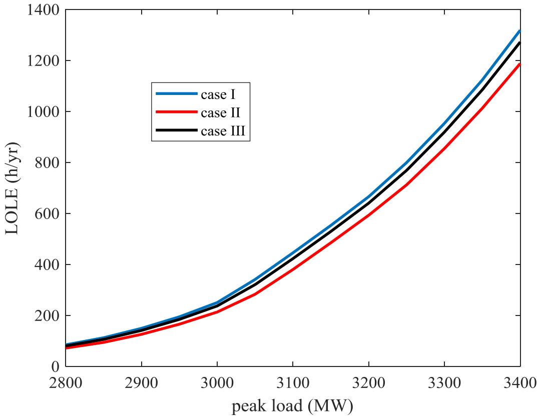

Figure 17. LOLE index versus peak load for IEEE-RTS

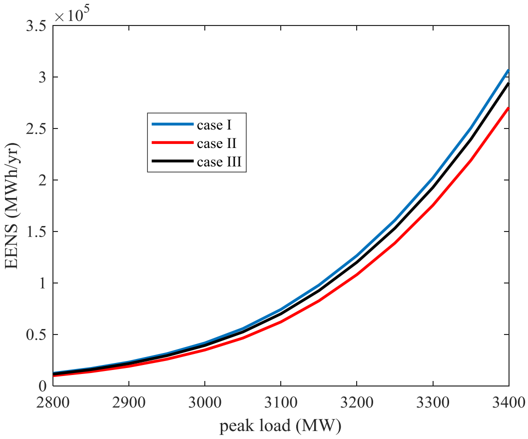

Figure 18. EENS index versus peak load for IEEE-RTS

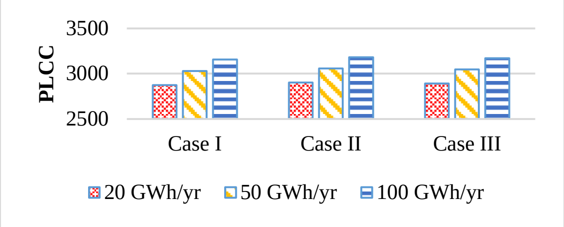

Figure 19. PLCC of the IEEE-RTS in three cases

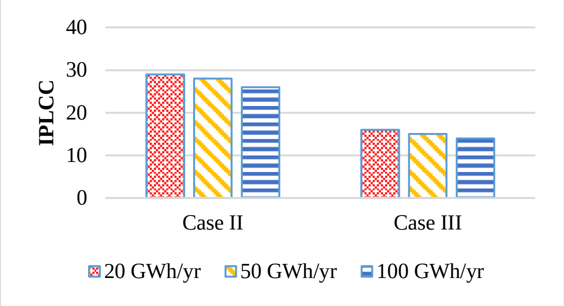

Figure 20. IPLCC of the IEEE-RTS in Cases II and III

6. Validation

In this section, to present the accuracy of the proposed work, a comparison between the outcomes obtained by proposed method and Monte Carlo simulation approach is performed. The procedures should be followed for adequacy analysis of a power system containing parabolic trough collector are:

- Generate random number in [0,1]. If the produced number is less than the availability of parabolic trough collector, the plant is up. Otherwise, if the produced number is more than the availability of the plant, the plant is considered to be down.
- At each hour, according to the hourly sun irradiance, the condition of the plant (up or down) and equations (1) & (2), the power of parabolic trough collector transmitted to the electric network is determined.
- Generate the random numbers in [0,1] for other power plants and determine the power of them at each hour.
- Determine total power of the generation system at each hour.
- Compare the power of the generation system with the load at each hour and determine the interrupted power.
- Perform the simulation for entire year including 8760 hours.
- Repeat the simulation for N years to achieve suitable accuracy.
- Calculate the average reliability index. The average interrupted energy is obtained by summing the hourly interrupted power divided by the number of simulated years.

The hourly peak load based on the IEEE pattern in per-unit is presented in Figure 21. According to the Monte Carlo simulation method performed for adequacy analysis of RBTS and IEEE-RTS containing understudied parabolic trough collector, reliability indices are computed and compared with outcomes obtained by proposed work as presented in Tables 4 and 5. In the Monte Carlo simulation method, the number of simulated years for RBTS and IEEE-RTS are 1000 and 100 years. It is deduced from these Tables that the proposed work accurately can be used for reliability evaluation of electric power networks containing solar power plants equipped with parabolic trough collectors.

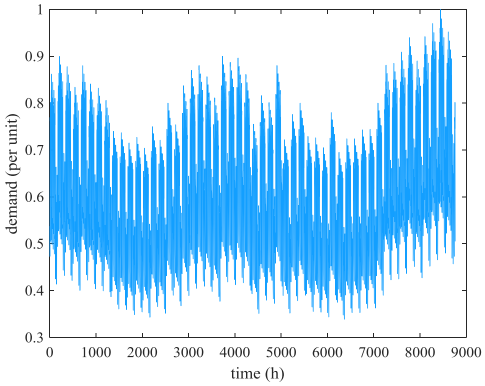

Figure 21. hourly load in per-unit [41]

Table 4. Average interrupted energy of RBTS (MWh/yr.)

Peak demand	proposed method	Monte Carlo method	%Error
170 MW	16.6570	16.1023	3.33
175 MW	28.5692	27.8514	2.51
180 MW	44.7561	43.2587	3.35
185 MW	69.8942	67.9585	2.77
190 MW	108.6657	105.2012	3.19
195 MW	162.5781	157.9854	2.82
200 MW	233.8483	227.3252	2.79
205 MW	373.0147	361.6352	3.05
210 MW	626.5070	612.2001	2.28
215 MW	995.8662	972.2587	2.37
220 MW	1487.1713	1449.5871	2.53
225 MW	2146.8611	2089.6502	2.66
230 MW	3032.4715	2987.8587	1.47

Table 5. Average interrupted energy of IEEE-RTS (MWh/yr.)

Peak demand	proposed method	Monte Carlo method	%Error
2800 MW	11509	11129	3.30
2850 MW	15914	15278	4.00

3900 MW	21764	20947	3.75
2950 MW	29461	28904	1.89
3000 MW	39368	37945	3.61
3050 MW	52477	50587	3.60
3100 MW	70065	66158	5.58
3150 MW	92589	86897	6.15
3200 MW	120157	111784	6.97
3250 MW	153204	146257	4.53
3300 MW	192743	188547	2.18
3350 MW	239553	228874	4.46
3400 MW	294402	279541	5.05

7. Conclusion

This research aims to analyze the reliability performance of electric network including solar power plants equipped with parabolic trough collectors. For this purpose, a multi-state reliability model considering both failures of composed components and variation of sun irradiance is developed for these renewable resources. In the healthy model of the solar plants, boiler, turbine, condenser, pump, generator and transformer are placed in series, and it is neglected from failure of parabolic mirrors. For reducing the number of power states in the reliability model of these solar plants, fuzzy c-means clustering technique is applied. Besides, for determining optimum number of clusters in the reliability model of them, XB index is calculated. The obtained multi-state reliability model of the solar power plants can be used for analytical reliability analysis of electric network containing these renewable units based on the construction of capacity outage probability table related to the generation units. To present the suitability of the suggested method, numerical outcomes associated with RBTS and IEEE-RTS integrated with solar power plants equipped with parabolic trough collectors are conducted. It is concluded from numerical outcomes that integration of new power plants into electric network improves the reliability performance of the system. However, compared to traditional power plants, solar power plants equipped with parabolic trough collectors have less impact on reliability improvement of the power network. It is arising from uncertain nature of solar power plants caused by variations in the sun irradiance. It makes the produced power of solar power plants less than rated capacity in the most time of operation. To investigate the accuracy of the proposed work, reliability indices calculated by suggested method are compared with the outcomes computed by Monte Carlo simulation approach. The results present that the error between the outcomes obtained by two methods is less than %3.33 and %6.97 for RBTS with 1000 simulated years and IEEE-RTS with 100 simulated years.

Unavailability of data related to the reliability performance of solar power plants equipped with parabolic trough collectors due to the new technology and consequently little history of these plants is one of the limitations of this work. Another limitation of this work is the high volume of calculations with the increase in the number of power plants in the electric network. Calculation the reliability indices of parabolic trough collectors by other methods such as numerical approaches, planning and operation studies of electric power systems containing large-scale parabolic trough collectors considering reliability criteria are some researches that can be done in the continuation of the research work conducted in the paper.

Nomenclature

A	Area of each parabolic mirror
n	Number of parabolic mirrors
η_{cos}	Cosine effect
η_{clean}	Optical correction of the mirror due to dirt
η_{mr}	Reflection of the mirror
η_{i}	Reflection action function (part of the Reflected light reflected by the receiving tube)
η_{ra}	Received absorbance (part of the radiation received by the receiving tube)
η_{rt}	Permeability received (part of the electricity taken from the receiver tube and sent to working fluid)
$\eta_{th\text{-}wf}$	Heat transfer of working fluid
η_{b}	Boiler efficiency
η_{tu}	Turbine efficiency
η_{g}	Generator efficiency
η_{PEC}	Efficiency of power electronic converter
η_{T}	Efficiency of transformer
P_G	Transmitted power to network
S	SUN irradiance
λ_m	Failure rate of each parabolic mirror
μ_m	Repair rate of each parabolic mirror
λ_S	Failure rate of series components
μ_S	Repair rate of series components
f	Fuzzy factor
PC_k	Center of ith cluster
U_{ik}	Fuzzy number between P_k and ith cluster
$Z_m(U,PC)$	Objective function of FCM method that reduces n data of generated power to m centers associated with the generated power
P_i	Probability of ith state
C	Capacity of the plant

$P_{healthy-state}$	Probability of healthy state
$P_{broken-state}$	Probability of broken state

Abbreviations

PLCC	Peak Load-Carrying Capability
IPLCC	Increase in Peak Load-Carrying Capability
LOLE	Loss of Load Expectation
EENS	Expected Energy Not Supplied
FCM	Fuzzy C-means Clustering Method
COPT	Capacity Outage Probability Table
XB	Xie-Beni
RBTS	Roy Billinton Test System
IEEE-RTS	IEEE Reliability Test System

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