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Research Article

Reliability Modelling of Central Receiver Power Plants

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Abstract: In solar power towers or central receiver generation units, solar radiation is concentrated on a central receiver placed at the top of a tower through a heliostat field. The concentrated solar energy can generate superheated steam in a Rankine cycle to produce electricity. Since solar energy fluctuates, the output power of solar tower power plants changes frequently, and many aspects of power networks incorporating high-capacity solar tower power plants may be affected, which must be investigated. For this purpose, this paper presents a reliability model for solar power generation units based on the failure of component devices and changes in produced power. To determine the reliability of these plants, the effects of failures in their elements, including the heliostat field, central receiver, thermodynamic cycle components, generator, cable, electrical converter, and transformer, on overall outage are considered. To decrease the number of states related to the reliability model of the solar power generation unit, the XB criterion is selected for calculation, and a fuzzy c-means clustering approach is used. The proposed multi-state reliability model is implemented to evaluate the adequacy assessment of RBTS and IEEE-RTS as two reliability test systems. Important reliability indices, including load and energy curtailed indices and those associated with the system's capability to supply the required load, are calculated.

Keywords: Central receiver power plant, heliostat field, reliability, rankine cycle, fuzzy c-means clustering, solar radiation.

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1. Introduction

Renewable resources, especially solar and wind, generate clean and sustainable electric energy in power networks. Due to the clean nature and sustainability of renewable energies, renewable energy-based generation units are used to produce electricity in bulk power systems and microgrids for improving different aspects of these networks. In [1-2], resiliency and reliability of power systems are enhanced by integration of renewable generation units into the power systems. Sunlight energy received on Earth during one hour is more than the required energy for humans of the world during one year [3]. Due to the high potential of solar radiation around the world, large-scale solar power plants based on different technologies including photovoltaic farms, parabolic troughs, Fresnel troughs, parabolic dish systems, and tower collectors are installed in regions with high solar radiation levels for integration into bulk power systems. Among different kinds of solar generation units, solar towers with high generated power can be connected to the power grid at the transmission level.

The 370MW Ivanpah Solar Electric Generating Station, the 200MW Bright Source Coyote Springs 1 and 2, the 200MW Bright Source PG&E 5, 6 and 7, the 245MW Gaskell Sun Tower, and the 150MW Rice Solar Energy Project are examples of large-scale central receiver power plants located in the USA [3]. Produced power of solar power towers is proportional to solar radiation. Due to wide variation in solar radiation, produced power of central receiver power plants changes a lot, and when the penetration level of renewable-based generation units in the power system is high, reliability and other aspects of the power network may be changed, which must be evaluated. To study the impact of solar towers on power systems, many researches have been carried out. In [4], the latest status of concentrating solar power towers is discussed, and the design and operating data of current central receiver power plants are examined. In this paper, new technologies are proposed to generate a better ratio of electric power to the power of heliostat field, better capacity factor, better matching of generation and consumption, lower cost of power plant, enhancement of reliability, and improved life span of component parts. For this purpose, materials and manufacturing processes, design of heliostat field and central receiver, Rankine cycle components and working fluid, optimal operation scheduling of the power plant, and integration of the power plant with thermal desalination and combined cycle power plants can be utilized. In [5], different optimal schemes of heliostat fields in central receiver generation units are performed using the campo code. In this paper, a new code is proposed to calculate quickly and accurately factors related to shadowing and blocking of heliostats to find the optimum layout for the heliostat field and yield maximum annual energy. In [6], an analytical study is performed on the PS10 solar power tower located in Aswan, Egypt. In this paper, a comparison between the Aswan 11MW central receiver power plant and Mayor solar power tower based on the solar irradiance model, sunshine duration, optical and geometric analysis, annual average efficiency, and plant performance values is carried out.

In [7], different heliostat field layout methodologies are compared, and the effect of these layouts on solar power tower efficiency is investigated. In this paper, a detailed comparison of heliostat fields according to efficiency and energy yield is performed to determine the advantages and disadvantages of the algorithms used for optimization of heliostat layout designs. It is deduced from this paper that new biomimetic techniques are better than classic algorithm patterns with radial staggered approaches. In [8], the impact of a 200MW solar power tower on the steady-state and transient performances of Oman's transmission system is studied. In this research, a central receiver generation unit composed of a heliostat field, power tower, molten salt storage tank, heat exchangers, steam generator, turbine, generator, and transformer is considered for connection to the transmission network in two proposed locations. The transient response to three-phase faults, load flow analysis, and short circuit level calculations are performed to investigate the effect of adding the solar power tower to the transmission system.

In [9], modal analysis of a heliostat for central receiver power plants is performed. In this paper, an analytical and experimental program is proposed to improve the response of heliostat fields to wind loading on them. Based on these results, the structural models of the heliostats can be evaluated and improved to predict the deformations of the heliostats arising from gravitational and dynamic wind loadings. In [10], an optical study of central receiver power plants is performed. In this study, a mathematical model is suggested for analyzing optical efficiency of solar towers and studying the effect of different factors including shading and blocking losses, cosine effect, atmospheric attenuation, and spillage losses on optical efficiency. In [11], a heliostat field of a solar tower based on a 10MW peak power unfired closed Joule-Brayton cycle installed in Seville is studied. In this paper, a variable mass flow rate is achieved for constant-temperature operation of the turbine inlet using an auxiliary compressor and bleed valve. Thus, the number of installed heliostats is important for determining the rated thermal power of the plant. In [12], the effectiveness of a small-scale central receiver generation unit used in a residential application located in Italy is simulated. This generation unit includes 48 heliostats with a total reflecting surface area of 8.7m² to generate 5kW of electricity. In this research, the design of the understudied solar tower is described, and the effect of different irradiance data on the performance of the system is evaluated.

In [13], optimal planning of a renewable energy-based microgrid considering the reliability cost is performed. In this paper, variable failure rates of component parts of renewable resources including wind turbines, current-type tidal turbines, and photovoltaic panels are used in the optimization algorithm. Paper [14] performs scheduling studies of the renewable energy-based microgrid considering the reliability effect. In this paper, different renewable resources including wind turbines, photovoltaic systems, wave energy converters, and stream-type tidal turbines are integrated into the system to reduce the reliability cost of the microgrid. In [15], reliability modeling of different types of wind turbines is carried out. In this paper, reliability assessments of various structures of wind turbines including doubly-fed induction generators, permanent magnet synchronous generators, wound rotor induction generators, brushless doubly-fed induction generators, and electrically excited synchronous generators are performed. Paper [16] studies the reliability of power systems containing ocean thermal energy conversion systems. In this research, variable failure rates of component parts of ocean thermal energy conversion systems considering variation in the outside temperature are determined.

In [17], the impact of different solar tracker systems on the reliability of photovoltaic power plants is studied. In this paper, a comparison from a reliability point of view among three photovoltaic power plants including fixed panel, PV systems equipped with single-axis trackers, and PV systems equipped with double-axis trackers is performed. Paper [18] studies the impact of variation in water flow rate on the failure rate of component parts of run-of-the-river power plants. Then, the obtained variable failure rate of run-of-the-river power plants is used for reliability assessment of the power system containing these renewable resources. In [19], reliability evaluation of power systems containing wave energy conversion systems is performed. In this paper, the reliability model of Pelamis as a large-scale wave power plant is determined considering both failure of component parts and variation in the generated power arising from variation in the height and period of the waves. In [20], reliability indices of the power system containing different types of renewable resources are calculated by Monte Carlo simulation technique. In this paper, various types of renewable resources including wind turbines, photovoltaic systems, tidal turbines, run-of-the-river power plants, and wave converters are integrated into the power system.

The current paper models the reliability performance of central receiver plants. The generated power of central receiver units is dependent on solar radiation. Solar radiation varies, and so, the generated power of solar power towers changes, too. Thus, similar to other renewable units, the uncertainty nature of central receiver plants affects many aspects of the power network. Due to the similarity between solar power towers and other renewable units such as wind turbines, photovoltaic systems, tidal stream turbines, tidal barrages, and run-of-the-river units, approaches developed to consider the uncertainty nature of renewable resources in the associated reliability models can be utilized. The reliability modeling of wind turbines, photovoltaic farms, run-of-the-river units, ocean thermal energy conversion systems, and current and barrage-type tidal generation units has been developed in [21-26]. In Table 1, all reviewed references are compared with the present article.

Table. 1: The comparison of the current research and reviewed references

References	Advantages	Drawback
[1]	Resiliency of power hub is improved by integration of renewable resources.	Reliability of power hub is not studied. Central receiver power plant is not investigated.
[2]	Reliability evaluation of pumped storage power plant is studied.	Reliability evaluation of central receiver power plant is not performed.
[3-4]	The current state of central receiver power plant is presented.	Reliability evaluation of central receiver power plant is not performed.
[5]	Different optimal schemes of heliostat field in central receiver generation units are performed using of the campo code.	Reliability assessment of heliostat power plant is not investigated.
[6]	A comparison between the Aswan 11MW central receiver power plant and Mayor solar power tower is carried out.	Reliability performance of two mentioned power plants is not compared.
[7]	Different heliostat field layout methodologies are compared.	Reliability analysis of heliostat field is not carried out.
[8]	The impact of solar power towers on the steady-state and transient performances of Oman transmission system is studied.	The impact of solar power towers on the reliability of Oman power system is not performed.
[9]	An analytical and experimental program is proposed to improve the response of the heliostat fields to the wind loading on them.	Reliability analysis of heliostat field considering the wind loading on them is not carried out.
[10]	An optical study of central receiver power plants is performed.	Reliability evaluation of central receiver power plant is not done.
[11]	A heliostat field of solar tower based on 10MW peak power unfired closed Joule-Brayton cycle installed in Seville is studied.	Reliability assessment of solar towers is not performed.
[12]	Effectiveness of small-scale central receiver generation unit used in residential application located in Italy is simulated.	Reliability studies of small-scale central receiver generation unit used in residential application located in Italy is not done.
[13-14]	Optimal planning and scheduling of renewable energy-based micro grids considering reliability effect are done.	In the understudied micro grids, the central receiver power plants are not considered.
[15-16]	Reliability evaluation of power system containing different wind turbines and ocean thermal energy conversion systems is done.	In the understudied power system, the central receiver power plants are not considered
[17]	The impact of different solar trackers on the reliability of PV systems is studied.	Reliability evaluation of thermal solar power plants is not performed.
[18-19]	Reliability assessment of power system including run of the river and wave power plants is performed.	Reliability analysis of central receiver solar power plants is not performed.
[20]	Reliability indices of the power system containing different types of renewable resources are calculated by Monte Carlo simulation technique.	In the understudied power system, central receiver power plants are not considered.
[21-26]	The reliability modelling of wind turbines, photovoltaic farms, run-of-the-river units, ocean thermal energy conversion systems, current and barrage kind tidal generation units have been developed.	Reliability modelling of central receiver power plants is not performed.

To construct a reliability model of solar power towers, the current study is organized as follows: In the second section, solar power towers are described. The reliability modeling of this power plant is constructed in the third section. The adequacy performance technique considering solar power towers in reliability assessment of power systems is discussed in the fourth section. Numerical results related to adequacy assessment of RBTS and IEEE-RTS, as well-known reliability test systems, are given in the fifth section to examine the effect of solar power towers on power network reliability. The conclusion of the paper is given in the sixth section.

2. Solar Power Towers

The share of solar generation units in electricity production is higher than other renewable energy sources. For conversion solar energy to the electricity, two technologies including solar photovoltaic and concentrated solar thermal systems are used. In photovoltaic systems, the energy of the sun is converted to the DC power through a p-n junction. In the second technology, i.e. concentrated solar thermal units; by using large number mirrors called reflectors with very high reflectivity, the direct sun radiation is concentrated onto a receiver. This radiation is absorbed through the receiver leads the receiver to heat. This heat is transferred to a suitable working fluid than can produce the steam in a heat exchanger and generate electric power using steam turbines connected to generators. Several kinds of concentrated solar thermal units are parabolic trough, Fresnel mirror system, parabolic dishes and central receiver towers. In the parabolic trough reflectors, the sunlight is concentrated onto receiver tubes contain transfer fluid such as special oil. The fluid is circulated in the tubes through a pump and then enters a heat exchanger to produce superheated steam. The steam can generate electricity through steam turbine connected to the generator. In the linear concentrating Fresnel mirror system, the sunlight is reflected onto a stationary thermal receiver located at a common focal point of the reflectors with the operation temperature of 100-400^{0}C. The concentrated energy is transferred to the thermal fluid through the absorber to produce the steam in the heat exchanger and generate the electricity. In the parabolic dish reflectors, like troughs the direct sunlight is concentrated to point focus of receiver, and heat the fluid inside this point to an operating temperature over 1000^{0}C. This high temperature fluid can produce steam and consequently the electricity is generated. In the central receiver tower system, large mirrors equipped to two-axis sun tracker called heliostats are used for concentrating sunlight onto fixed receiver placed top of a tower. The concentrated energy in absorber is transferred to heat transfer fluid. The operating temperature of fluid would be over than 1000^{0}C. This fluid can produce the steam through a heat exchanger and so the electricity is generated using of the steam turbine connected to the generator. The structure of a typical solar power tower and composed components are presented in Fig. 1.

Heliostat fields play an important role in determining the performance and cost of solar power towers. Central receiver plant performance is defined as the ratio between net power captured by the receiver to normal radiation power shining on heliostats. Heliostat field optical losses are due to cosine effect, shading and blocking losses, imperfect mirror reflection coefficient, atmospheric attenuation, and spillage losses. Heliostat field losses are mainly due to the cosine effect, which is the cosine of the angle between sunlight and the normal vector on the surface of the heliostat. The cosine effect depends on the positions of the sun and heliostat and, based on Fig. 2, it can be calculated as cos(θ). Due to the movement of Earth relative to the sun, the position of heliostats relative to the sun changes over time, and so the cosine effect changes too. The value of the cosine effect also depends on the layout of the heliostat field, and in a heliostat field, it may differ from one heliostat to another. A heliostat consists of optical sensors to sense the solar radiation on the

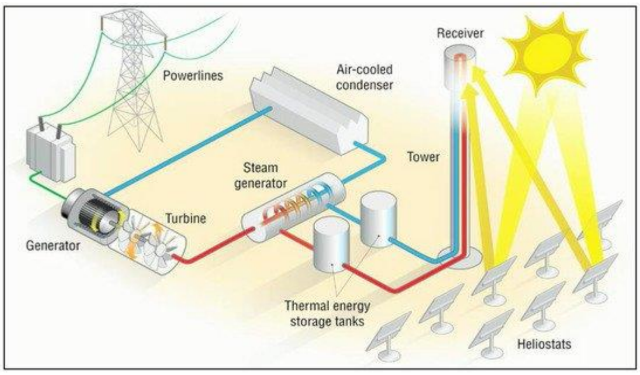

Fig. 1: Typical solar tower [27]

heliostat, servomotors to track the sun and move the heliostat to reflect the sunlight onto the receiver, a control system, mirror, and the main structure. The concentrated energy can heat the receiver and the fluid inside it to temperatures above 1000°C. Water, based on the Rankine thermodynamic cycle, enters a heat exchanger called a steam generator where the heat transfer fluid can transfer heat to it and produce steam. Then, the steam is conducted to the turbine, and electricity is generated. In Fig. 3, the Rankine thermodynamic cycle is presented [28]. In state 1 of the Rankine cycle, water is pumped to the boiler or steam generator to reach state 2. The heat from the high-temperature fluid is transferred to the water, and steam is generated in state 3. Then, the steam enters the turbine and generates electricity. The low-pressure steam of state 4 is condensed in the condenser, and the cycle is repeated.

The turbine work can be calculated as (1). In (1), h_3 and h_4 are the enthalpies of states 3 and 4, respectively. The work of pump can be determined as (2).

$$w_{turbine} = h_3 - h_4 \tag{1}$$

$$w_{pump} = V(P_2 - P_1) \tag{2}$$

Where, P_2 and P_1 are respectively the pressure of boiler and condenser. The heat transferred from the heat transfer fluid to the boiler is calculated as (3):

$$q_{in} = h_3 - h_2 \tag{3}$$

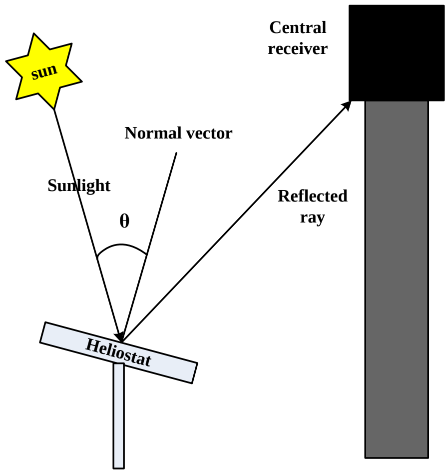

Fig. 2: The concept of cosine effect

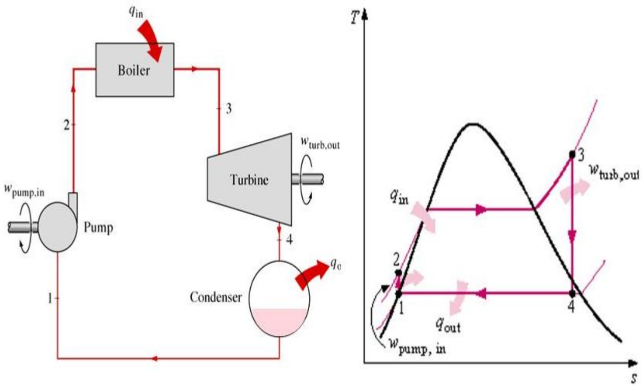

Fig. 3: The Rankine cycle

Where, h_3 and h_2 are, respectively the enthalpies of state 3 (high pressure steam) and 2 (high pressure water). The efficiency of the Rankine cycle can be determined as (4), [28]:

$$\eta = \frac{w_{turbine} - w_{pump}}{q_{in}} \quad (4)$$

To determine the generated power of solar power towers, based on the solar radiation, the area of the heliostats, the reflectivity of each heliostat, the number of heliostats and the reflection efficiency of the heliostats, the concentrated energy on the central receiver is calculated. According to heat transfer efficiency of understudied fluid and receiver concentrated thermal energy, the transferred heat to the boiler is determined. The thermal energy generated in the boiler is determined based on the boiler efficiency and the produced kinetic energy of the turbine is calculated by multiplying the generated thermal energy of boiler by the turbine efficiency. The generated electric power is obtained considering generator efficiency and produced kinetic energy. Thus, output power of central receiver unit is determined as (5):

$$P_{out} = sr \times n \times A \times R\eta_{atm} C \times CE \times SB \times \eta_{HTF}\eta_b\eta_T\eta_{ec}\eta_{tr} \quad (5)$$

where, P_{out} is plant produced power, sr is solar radiation (w/m^2), n is heliostats number, A is heliostat area (m^2), R is the reflectivity of the heliostats, η_{atm} is the atmosphere attenuation, C is the cleanliness of the mirrors, CE is the cosine effect, SB is the shading and blocking coefficient, η_{HTF} is heat transfer fluid efficiency, η_b is boiler efficiency, η_T is turbine efficiency, η_{ec} is the electrical converter efficiency and η_{tr} is the transformer efficiency.

3. Reliability Model of Solar Power Towers

In this part, to develop multi-state reliability model for solar power towers, the effect of composed components failure and change in solar radiation are considered. Proposed model can be used to perform adequacy assessment related to the power networks with high-capacity central receiver units.

3.1. The impact of composed components failure

Main components of typical central receiver unit include heliostats, central receiver, thermodynamic cycle components including boiler, turbine, condenser and pump, generator, AC/AC converter, transformer and cable. To model each component of the solar power tower from reliability point of view, a Markov model with 2 states including up and down states is used. In this model, failure rate is transition rate from up to down state, and repair rate is transition rate from down to up state. In solar tower composed of n heliostats, failure of any heliostat results reduction in generated power by $(n-1)/n$ factor. The failure of other components, i.e. central receiver, thermodynamic cycle components, generator, electrical converter, transformer and cable, leads plant operation stops. In this circumstance, produced power of plant would be zero. Thus, reliability model of solar tower is as Fig. 4.

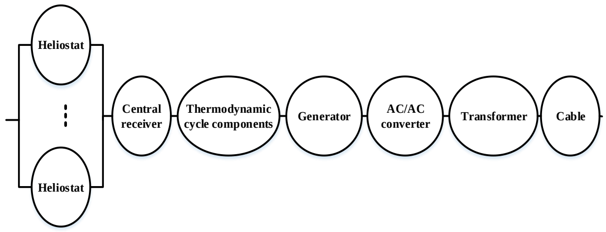

Fig. 4: Reliability model of solar tower considering components failure

If a solar power tower composed of n heliostats, each with CMW nominal generation capacity, plant reliability model would be as Fig. 5.

The equivalent failure rate (λ) and repair rate (μ) associated to systems with series elements can be determined as (6) [29]:

$$\lambda = \sum \lambda_i \quad , \quad \mu = \frac{\sum \lambda_i}{\sum (\lambda_i / \mu_i)} \quad (6)$$

In the reliability model of Fig. 5, λ_H and μ_H are heliostat failure and repair rates, λ_V and μ_V are equivalent failure and repair rate associated to a system composed of series connection of central receiver, thermodynamic cycle components, cable, generator, transformer and electrical converter.

3.2. Impact of change in solar radiation

In this part, the effect of variation in the solar radiation on plant reliability is investigated. Generated power of a solar tower is dependent on the solar radiation as (5). In Fig. 6, the hourly solar radiation in the Jask region in Iran during a year is presented. As can be seen in the figure, the solar radiation varies widely, and consequently generated power of solar plant changes. For integration solar tower in the analytical reliability analysis of power network, states number in the generated power of this plant must be reduced.

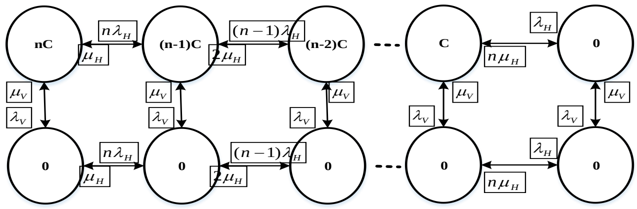

Fig. 5: The reliability model of solar power tower composed of n heliostats

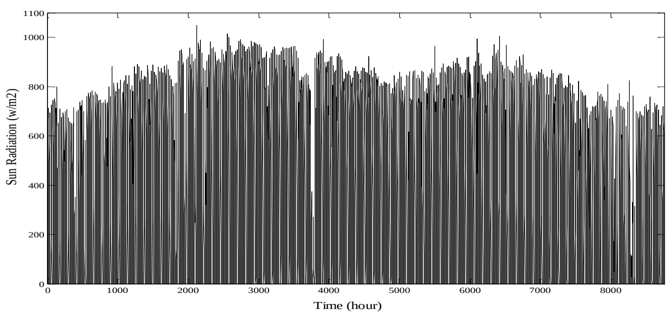

Fig. 6. The hourly solar radiation during a year

In this research, based on the *XB* index the appropriate reduced states number of produced power in solar tower is determined. Besides, to determine probability of reduces states, fuzzy c-means clustering algorithm is utilized. This clustering technique can categorize the objective data *x* including *n* various states to *c* clusters through minimizing objective function *J* as (7) [30]:

$$J = \sum_{i=1}^{c}\sum_{k=1}^{n} u_{ik}^{m} \left| s_k - z_i \right| \tag{7}$$

Where, s_k is generated power of solar power tower in time *k*, z_i is center of i^{th} cluster, *c* is number of clusters or reduced states, *n* is number of input states, *m* is a real number (>1) associated to fuzzification (in the study it is 2), u_{ik} is fuzzy degree between s_k and i^{th} cluster. In the proposed clustering technique, number of reduced states as input date is required. To determine optimum number of reduced states, this paper proposes *XB* index. To calculate this index, equation (8) is used [31]. Based on the proposed method, *XB* index value at optimal condition is minimal. Thus, optimal state number is obtained.

$$XB = \frac{J_m(U,z)}{n \times \min_{i \neq j} \left(\left| z_i - z_j \right|^2 \right)} \tag{8}$$

3.3. Total reliability model of solar tower

For determination total reliability model of solar towers, plant reliability model related to components failure must combine with reliability model related to variation in plant power. The complete plant reliability model that resulted in *h* states by clustering method implementation with *P1, P2, ..., Ph* is presented in Fig. 7. In this model, the states with same capacity can be merged.

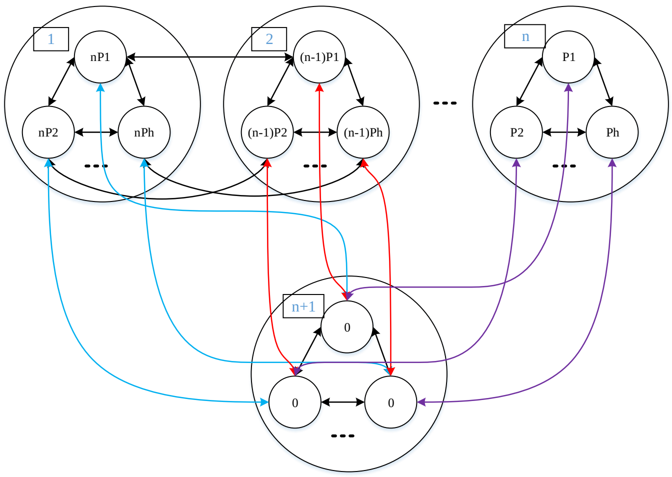

Fig. 7. The complete reliability model of solar power tower composed of n heliostats

4. Adequacy Performance of Power Systems with Solar Towers

Power network reliability defines as ability of power network for supplying required loads that is studied in two categories including security and adequacy. Adequacy requires sufficient devices for supplying required loads and security studies the ability of power network to response in occurrence of different disturbances such as power plant or transmission lines outage. Reliability studies of power network can be performed in three hierarchical levels. In the first level, only generation system is considered and transmission and distribution networks are neglected. Second level is composite power network that is composed of generation and transmission sections. In the third level, all power system elements in generation, transmission and distribution sections are taken into account. For evaluation adequacy of power networks incorporating high-capacity solar towers, all generation units, i.e. conventional and central receiver power plants and also system load are connected to common bus as can be seen in the Fig. 8. Capacity outage probability table (COPT) is a table containing state capacity and probability is developed for each generation units. The total COPT can be determined by combining the COPT of all generation units. With convolving generation system model, i.e. total COPT and load model, reliability indices such as loss of load expectation (LOLE), expected energy not supplied (EENS), peak load carrying capability (PLCC) and increase in peak load carrying capability (IPLCC) are calculated.

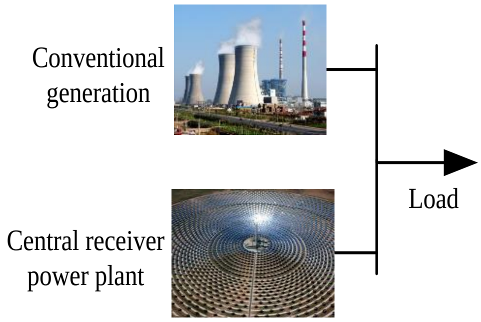

Fig. 8: Adequacy assessment technique

5. Numerical Results

In this part, reliability model of central receiver plant is obtained. Solar radiation data associated to Jask region in Iran is utilized for simulation. Proposed multi-state reliability model is used for adequacy assessment performance of well-known reliability test networks, i.e. RBTS and IEEE-RTS that are integrated into central receiver power plant.

5.1. Reliability modelling of the understudied solar power tower

In this part, a 30MW solar power tower composed of 3750 heliostats, each with 36-m2 area is installed in Jask. Characteristic of understudied plant is assumed so that the performance parameters of the plant would be as presented in Table 2. The heliostats are equipped to the two-axis sun tracker that leads the reflected sunlight is concentrated on the central receiver.

Table. 2: The parameters of the understudied solar power tower

Reflectivity	0.94
Atmosphere attenuation coefficient	0.95
Cleanliness of the mirrors	0.85
Cosine effect	0.93
Shading and blocking coefficient	1
Heat transfer fluid efficiency	0.85
Boiler efficiency	0.89
Turbine efficiency	0.45
Generator efficiency	0.97
Electrical converter efficiency	0.98
Transformer efficiency	0.98

Based on the (5), hourly solar radiation and the parameters presented in table 2, the hourly generated power of the understudied solar power tower during a year is calculated and presented in Fig. 9. According to proposed approach, value of *XB* index considering number of clusters is calculated and illustrated in Fig. 10. It is seen from the figure that when cluster number is six, *XB* index is minimal, and so, six clusters as shown in table 3 can be used to model variation in output power of understudied solar power tower in term of reliability.

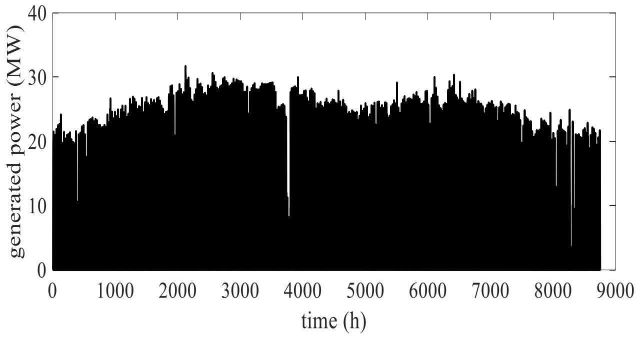

Fig. 9: Hourly produced power of understudied solar tower

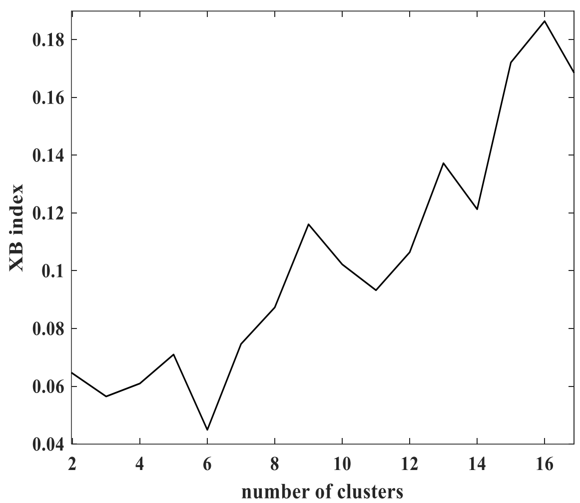

Fig. 10: Value of XB index versus cluster number

To obtain the complete reliability model of central receiver power plant, the Markov model of the plant developed in section 3-1 should be combined with the model determined Table 3. In this power plant, the number of heliostats is high and if one or several heliostats are failed the reduction in the generated power is not significant. Thus, with good accuracy, it can be neglected from heliostats failure in solar tower reliability model. Based on this assumption, a two-state Markov model considered the failure of main components can be developed to model the understudied central receiver power plant. Then, the obtained model should be combined with the model determined in Table 3. Solar tower failure and repair rates are 1.39 and 90.5 occurrence in year, respectively, and so, plant availability is 0.98. With combining two-state reliability model obtained due to failure of components and 6-state reliability model obtained due to variation in solar radiation, the total reliability model of understudied plant is determined and illustrated in Table 5. The resulted model is used to evaluate adequacy performance of RBTS and IEEE-RTS integrated to the solar power tower.

The reliability parameters of the composed components of the understudied solar power tower including failure rate and repair time are presented in table 4.

5.2. RBTS

Adequacy studies of RBTS is performed for evaluation effect of integration of solar towers on reliability indices of power networks. The RBTS has 11 power plants with 240MW installed capacity. Characteristic of RBTS power plants is given in [32]. In this study, load duration curve is a straight line that extends from yearly peak load to 60% of yearly peak load. To evaluate effect of solar tower on system reliability indices, three cases are studied that includes: original RBTS as case I, RBTS with 30MW conventional unit with availability of 0.98 as case II and RBTS integrated to understudied solar tower as case III. The value of LOLE and EENS of these cases considering different loads are determined and illustrated in Figs. 11 and 12, respectively. These figures present that reliability of power network gets worse when system peak load increases. Thus, in power network planning, new generation units must be added to the system when the load is grown. Besides, the figures present that addition of new power plants results in reliability indices improvements. However, conventional generation units have improved the reliability indices more than the solar power tower.

Table. 3: Clustering results

Capacity (in MW)	Probability
0	0.5096
5.8	0.0533
11.3	0.0634
17.8	0.0880
22.4	0.1550
26.4	0.1307

Table. 4: Reliability parameters of solar tower

Elements	Failure rate (number per year)	Repair time (hour)
Heliostat	0.1	50
Central receiver	0.1	100
Thermodynamic cycle components	1	100
Generator	0.1	100
transformer	0.05	50
Electrical converter	0.04	50
Cable	0.1	100

Table. 5: The complete reliability model of understudied solar power tower

Capacity (in MW)	Probability
0	0.5195
5.8	0.0522
11.3	0.0621
17.8	0.0862
22.4	0.1519
26.4	0.1281

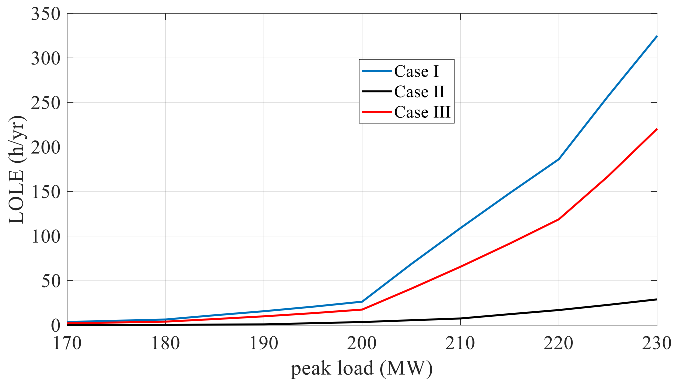

Fig. 11: The LOLE index in different peak loads

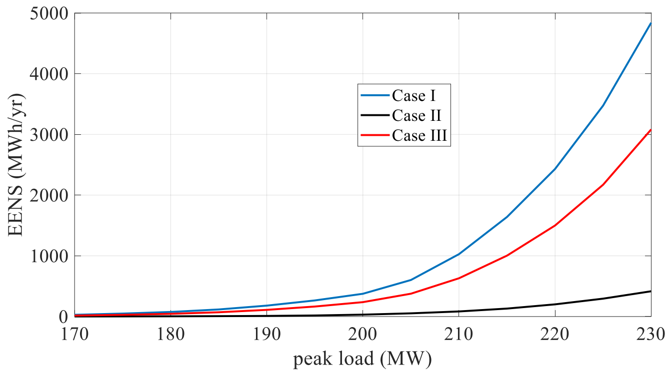

Fig. 12: The EENS index in different peak loads

In this stage, the peak load carrying capability (PLCC) index associated with these cases is determined. To calculate PLCC, an increase in system peak load is performed. PLCC is the maximum peak load that satisfies the reliability criterion. If the peak load increases more than the PLCC, the risk criterion is not satisfied. The PLCC index of these cases for different reliability criteria is determined and illustrated in Table 6. In this research, three reliability criteria based on the Expected Energy Not Supplied (EENS) index are considered. The table shows that the capability of the power network to supply the required load improves with the addition of a new power plant. However, conventional units improve the capability of the power network in supplying the required load more than solar power towers. The increase in peak load carrying capability of RBTS with the new power plant is calculated and presented in Table 7. The table shows that the system peak load can be increased when either conventional units or solar power towers are integrated into the network. However, conventional units improve the peak load carrying capability of the system more than solar power towers.

Table. 6: The PLCC

Cases	100 MWh/yr	200 MWh/yr	300 MWh/yr
Case I	183	191	196
Case II	211	219	225
Case III	188	197	202

Table. 7: The PLCC

Cases	100 MWh/yr	200 MWh/yr	300 MWh/yr
Case II	28	28	29
Case III	5	6	6

5.3. IEEE-RTS

Characteristics of power plants installed in IEEE-RTS as high-capacity reliability test network are illustrated in [33]. For study solar tower effect on reliability indices of IEEE-RTS, three cases are simulated as below: original IEEE-RTS as case I, IEEE-RTS whit 30MW conventional power plant with unavailability 0.02 as case II and IEEE-RTS integrated to the understudied central receiver power plant as case III. The LOLE and EENS indices for three cases are determined and illustrated in Figs. 13 and 14, respectively. Besides, PLCC and IPLCC associated to understudied cases for three reliability criteria including EENS of 20, 50 and 100 GWh/yr are calculated and presented in Table 8 and 9, respectively.

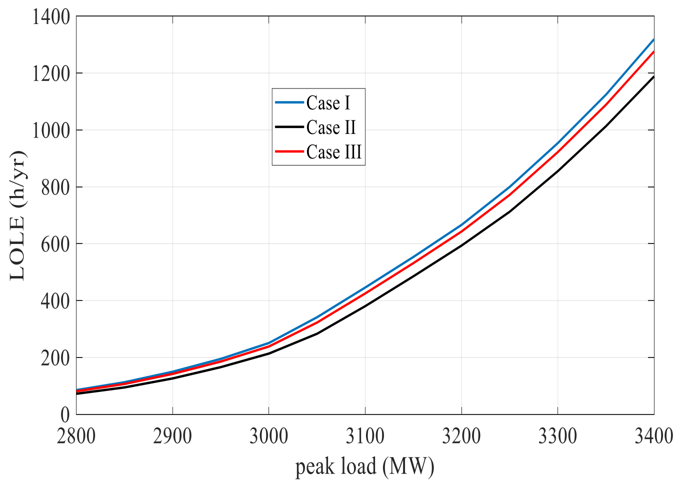

Fig. 13: The LOLE index in different peak loads

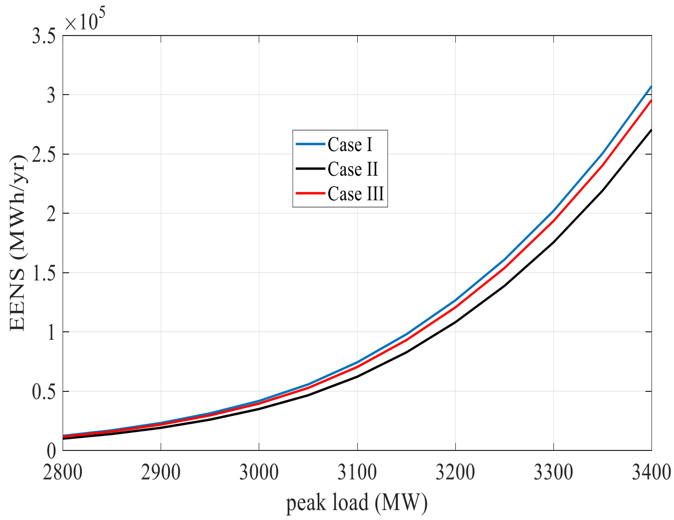

Fig. 14: The EENS index in different peak loads

Table. 8: PLCC

Cases	20 GWh in year	50 GWh in year	100 GWh in year
Case I	2875	3031	3153
Case II	2904	3060	3181
Case III	2885	3040	3163

Table. 9: IPLCC

Cases	20 GWh in year	50 GWh in year	100 GWh in year
Case II	29	29	28
Case III	10	9	10

Numerical results present central receiver power units improve reliability indices of IEEE-RTS. However, effect of central receiver power plant on the reliability enhancement is less than conventional power plants with same size.

6. Conclusion

In this research, among different kinds of solar generation units, central receiver power plants that can be constructed with high generation capacity and connected to the bulk power system are considered to evaluate their effect on the adequacy of power systems. In this regard, a multi-state reliability model is introduced for this power plant that takes into account both changes in plant power arising from changes in solar radiation and component failures. The main components affecting the performance of a solar tower are heliostats, central receiver, thermodynamic cycle, generator, power electronic converter, cable, and transformer. To model each component of the solar power tower from a reliability point of view, a Markov model with two states, including up and down states, is used. In a solar tower composed of n heliostats, failure of any heliostat results in a reduction of generated power by a factor of $(n-1)/n$. The failure of other components, i.e., central receiver, thermodynamic cycle components, generator, electrical converter, transformer, and cable, leads to plant operation stoppage. In this circumstance, the produced power of the plant would be zero. In the Markov model, it is assumed that only one failure may occur at a time. Because there are a large number of heliostats in the power plants, the reduction of plant produced power due to the failure of one or several heliostats is insignificant and is therefore neglected in the reliability model. A two-state model can present an equivalent reliability model of the plant that considers the failure of component parts. The variation in solar radiation leads to many power states existing in the reliability model of the plant, making analytical reliability assessment of the power network difficult. Thus, this research proposes a fuzzy c-means clustering method for reducing the number of power states. Additionally, the XB index is selected to determine the optimal number of power states in the model. The optimum number of states is determined when the XB index is minimal. The complete plant reliability model is obtained by combining the reliability model related to the failure of component elements and the reliability model related to the uncertainty nature of produced power arising from variation in solar radiation. The proposed multi-state reliability model related to a 30MW solar tower is obtained to evaluate the impact of central receiver generation units on the adequacy performance of RBTS and IEEE-RTS. Numerical results show that integration of central receiver plants into the power network leads to improved reliability indices. However, the produced power of central receiver plants is dependent on solar radiation. Since wide variation occurs in solar radiation, the output power of solar towers changes significantly, and the produced power of central receiver generation units is less than nominal capacity most of the time. Thus, central receiver power plants improve power network reliability indices less than conventional power plants with the same capacity.

Credit Authorship Contribution Statement

Amir Ghaedi: Conceptualization, Investigation, Methodology, Software, Supervision, Validation. **Mehrdad Mahmoudian**: Data curation, Formal analysis, Resources, Writing - review & editing.

Declaration Of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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