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Well-being Approach of the Power Systems Integrated to the Central Receiver Power Plants

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ABSTRACT: The solar power tower (central receiver power plant) as one type of concentrated solar thermal power systems can be used to generate electricity in a way similar to the thermal power plants and so, numerous large-scale central receiver power plants have been constructed and connected to the bulk power system to transfer their generated power to the power network. The variation in solar radiation leads the generated power of these power plants to change, too. Thus, the integration of these large-scale solar power towers into the power system results in some challenges that must be addressed. To study the effect of solar power towers on the power system, new techniques must be developed to consider the uncertain nature of these plants. For this purpose, in this paper, to investigate the impact of central receiver power plants on the operation studies of the power system, the well-being approach is proposed. To consider the solar power towers in the operation studies of the power system, a multi-state model is developed for these plants that both variations in the generated power and failure of composed components are taken into account. To evaluate the effectiveness of the proposed technique, the well-being models of two reliability test systems including RBTS and IEEE-RTS are determined and the effect of the central receiver power plant on the operation indices such as health state probability, risk, spinning reserve, peak load carrying capability and increase in peak load carrying capability is investigated.

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1- Introduction

Solar energy as a renewable and sustainable energy is the most abundant energy resource in the world. There are two technologies used to convert solar energy to electricity including solar photovoltaic systems and concentrated solar thermal power systems. In photovoltaic systems composed of solar cells, the solar energy is converted to the direct current by using a p-n junction. In concentrated solar thermal power plants, the sunlight is reflected and concentrated to heat a fluid. In the boiler, the high-temperature fluid can heat the water to generate steam. The steam is transferred from the turbine and produces the electricity. Among different technologies of the concentrated solar thermal power plants including parabolic trough reflectors, Fresnel reflectors, parabolic dish systems, and solar power towers, the temperature of the central receiver in the solar power tower can be more than 1000^0C and so, it can drive a Rankine cycle similar to the thermal power plants. The number of mirrors called heliostats in the solar power towers is numerous and so, these power plants can be constructed with large capacities and connected to the transmission network to transfer their generated power to the power system. The output power of the central receiver power plant depends on solar radiation. Due to the variation in the solar radiation during the time, the output power of solar power towers changes too and so, in the power systems with high penetration levels of solar power towers, many aspects of the power system such as reliability, dynamic, transient and operation may be affected that must be addressed. The uncertain nature of the solar power towers leads to the generated power of solar power towers change widely and is not accurately predictable. In the operation studies of the power system, the balance between generation and consumption must be established to prevent frequency deviation or load curtailment. To perform the operation studies of the power system, stochastic methods are used to consider the uncertain nature of load and outage of power system elements. In the understudies power system that is integrated into the large-scale solar power towers, the uncertain nature associated with the generated power of the solar power towers is added to the problem and so, the appropriate method must be developed to consider the effect of these plants in the studies. In the operation studies of the power system, different disturbances such as an outage of generation units, transmission lines, and deviation of the load from the predicted values may be occurred. To respond to these disturbances, a spinning reserve must be established in

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the power system. The spinning reserve is the excess power of synchronous generation units the current generation power of them is less than the associated rated capacity. In the operation studies of the power system, the determination of the appropriate value for the spinning reserve is an important work and so, in the literature review, many researches have been performed to study the power system operation. In [1], the impact of operating reserves on the generation capacity investment planning in the renewable-based power system is investigated. It is deduced from this paper that operating reserves have a substantial impact on the operation of generation systems and lead to a substantial increase in renewable integration costs. To reduce this cost, improved reserve strategies including dynamic reserve sizing and participation of renewable resources in the supply of downward reserves are proposed. In [2], an economic dispatch based on the scenario method with tunable risk level is performed in the power systems with high penetration levels of renewable resources. In this paper, the uncertainties associated with the distributed energy resources in the supply and the demand sides are considered and an empirical approach is proposed to dispatch the resources in the real-time power system operation. In [3], a new flexible modeling framework is proposed to determine the appropriate value of the reserve in the power systems. In this paper, the flexibility provision and flexibility requirements are characterized via dynamic envelopes that can reflect variability, uncertainty, and the higher-order dynamics of the power system resources. In [4], the flexible frequency operation strategy is proposed for the power systems integrated with significant renewable resources to achieve the flexibility of the power systems. The proposed method provides customized frequency through back-to-back high-voltage DC transmission and the overall system can be operated with relaxed frequency regulation. In this paper, the swing equation is modified to model the frequency dynamic of the power systems with significant penetration levels of renewable resources. In [5], a stochastic unit commitment program with topology control resources is proposed for a power system containing large-scale renewable resources. In this paper, the topology control through transmission switching is modeled as a resource action in the day-ahead operation of power systems with a high penetration level of renewable generation resources. In the absence of congestion, the linear objective value of direct current optimal flow and the unit commitment cost are reduced by using transmission switching. In [6], a technique is proposed to perform the day-ahead optimal operation for multi-energy residential systems containing renewable resources. For this purpose, a framework and mathematical models of multi-energy residential systems are proposed, and based on the characteristics of the residential energy distribution networks, the complex multi-energy residential system models are reformulated to relieve the computational burden. In [7], the heuristic algorithm based on the imperialist competitive algorithm is proposed to perform the optimal operation of distributed generations in the micro-grids considering the uncertainties associated with the load, and renewable generation is performed. In this paper, a typical micro-grid composed of the wind turbine, photovoltaic system, fuel cell, combined heat and power, and electric loads is considered and the probabilistic analysis of optimal power scheduling based on the economic aspects in the micro-grid environment is taken into account the technical constraints is carried out. In [8], the real-time dispatch ability of bulk power systems containing volatile renewable generation resources is investigated. In this paper, to address the significant challenges of the real-time power system operation arising from the limited predictability and high variability of renewable resources, a closed polyhedral form of real-time dispatch ability is proposed that its boundaries are computed by using an adaptive constraint generation algorithm. In [9], an offshore wind farm with several GW generation capacities on the Atlantic coast is integrated into the PJM interconnected power system in the United States. In this paper, the detailed reliability and economic analysis of integrating such offshore wind farms into the PJM system is investigated. In [10], an operation practice-driven and control performance-based reserve allocation approach is proposed to determine adequate frequency regulation reserve in an island power system containing significant renewable generation resources. In this paper, analyses of online available frequency regulation reserves and control performance data recorded in the energy management system based on the conditional probability approach are performed to determine the risk of non-compliance associated with the frequency control standard.

In [11], a mixed integer non-linear programming method is used to schedule generation units integrated into a renewable-energy-based microgrid. In this research, the understudied microgrid contains thermal power plants, wind turbines, solar energy systems, and plug-in electric vehicles. Paper [12] analyses the reliability performance of multi-microgrids, as future smart distribution networks, considering uncertainties associated with small-scale energy resources. In this research, probability density functions of renewable resources and load are developed, and to optimize the operating problem, the particle swarm optimization method is implemented. In [13], a distributed control method is proposed to study the autonomous operation of a microgrid containing both AC and DC resources. The understudied microgrid contains renewable resources such as photovoltaic panels, and so the proposed energy management system is designed based on proportional resonance and proportional integral controllers in two separate control parts. Paper [14] studies the security-constrained operation of the power system containing wind power plants considering the demand response program. In this research, stochastic wind power generation and demand response are combined in the security-constrained unit commitment problem of the power system, and to reduce the volume of the computation and complexity of the problem, the bender decomposition method is utilized.

In [15], a novel mathematical technique is proposed to optimize the optical efficiency of solar tower power plants. In this research, different losses of solar tower power plants including blocking, shading, spilling, and atmospheric mitigation are considered to analyze the optical efficiency of the plant. Paper [16] studies the impact of external receivers on energy storage and the performance of solar tower power plants. In this paper, molten salts are used as heat transfer fluid in the energy storage of solar tower power plants. To determine the performance of the plant, different losses occurring in the heliostat field, solar flux flow patterns, external tubular receiver designs, and heat transfer fluid are studied. In [17], a practical method is proposed to design composed components of solar tower power plants and estimate their investment costs and economic indices. This paper proposes three main stages including data collection, sizing and cost estimation, for design and cost estimation of solar tower power plants. It is concluded from numerical results performed in the paper that there is the strong influence of the size of the solar tower power plant on the investment cost, as well as on the economic indices including payback period, internal rate of return, total life charge costs and cost of produced electric power by the plant. In [18], the optimal design of the heliostat field of solar tower power plants is proposed by considering different shapes of heliostat fields. In this research, different shapes of heliostats including rectangular, square, pentagon, hexagon, heptagon, octagon, and circular shapes are simulated by MATLAB software, and among them, the optimal shape is selected. The paper concludes that circular and octagon heliostat shapes provide better efficiency with minimum land area. Paper [19] presents the design and analysis of a solar tower power plant that can be integrated with a thermal energy storage system for cogeneration purposes. In this paper, molten salts used for high-temperature thermal energy storage systems combine with solar tower power plants to produce both electricity and freshwater by distillation and reserve osmosis technologies. In [20], the optimal height and tilt angle of the solar receiver associated to a 30 kW solar tower power plant are determined through the Monte Carlo ray tracing approach. In this research, MATLAB software is used to simulate the solar tower power plant installed in the Sahelian zone.

Due to the uncertain nature associated with the variation in the generated power of the solar power towers arising from the variation in the solar radiation, in this paper, to perform the operation studies of the power system containing large-scale central receiver power plants, a well-being approach is proposed. For this purpose, a multi-state reliability model must be developed for the solar power towers. Thus, the contributions of the paper would be as below:

- A multi-state reliability model considering both failure of composed components and variation of output power arising from variation of solar radiation is developed for solar tower power plants.
- The PJM method is modified to consider the solar tower power plants with variable output power in the operation studied of the power system.
- The matrix multiplication technique is proposed to determine the probability of different states of solar tower power plants at desired operation study times.
- A well-being model of a power system containing solar tower power plants is developed.
- The required spinning reserve of the power system containing solar tower power plants is determined by the well-being model of the power system.

To achieve this aim, this paper is organized as below: in the second section, the solar power towers are introduced and in the third section reliability modeling of these generation units suitable for operation studies is developed. The well-being approach of the power system and the proposed technique to integrate the large-scale solar power towers in the operation studies of the power system are described in the fourth section. The numerical results associated with the RBTS and IEEE-RTS to investigate the effectiveness of the proposed technique are given in the fifth section. The paper's conclusion is summarized in the sixth section.

2- Solar Power Towers

Sun as the most abundant renewable resource, can generate electricity based on two technologies including solar photovoltaic systems and concentrated solar thermal power plants. The photovoltaic farms are composed of numerous solar cells that can convert the sunlight energy to the direct current. In the concentrated solar thermal power plants the sunlight is reflected and concentrated that can heat a fluid such as aromatic oil. The high-temperature fluid can transfer the heat to the water and generate steam. The steam is transferred through the turbine connected to the generator and generates electricity. The concentrated solar thermal power plants are categorized into four technologies including parabolic trough reflectors, Fresnel reflectors, parabolic dishes, and solar power towers. In the parabolic trough reflectors, using parabolic mirrors the sunlight is reflected and concentrated onto the tubes including the heat transfer fluid. The heat transfer fluid can generate the steam in the heat exchanger containing the water and produce the electricity. In the Fresnel reflectors, the linear mirrors reflect and concentrate the sunlight onto a fixed thermal receiver located and extended above the mirrors. The concentrated energy can heat the fluid used for the generation of steam and electricity. In the parabolic dishes, the sunlight can be reflected and concentrated onto the focal point through the large parabolic dish-shaped mirrors. The heat transfer fluid is placed at the focal point of mirrors and the concentrated energy can heat it. The fluid is entered onto a heat exchanger containing the water and the steam is generated to produce the electricity. The central receiver power plants consist of numerous number of mirrors called heliostats. The arrangement of heliostats in the heliostat field is so that, the sunlight is reflected and concentrated onto a central receiver containing heat transfer fluid. Due to the high reflectivity of the heliostats, the concentrated energy of the central receiver can heat the fluid to a temperature of more than 1000°C. The heat transfer fluid can transfer its energy to the water through a heat exchanger and leads the water to convert to steam. The produced steam is transferred through the turbine connected to the generator and the electricity is generated. In Fig. 1, the structure and the components of a central receiver power plant are presented.

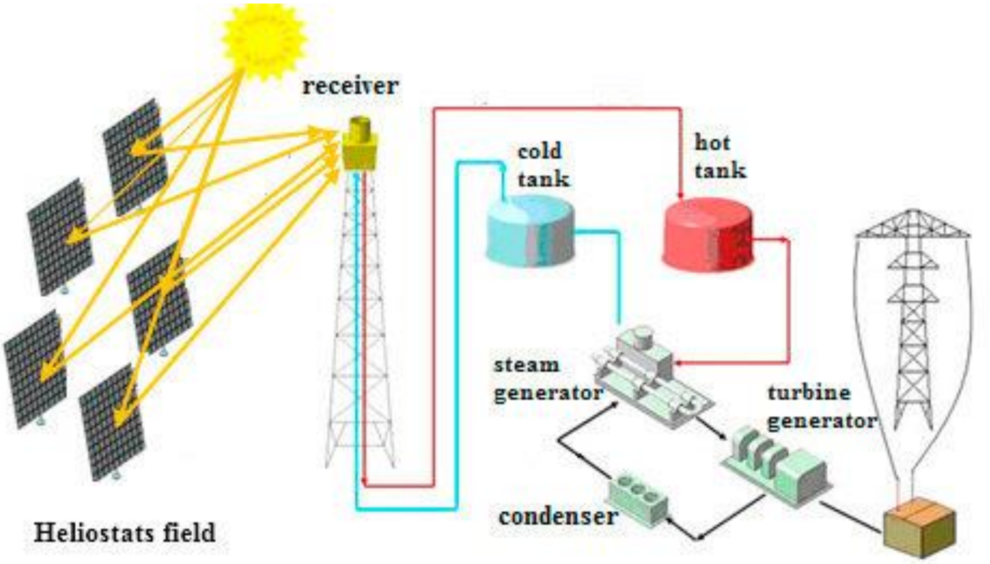

Fig. 1. The composed components of a central receiver power plant [21]

The generation capacity of the solar power towers is adequately high to connect to the bulk system to transfer the output power to the grid and so, in this paper, the operation studies of the power systems integrated to the large-scale solar power towers are performed. The Barstow solar power tower with 10MW capacity in California, the Planta soar 10 and 20 with respectively 10 and 20MW capacities in Spain and the Ivanpah solar electric generation system with 392MW capacity in the United States are some of the large-scale solar power plants based on the solar power tower technology that are installed in the world [22]. The generated power of a solar power tower is dependent on the solar radiation, the number of heliostats, the area of the heliostats, the angle between the solar ray and the heliostat normal vector, the heliostat reflectivity, the atmosphere attenuation losses, mirror cleanliness, shading and blocking losses, the heat transfer fluid efficiency, boiler efficiency, turbine efficiency, and the electrical losses. In (1), the generated power of a central receiver power plant based on the characteristics of the plant and the solar radiation in a specified hour is given.

$$P = S.N.A.R.C.\cos\theta.\eta_{atm}\eta_{htf}\eta_{sb}\eta_b\eta_t\eta_e \qquad (1)$$

Where, P is the generated power of central receiver power plant, S is the solar radiation (w/m^2) associated to the understudied hour, N is the number of heliostats, A is the area of each heliostat, R is the heliostat reflectivity, C is the mirror cleanliness, $cos\theta$ is the cosine effect, η_{atm} is the atmosphere efficiency (the ratio between the concentrated energy on the central receiver to the reflected energy from the heliostats), η_{htf} is the efficiency of the heat transfer fluid (the ratio between the energy of fluid transferred to the boiler to the energy that the fluid receives from the central receiver), η_{sb} is the efficiency of the heliostats considered the shading and blocking effects, η_b is the boiler efficiency (the ratio between the energy transferred to the water to generate the steam to the boiler energy that is received from the heat transfer fluid), η_t is the turbine efficiency and η_e is the electrical efficiency considering the losses associated to the electrical converters and the transformer.

3- The Reliability Model of Central Receiver Power Plant

In this paper, operation studies of the power systems containing large-scale solar power towers based on the well-being approach are performed. For this purpose, a multi-state reliability model is developed for these renewable power plants that are considered both the failure of main components and the variation in the generated power of them.

3- 1- Reliability model of solar power towers considering the failure of composed components

In Fig. 1, the composed components of a typical central receiver power plant including the heliostats (each heliostat is composed of the mirror, the retaining structure, the two-axis solar tracker system including the solar sensors, control system and the servo motors), central receiver located at the top of a tower, heat transfer fluid (HTF) cycle (that is composed of the tubes containing the heat transfer fluid, the pump for circulating the fluid, hot tank and cold tank), the components associated to the thermodynamic Rankin cycle (including the boiler or heat exchanger for transferring the heat of the fluid to the water and generate the steam, the turbine for turning the generator shaft, the condenser for converting the steam to the water and the pump for circulating the water in the cycle),

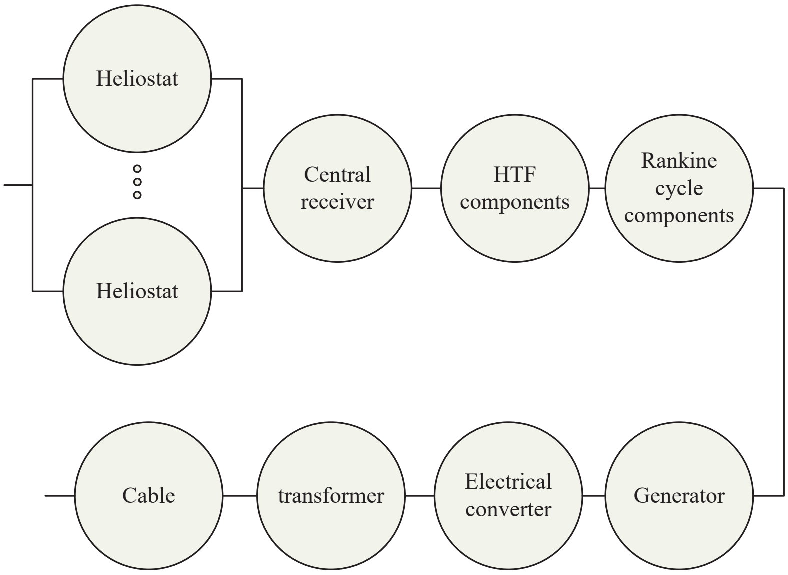

Fig. 2. The reliability model of central receiver power plant considering the failure of components

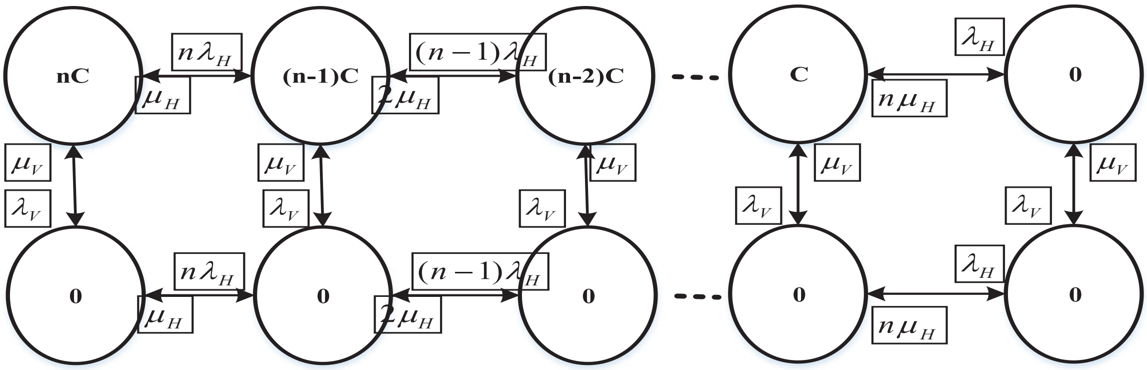

Fig. 3. The reliability model of central receiver power plant with n heliostats

generator for producing the electricity, the AC/AC converter for matching the voltage and frequency of the produced electricity, the step-up transformer for voltage enhancing and the cable for transmitting the produced electricity to the grid. In this section, the effect of the failure of each component on the failure of the system is investigated. The failure of each heliostat leads the generated power of the plant-associated to the failed heliostat to be zero and so, in a central receiver power plant composed of *N* heliostats, the failure of heliostat results in the reduction of the generated power by *(N-1)/N* factor. The failure of other components including the central receiver, the components of the heat transfer fluid cycle, the components of the Rankine cycle, the generator, the electrical converter, the transformer, and the cable leads the plant to stop the power generation and so, these components are placed in series in the reliability model of the plant. Thus, the reliability model of a solar power tower considering the failure of composed components would be as Fig. 2. The reliability model of a central receiver power plant consists of *n* heliostat that the rated capacity of each heliostat in the nominal solar generation is *CMW*, is presented in Fig. 3. In this figure, the transition of states in the first row is occurred due to the failure or repair of heliostats, and the transition from the first row states to the associated states in the second row is occurred due to the failure of any other components. Thus, the equivalent failure rate (λ) and repair rate (μ) between the first and second row states are calculated based on the series components' equivalent failure and repair rates as presented in (2) [23].

$$\lambda = \sum \lambda_i ,\ \mu = \frac{\sum \lambda_i}{\sum (\lambda_i / \mu_i)} \tag{2}$$

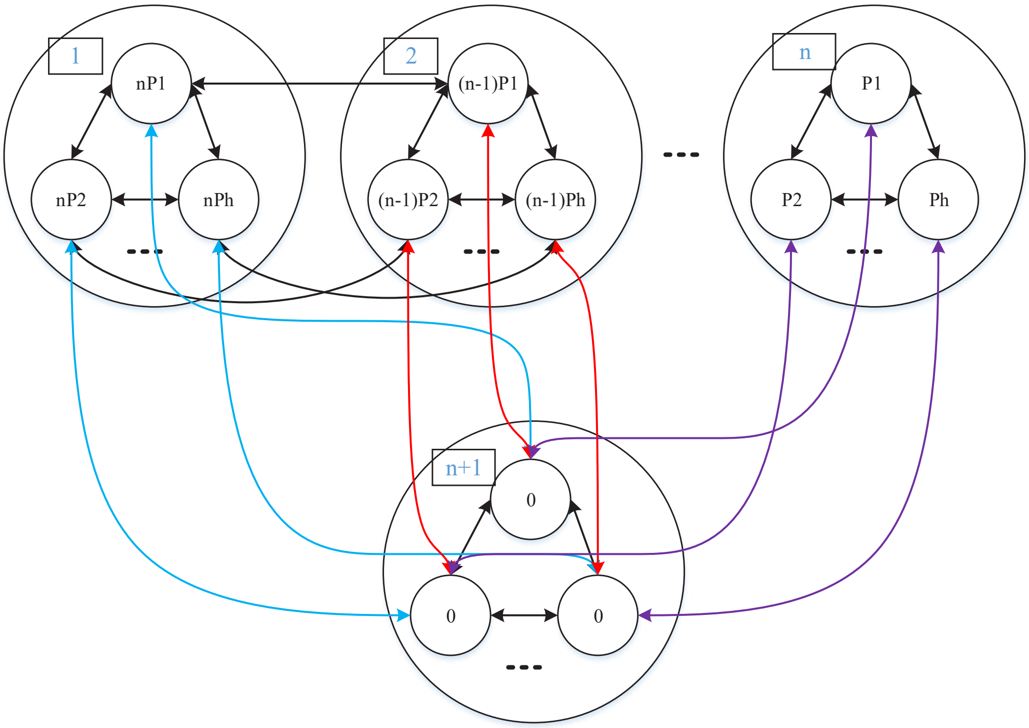

Fig. 4. The complete reliability model of the central receiver power plant

Where λ_i and μ_i are respectively, the failure rate and repair rate of series components. Thus, in the reliability model of Fig. 3, λ_H and μ_H are the failure and repair rates of the heliostat, λ_V and μ_V are the equivalent failure and repair rates associated with the series connection of central receiver, the components of heat transfer fluid cycle, the components of the Rankine cycle, generator, electrical converter, transformer, and cable.

3- 2- The effect of variation of solar radiation on the reliability model of solar power tower

The generated power of solar power towers is dependent on solar radiation. Solar generation changes widely in time and so, the generated power of solar power towers changes a lot, too which affects the reliability model of these plants. Thus, there are numerous states in the reliability model of central receiver power plant, that is not suitable for reliability-based operation studies of the power system containing large-scale central receiver power plants based on the analytical approach. For this purpose, in this paper using the fuzzy c-means clustering method as a robust method with good performance [24], the number of states in the reliability model is reduced. Based on this method, to reduce the number of initial power data with n various states to the c clusters the objective function presented in (3) must be minimized. In (3), x_k is the produced power of the central receiver power plant in hour k, v_i is the generated capacity of i^{th} cluster, c is the number of clusters or reduced states, n is the number of power data, m is fuzzification parameter that is a real number greater than 1 (in this paper it is assumed to be 2), u_{ik} is the fuzzy degree to which x_k belongs to the i^{th} cluster.

$$J=\sum_{i=1}^{c}\sum_{k=1}^{n}u_{ik}^{m}\left|x_k-v_i\right| \tag{3}$$

In the proposed fuzzy c-means clustering method, the number of states must be specified and given to the algorithm as input data. For this purpose, in this paper, by calculating the XB index as (4), the number of suitable clusters can be determined. Based on [25], in the optimal number of clusters, the XB index is minimal.

$$XB=\frac{J_m(U,v)}{n\times\min_{i\neq j}\left(\left|v_i-v_j\right|^2\right)} \tag{4}$$

3- 3- Complete reliability model of central receiver power plant

The complete reliability model of the central receiver power plant is obtained by combining the reliability model of this plant related to the failure of different components and the reliability model associated with the variation in the generated power arising from variations in solar radiation. In Fig. 4, the complete reliability model of a central receiver power plant is presented. In this model, it is assumed that the clustering technique results in h clusters with generated capacities of $P1$, $P2$, ..., Ph. To decrease the number of states of this model, the states with the same capacity can be merged.

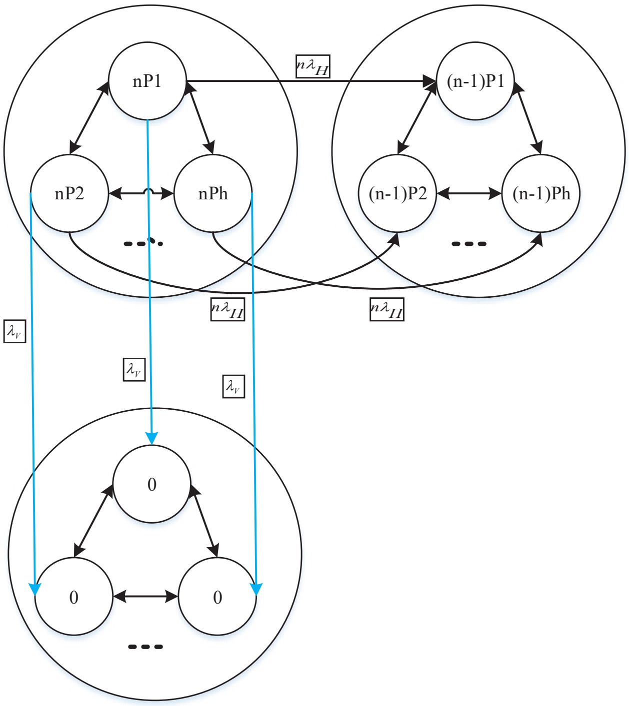

Fig. 5. The reliability model of solar power tower suitable for operation studies

3- 4- Reliability model of central receiver power plant in the operation studies

In the operation studies of the power system, some assumptions are considered as below:

The duration of operation studies is short and in this short time, the repair is not possible. Thus, it can be neglected from the repair rates in the reliability model of the central receiver power plant.

At the beginning of the operation studies, all components are assumed to be perfect.

Based on the Markov model assumption, only one component can be damaged and it is neglected from the failure of two components or more. Also, due to the short time of operation studies, if the failure of one element occurs, there is no time left for the failure of the other elements.

Based on the considered assumptions, the reliability model of a solar power tower suitable for operation studies of the power systems containing large-scale central receiver power plants can be determined as presented in Fig. 5.

4- Operation Studies of the Power System Based on the Well-Being Approach

The operation studies of the power system are placed in the security part of the power system reliability. In these studies, the response of the power system to different disturbances such as outage of generation units or transmission lines is investigated. In the operation studies of the power system, to prevent from the load curtailment in the power system, some reserves must be established. In past, the amount of required spinning reserve in the power system is determined based on deterministic criteria. In these methods, the amount of spinning reserve is considered as a certain percentage of the load or the certain percentage of the generation capacity. The *n-1*criterion is one of the deterministic criteria that the amount of spinning reserve is considered to be equal to the value of the largest synchronous generation unit. Thus, if any of the synchronous generation units is failed, the remaining generation units can supply the required loads. In the deterministic approach, the random behavior of power system components is not considered and the value of the spinning reserve determined based on this method may lead to a power system with low reliability or it may make the system too reliable which is not necessary. Thus, in this paper, the amount of spinning reserve is determined based on the probabilistic approach. For this purpose, the PJM method is used to determine the spinning reserve of the power system containing a large-scale central receiver power plant.

4- 1- The PJM method

In this method, the required spinning reserve is calculated based on the unit commitment risk that is obtained by summing the probabilities of the states that the generation capacity is less than the required load. The conventional generation units are presented with two up and down states. In the operation studies of the power system, due to the short study time, the repair cannot be performed and so, the reliability model of conventional units would be as Fig. 6.

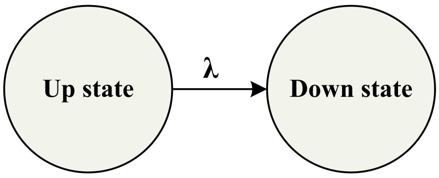

Fig. 6. The two-state Markov model of conventional units suitable for operation studies

The probability of a down state in the reliability model of conventional units in the operation time study (*T*) can be determined as *ORR=λT*. However, for the central receiver power plants due to the uncertain nature of solar radiation, their reliability model composed of more than two states, *ORR* cannot be used. To determine, the probabilities of different states of the central receiver power plant with *m* states in the study time *T*, the matrix multiplication technique is proposed as (5).

$$P(t=T)]=[P(0)].[STPM]^{N} \tag{5}$$

Where, *[P(t=T)]*, including a row and m columns is a matrix associated with the probabilities of the m states in the study time *T*, *[P(0)]* including a row and m columns is a matrix associated with the probabilities of m states at the beginning of the study that is specified, *[STPM],* including m rows and m columns is the stochastic transitional probability matrix that presents the transition among different m states of the reliability model of central receiver power plant. If the hourly generated power data of the central receiver power plant is available the *[STPM]* in occurrence per hour can be determined as:

$$STPM_{ij}=\begin{cases}(\sum_{k=1}^{8760}(U_{ik}U_{j(k+1)}))/(\sum_{k=1}^{8760}(U_{ik}U_{i(k+1)})) & i\neq j\\ 1-\sum_{j=1,j\neq i}^{m}STPM_{ij} & i=j\end{cases} \tag{6}$$

Where U_{ij} is the fuzzy degree between the produced power of the central receiver power plant in hour *k* and i^{th} cluster. In (5), to determine the probabilities of different states of the plant in study time *T*, this time is divided into the *N* time steps each with Δ*t* duration (*N=T/*Δ*t*), and the *[STPM]* must be in occurrence per time interval Δ*t*. The *[STPM]* associated with the time interval Δ*t*, can be calculated as:

$$STPM_{ij}=\begin{cases}STPM_{ij} & i\neq j\\ 1-\sum_{j=1,j\neq i}^{m}STPM_{ij} & i=j\end{cases} \tag{7}$$

To perform the operation studies of the power system containing a large-scale central receiver power plant, the capacity outage probability table (COPT) of conventional and renewable generation units is determined. In the COPT of the generation units, different generation capacities and associated probabilities are presented. By combining the COPT of generation units of the power system, the total COPT of the system is determined. Due to the short time of operation studies of the power system, the load is considered to be constant. The unit commitment risk is determined by summing the probabilities of the states that the generation capacity is less than the required load. For a certain load, the generation units, based on the priority order, are added to the power system to the extent that the amount of the unit commitment risk is less than the allowable amount. The spinning reserve is determined as the difference between the total capacity of the synchronous generation units and the peak load. In this paper, for the renewable-based power systems, due to the uncertain nature of renewable resources, to determine the required spinning reserve, it is proposed to use from the well-being approach of the power system.

4- 2- The Well-being approach

In the PJM method, to determine the spinning reserve of the power system, a two-state model including risk state and non-risk state is considered for the power system. For this purpose, the generation units are added to the power system based on the priority order until the risk of the power system is less than the permissible value and the spinning reserve is determined. In the well-being model of the power system, three states including the health state, marginal state, and risk state are considered for the power system. In Fig. 7, the traditional two-state and well-being approach of the power system is presented based on the different states of a person that is placed on the rooftop.

In the well-being approach of the power system that is presented in Fig. 8, in the health state, the generation capacity is more than the required load, and adequate reserve is established in the power system. In this paper, the adequate reserve must be more than the capacity of the largest synchronous generation unit. Thus, the probability of a health state is determined as:

$$P_i,\ (C_i>(load+capacity\ of\ largest\ unit)) \tag{8}$$

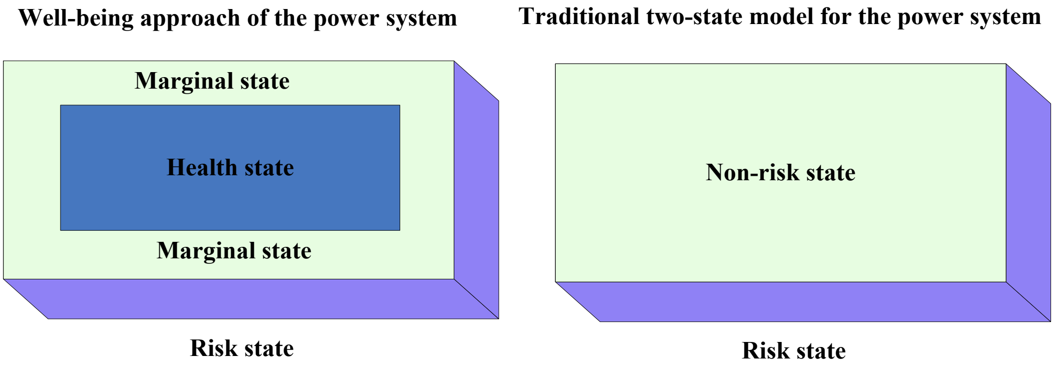

Fig. 7. The two-state Markov model of conventional units suitable for operation studies

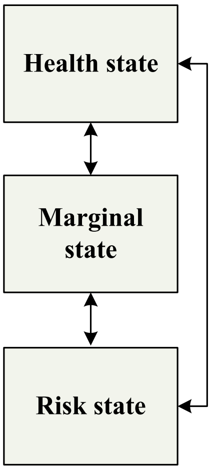

Fig. 8. The well-being model of the power system

In the marginal state of the power system, the generation capacity is more than the required load, but the reserve is not adequate, i.e. the reserve is less than the largest synchronous generation unit. Thus, the probability of marginal state is calculated as:

$$P(M)=\sum_{i=1}^{k}P_i,\ (C_i > load\ \ but\ \ C_i < (load+capacity\ \ of\ \ largest\ \ unit)) \tag{9}$$

In the risk state, the generation capacity is less than the required load. The probability of risk state can be determined as:

$$P(R)=1-P(H)-P(M) \tag{10}$$

To determine the spinning reserve of the power system for a certain load based on the well-being approach, the generation units are added to the power system based on the priority order until the probability of the health state is more than the permissible value and the risk value is less than allowable value.

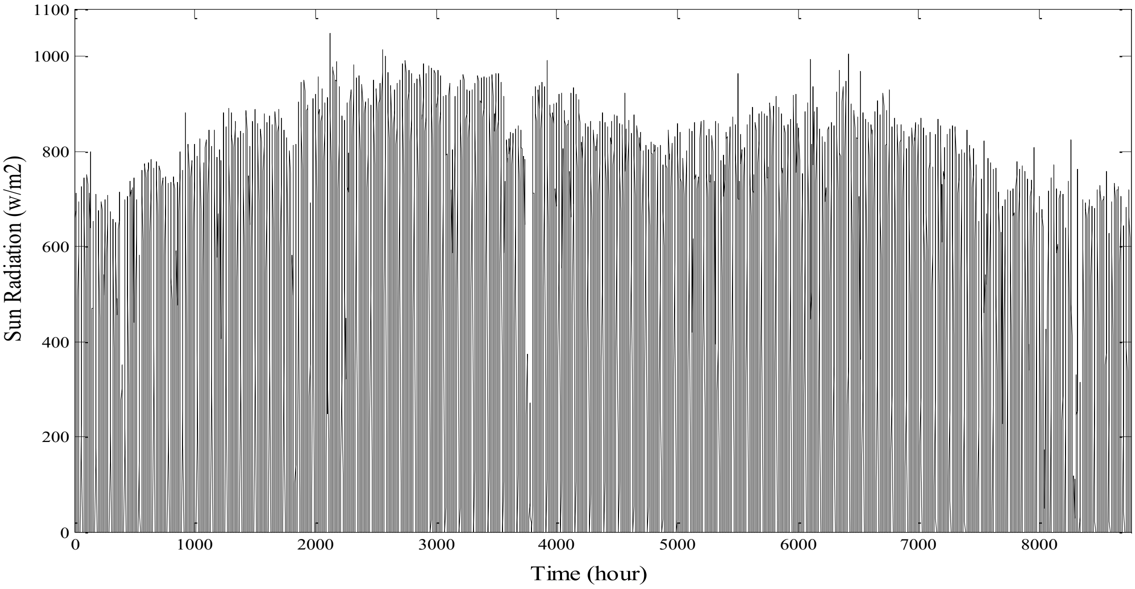

Fig. 9. The hourly solar radiation data during a year

Table 1. The performance parameters of the understudied central receiver power plant

Heliostat reflectivity	0.94
Atmosphere efficiency	0.95
Mirrors cleanliness	0.85
cosθ	0.93
Efficiency associated to the shading and blocking effect	1
Efficiency of heat transfer fluid	0.85
Boiler efficiency	0.89
Turbine efficiency	0.45
Generator efficiency	0.97
Electrical efficiency	0.98
Transformer efficiency	0.98

5- Numerical Results

In this section, the well-being model of RBTS and IEEE-RTS as two reliability test systems integrated to the large-scale central receiver power systems is obtained.

5- 1- The reliability model of understudied solar power tower

In this paper, a 30MW central receiver power plant composed of 3750 heliostats, each with an area of 36 m^2 is considered to be installed in the Jask region in Iran. The hourly solar radiation data of this region during a year is presented in Fig. 9. As can be seen in the figure, the solar radiation varies widely over time. Thus, the solar radiation, and consequently, the produced power of solar tower power plants at different seasons, months, days, and different times of day is different.

The characteristics of the understudied central receiver power plant are presented in Table 1. In this plant, a two-axis sun tracker system is considered for the heliostats and so, the mirrors can track the sun and receive the maximum solar radiation.

The hourly generated power of the understudied central receiver power plant is determined by multiplying the hourly solar generation by the performance parameters presented in Table 1 and presented in Fig. 10. To reduce the number of clusters in the reliability model of the understudied central receiver power plant, *XB* index is calculated and presented in Fig. 11. As can be seen from the figure, for six clusters, the *XB* index is minimal and so, the optimum number of clusters is considered to be six. The fuzzy c-means clustering algorithm is applied to the produced power data of the

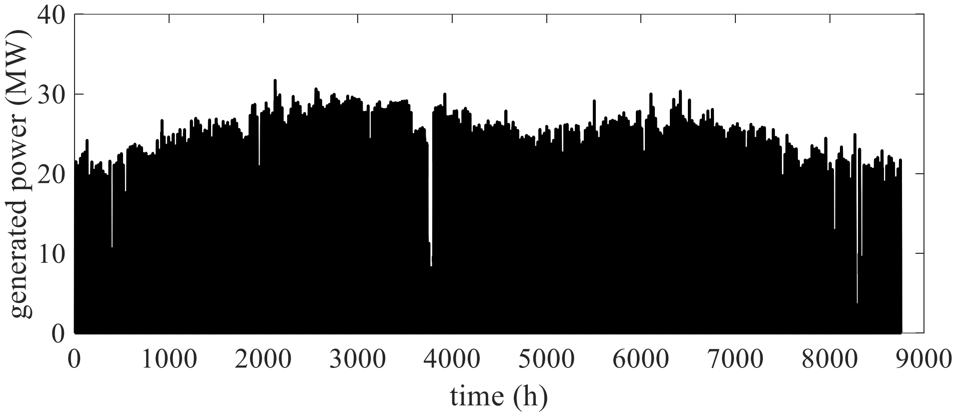

Fig. 10. The hourly produced power of understudied central receiver power plant

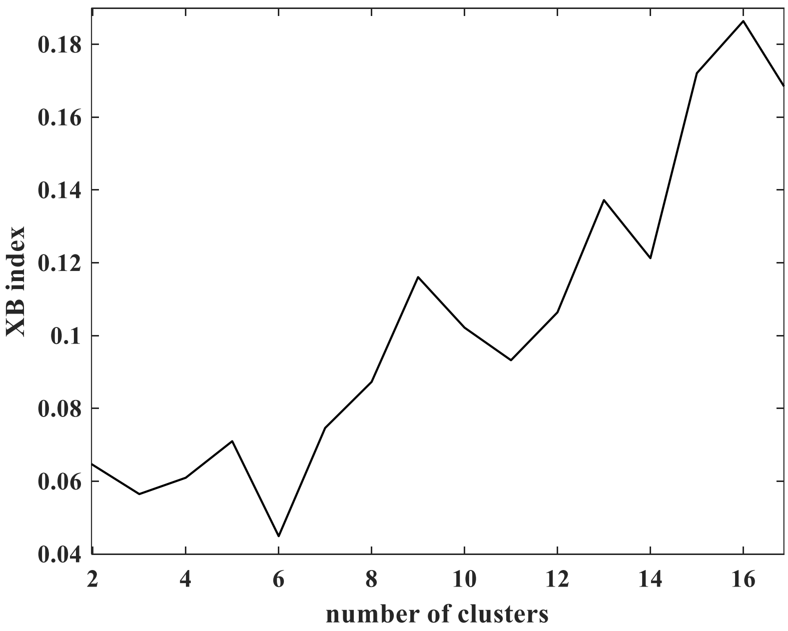

Fig. 11. The XB index considering the number of clusters

understudied central receiver power plant and the capacities of the clusters including 0, 5.8, 11.3, 17.8, 22.4, and 26.4MW are determined. The transition among these differed states is determined and presented in Table. 2.

In Fig. 5, the reliability model of the central receiver power plant is determined. In the understudied solar power tower composed of 3750 heliostats, the reduction power due to the failure of a heliostat is not significant and so, it can be neglected from the failure of heliostats in the reliability model of the understudied central receiver power plant. Thus, the reliability model of the understudied solar power tower is presented in Fig. 12.

The failure and repair rates of the composed components of the understudied central receiver power plant are presented in Table 3.

Table 2. The transition among different states in occurrence per hour

States	1	2	3	4	5	6
1	0.916443	0.047491	0.032034	0.004032	0	0
2	0.4197	0.115632	0.214133	0.205567	0.040685	0.004283
3	0.282883	0.142342	0.104505	0.327928	0.126126	0.016216
4	0.02594	0.141375	0.220493	0.219196	0.347601	0.045396
5	0	0.008837	0.055965	0.208395	0.549337	0.177467
6	0	0.000873	0.006987	0.020087	0.222707	0.749345

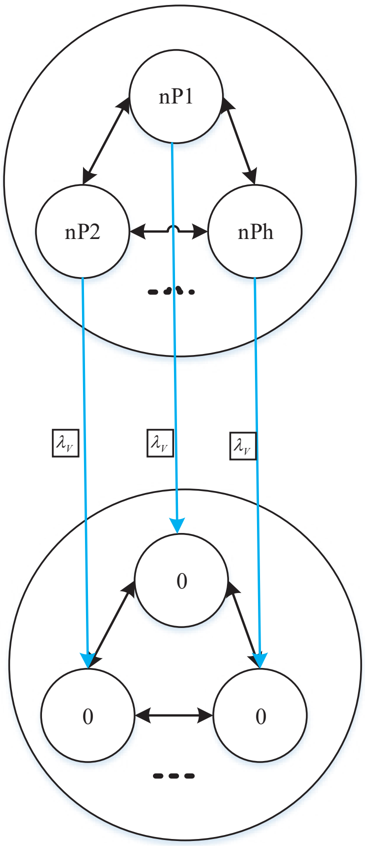

Fig. 12. The reliability model of the understudied solar power tower suitable for operation studied

Table 3. The failure and repair rates of solar power tower components

Component	Failure rate (occ./yr)	Repair time (hour)
Heliostat	0.1	50
Central receiver and HTF components	0.1	100
Rankine cycle components	1	100
Generator	0.1	100
transformer	0.05	50
Electrical converter	0.04	50
Cable	0.1	100

The λ_V is the equivalent failure rate of the series connection of the central receiver and HFT components, Rankine cycle components, generator, transformer, electrical converter, and cable. Based on (2), λ_V=1.39 failure per year or 0.00016 failure per hour. The stochastic transitional probability matrix of the understudied central receiver power plant in occurrence per hour is presented in (11).

$$
\begin{aligned}
& STPM=\begin{bmatrix} A\ B \\ C\ D \end{bmatrix}, C=[0]; \\
& A=D=\begin{bmatrix}
0.9164 & 0.0475 & 0.03203 & 0.0040 & 0 & 0 \\
0.4197 & 0.1156 & 0.2141 & 0.2056 & 0.0410 & 0.0043 \\
0.2829 & 0.1423 & 0.1045 & 0.3279 & 0.1261 & 0.0162 \\
0.0259 & 0.1414 & 0.2205 & 0.2192 & 0.3476 & 0.0454 \\
0 & 0.0088 & 0.0560 & 0.2084 & 0.5493 & 0.1775 \\
0 & 0.0009 & 0.0070 & 0.0201 & 0.2227 & 0.7493
\end{bmatrix} \\
& B=\begin{bmatrix}
0.0002 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.0002 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.0002 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.0002 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.0002 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.0002
\end{bmatrix}
\end{aligned} \tag{11}
$$

To perform the operation study of the power system, the time interval is considered to be 10 minutes and so, the stochastic transitional probability matrix in occurrence per 10 minutes is presented in (12).

$$
\begin{aligned}
& [P]=\begin{bmatrix} A\ B \\ C\ D \end{bmatrix}, C=[0]; \\
& A=\begin{bmatrix}
0.9860 & 0.0079 & 0.0053 & 0.0007 & 0 & 0 \\
0.0700 & 0.8526 & 0.0357 & 0.0343 & 0.0068 & 0.0007 \\
0.04715 & 0.0237 & 0.8507 & 0.0547 & 0.0210 & 0.0027 \\
0.0043 & 0.0236 & 0.0367 & 0.8698 & 0.0579 & 0.0076 \\
0 & 0.0015 & 0.0093 & 0.0347 & 0.9249 & 0.0296 \\
0 & 0.0001 & 0.0012 & 0.0033 & 0.0371 & 0.9582
\end{bmatrix} \\
& B=\begin{bmatrix}
2.67E-05 & 0 & 0 & 0 & 0 & 0 \\
0 & 2.67E-05 & 0 & 0 & 0 & 0 \\
0 & 0 & 2.67E-05 & 0 & 0 & 0 \\
0 & 0 & 0 & 2.67E-05 & 0 & 0 \\
0 & 0 & 0 & 0 & 2.67E-05 & 0 \\
0 & 0 & 0 & 0 & 0 & 2.67E-05
\end{bmatrix} \\
& D=\begin{bmatrix}
0.9861 & 0.0079 & 0.0053 & 0.0007 & 0 & 0 \\
0.0700 & 0.8526 & 0.0357 & 0.0343 & 0.0068 & 0.0007 \\
0.0471 & 0.0237 & 0.8508 & 0.0547 & 0.0210 & 0.0027 \\
0.0043 & 0.0236 & 0.0367 & 0.8691 & 0.0579 & 0.0076 \\
0 & 0.0015 & 0.0093 & 0.0347 & 0.9249 & 0.0296 \\
0 & 0.0001 & 0.0012 & 0.0033 & 0.03712 & 0.9582
\end{bmatrix}
\end{aligned} \tag{12}
$$

5- 2- RBTS case study

In this part, the RBTS including 11 generation units with total capacity 240MW is considered as a reliability test system to study the effect of the large-scale central receiver power plant on the operation studies of this system. The characteristics of the generation units of the RBTS are given in [26]. To study the impact of solar power towers on the operation studies of the power system, in this stage four cases are considered. case I is the original RBTS. Case II is the RBTS integrated into a 30MW conventional generation unit with a failure rate of 5 failures per year. Case III is the RBTS integrated into the understudied central receiver power plant when the initial solar radiation is high and the generation power is maximum. Case IV is the RBTS containing an understudied central receiver power plant when the initial solar radiation is low and he generation capacity is minimum. For the study time 1 hour, the probability of health state, marginal state, and risk state associated to these four cases are determined and presented in Fig. 13 to 15, respectively. As can be seen in the figure, when a new generation unit is added to the system, the probability of health state increases and the probability of risk state reduces. However, the addition of conventional generation units to the power system improves the well-being approach indices of the power system more than the addition of a central receiver power plant. It is also deduced from the figures that the effect of the central receiver power plant in the improvement of well-being approach indices is more when the initial solar radiation is high. In a health state, the generating capacity of the power system is more than the required load plus the capacity of the largest synchronous unit. Thus, when a new generating unit is added to the power system, the states with a generating capacity more than the required load plus the capacity of the largest unit would be increased. For this reason, when the conventional unit or solar tower power plant is integrated to the system, the probability of health state increases. In risk state, the capacity of generating units is less than the required load. When a new generating unit is added to the power system, the capacity of generating units is increased, and so, the probability of states that generating capacities are less than the required load decreases. Thus, when conventional or solar tower power plants are integrated to the system, system risk decreases. The output power of solar tower power plant depends on solar radiation. Due to wide variations in solar radiation, output power of solar tower power plant varies, too. Thus, in most times, the produced power of the central receiver power plant is less than rated capacity. For this reason, increase in probability of health state, and decrease in system risk for integration of conventional unit is more than solar tower power plant.

The probabilities of different well-being states associated to four cases for the study time 4 hour are calculated and presented in Fig. 16 to 18. As can be seen in the figures, with the increase in the time study the effect of the initial solar radiation on the well-being approach indices is reduced. When, the operation study time is increased, the probability of down state of power plants increases, too. Thus, at long operation study time, the probability of health state decreases and the system risk increases.

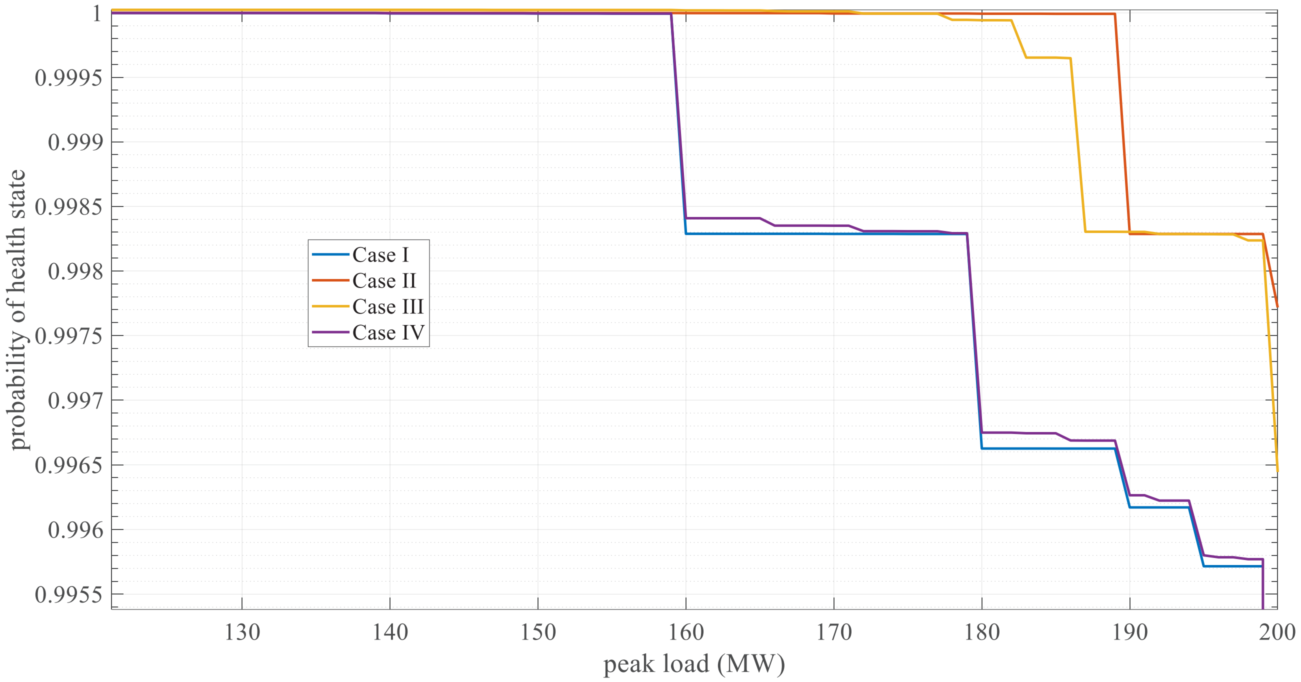

Fig. 13. The probability of health state for study time 1 hour

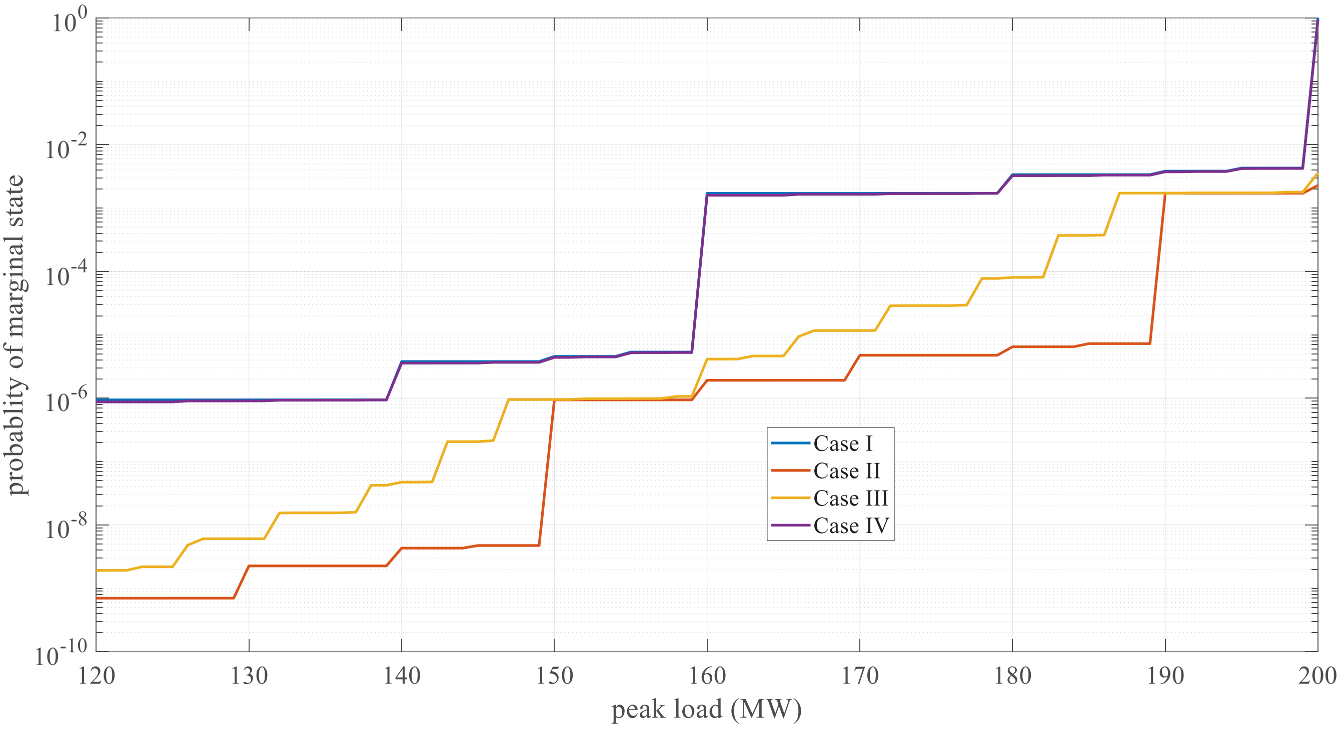

Fig. 14. The probability of marginal state for study time 1 hour

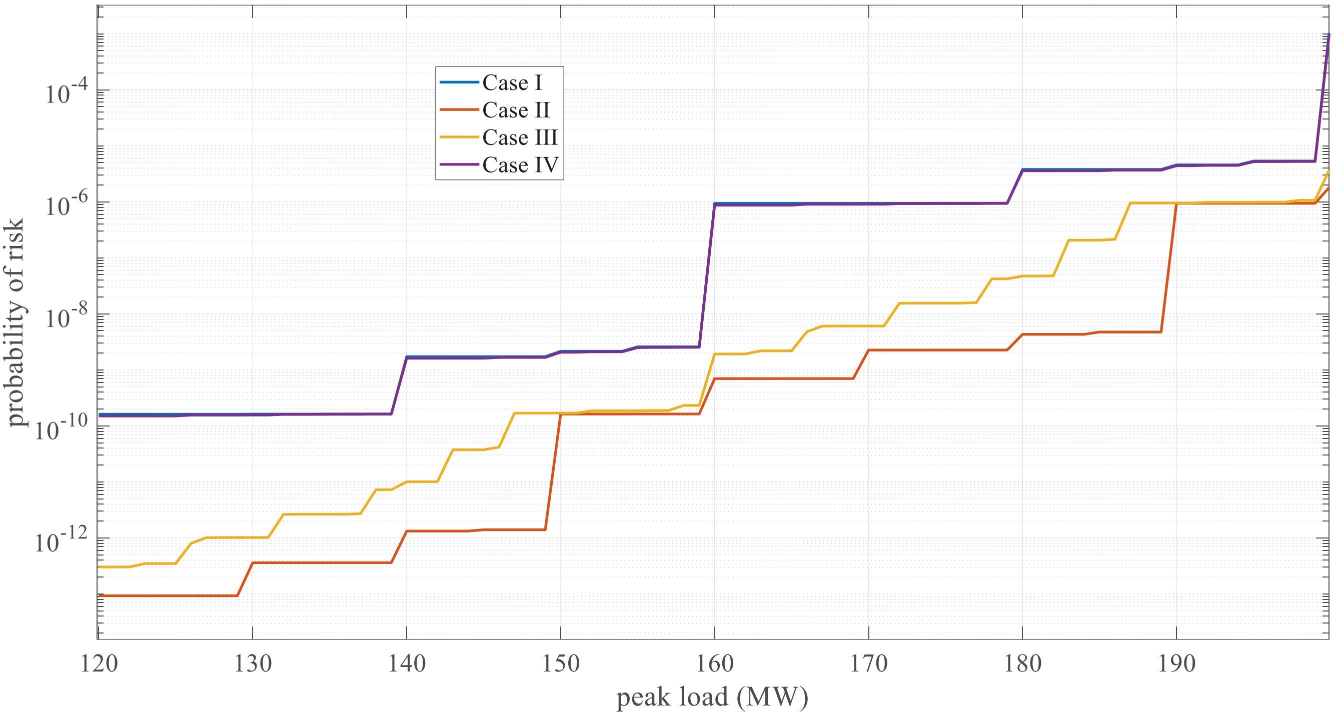

Fig. 15. The probability of risk state for study time 1 hour

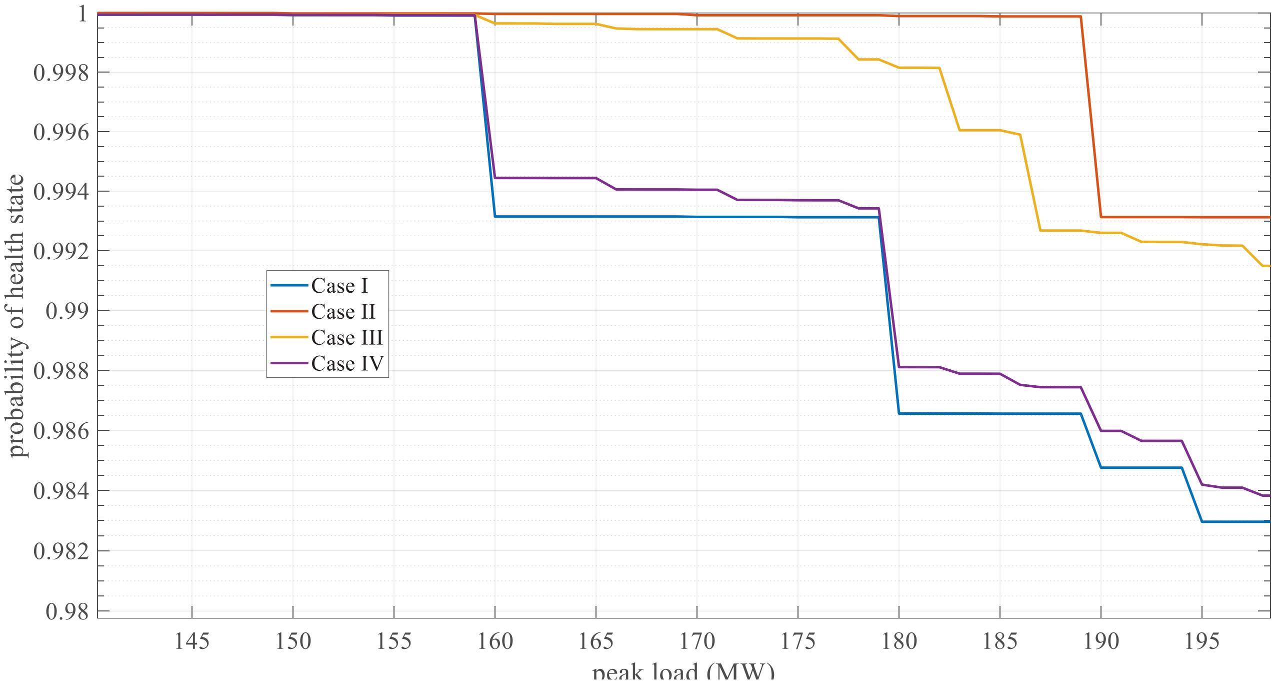

Fig. 16. The probability of health state for study time 4 hour

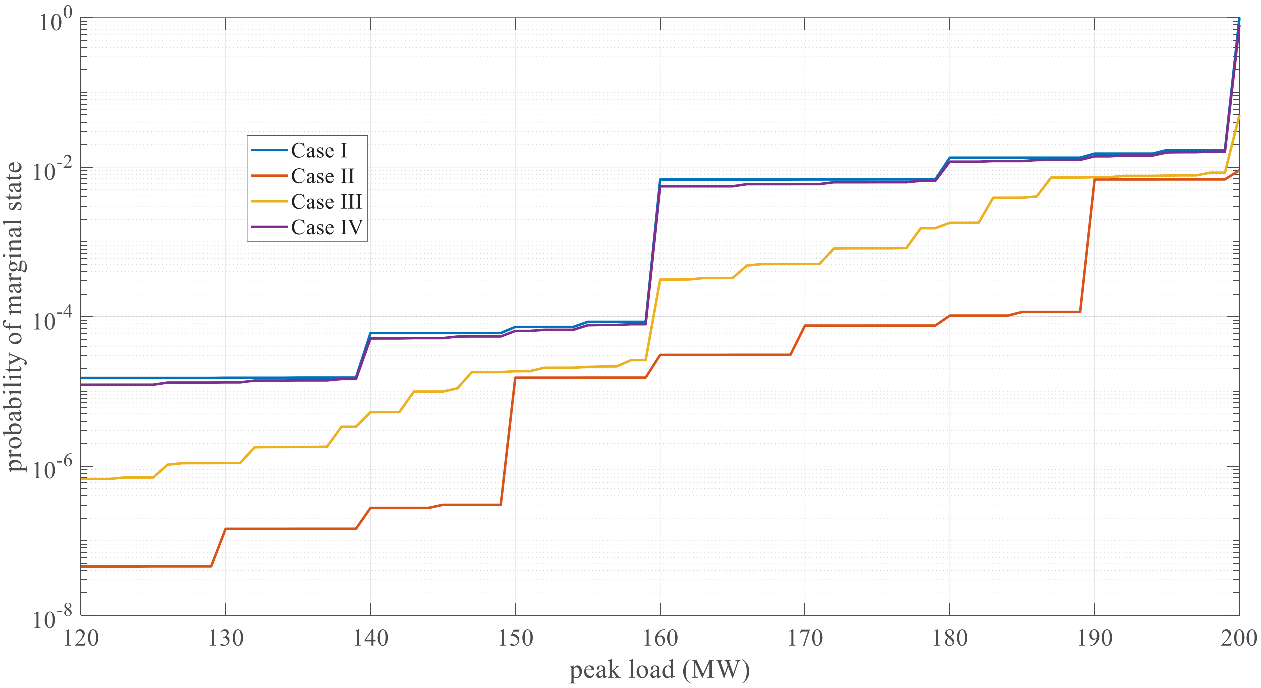

Fig. 17. The probability of marginal state for study time 4 hour

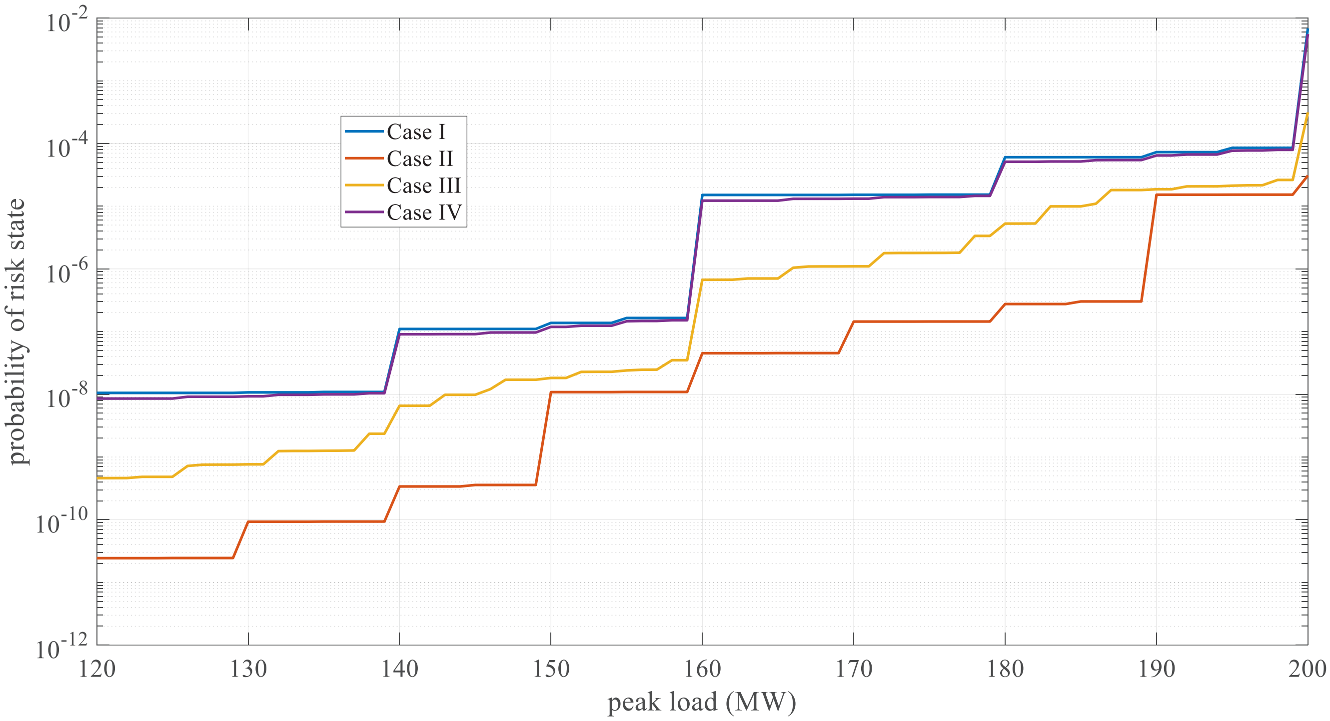

Fig. 18. The probability of risk state for study time 4 hour

Table 4. The PLCC for four cases

Cases	1 h	4 h
Case I	179 MW	159 MW
Case II	199 MW	189 MW
Case III	199 MW	182 MW
Case IV	179 MW	159 MW

Table 5. The IPLCC for three cases

Cases	1 h	4 h
Case II	20 MW	30 MW
Case III	20 MW	23 MW
Case IV	0 MW	0 MW

Table 6. The priority order of RBTS generation units

Cap. MW	Type	NO. of units	Priority order	Failure rate
40	Hydro	1	1	3 (occ./yr)
20	Hydro	2	2-3	2.4 (occ./yr)
40	Thermal	2	4-5	6 (occ./yr)
20	Thermal	1	6	5 (occ./yr)
10	Thermal	1	7	4 (occ./yr)
20	Hydro	2	8-9	2.4 (occ./yr)
5	Hydro	2	10-11	2 (occ./yr)

In this stage, the peak load carrying capabilities (PLCC) of these four cases provided that the probability of the health state is more than 0.998 and the risk is less than 0.00001 for study times 1 and 4 hours are determined and presented in Table .4. Also, the increase in peak load carrying capability associated to the states II, III and IV, when a new generation unit is added to the RBTS is calculated and presented in Table. 5.

As can be seen in the tables, the addition of conventional unit and understudied solar power towers with high initial solar radiation to the RBTS leads the peak load-carrying capability of the system increases. However, the effect of the conventional generation unit in the improvement the PLCC is more than the addition of central receiver power plant. Also, the central receiver power plant with low initial solar radiation has no significant effect on the PLCC and IPLCC of the RBTS. When a new power plant is added to the power system, the generating capacity of the system increases. In this condition, if the system load is remained constant, the probability of a health state increases and system risk decreases. Thus, at permissible reliability criteria, the peak load of the system can be increased. For this reason, when a new generating unit is added to the system, the peak load-carrying capability of the power system increases. However, in most times, the produced power of solar tower power plants is less than rate capacity. Thus, conventional units improve peak load-carrying capability of the system more than solar tower power plants.

The priority order of RBTS generation units is presented in Table. 6. For a certain load, the generation units of the RBTS are added to the power system until the probability of a health state is more than 0.998 and the risk is less than 0.00001. For a study time of 4 hours, the capacity of the scheduled generation units considering the peak load, for three cases are calculated and presented in Fig. 19. These three cases, respectively, include RBTS, RBTS with understudied central receiver power plant when the initial solar radiation or generated power is high and RBTS with the understudied solar power tower when the initial solar radiation is low.

As can be seen in the figure, the addition of the central receiver with high initial generation capacity reduces the required scheduled capacity of the power system. However, the understudied central receiver power plant has no significant effect on the required scheduled capacity of the RBTS. Based on the scheduled capacity, the required spinning reserve associated to these three cases are calculated and presented in Fig. 20. As can be seen in the figure, the required spinning reserve is reduced with the addition of the understudied central receiver power plant with high initial solar radiation to the power system. However, the understudied solar power tower with low initial solar radiation has no significant effect on the spinning reserve value. When spinning reserve of the power system decreases, the capacity of generating units that must be committed in the power system decreases, and so, the operating cost of the power system decreases, too. Thus, when solar tower power plants with insignificant operating cost integrated to the power system, due to decrease in required spinning reserve, the operating cost of the power system decreases.

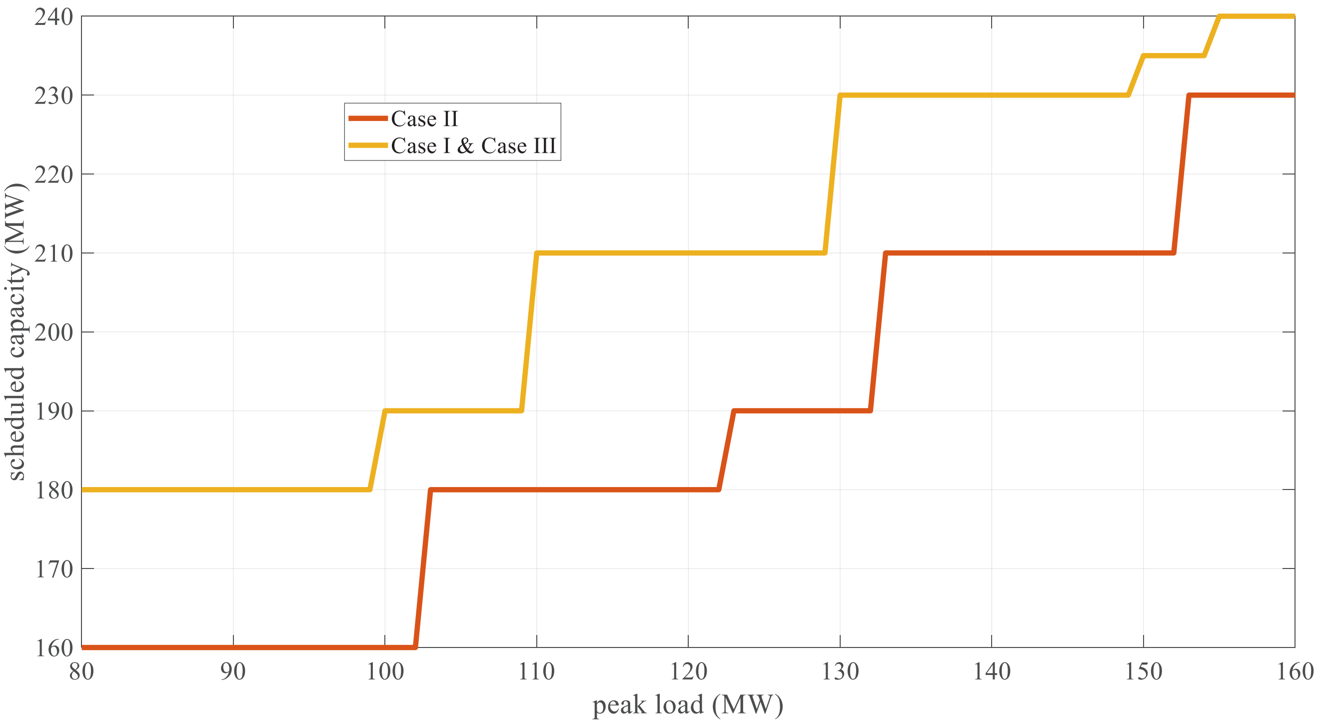

Fig. 19. The scheduled capacity for three cases considering the peak load

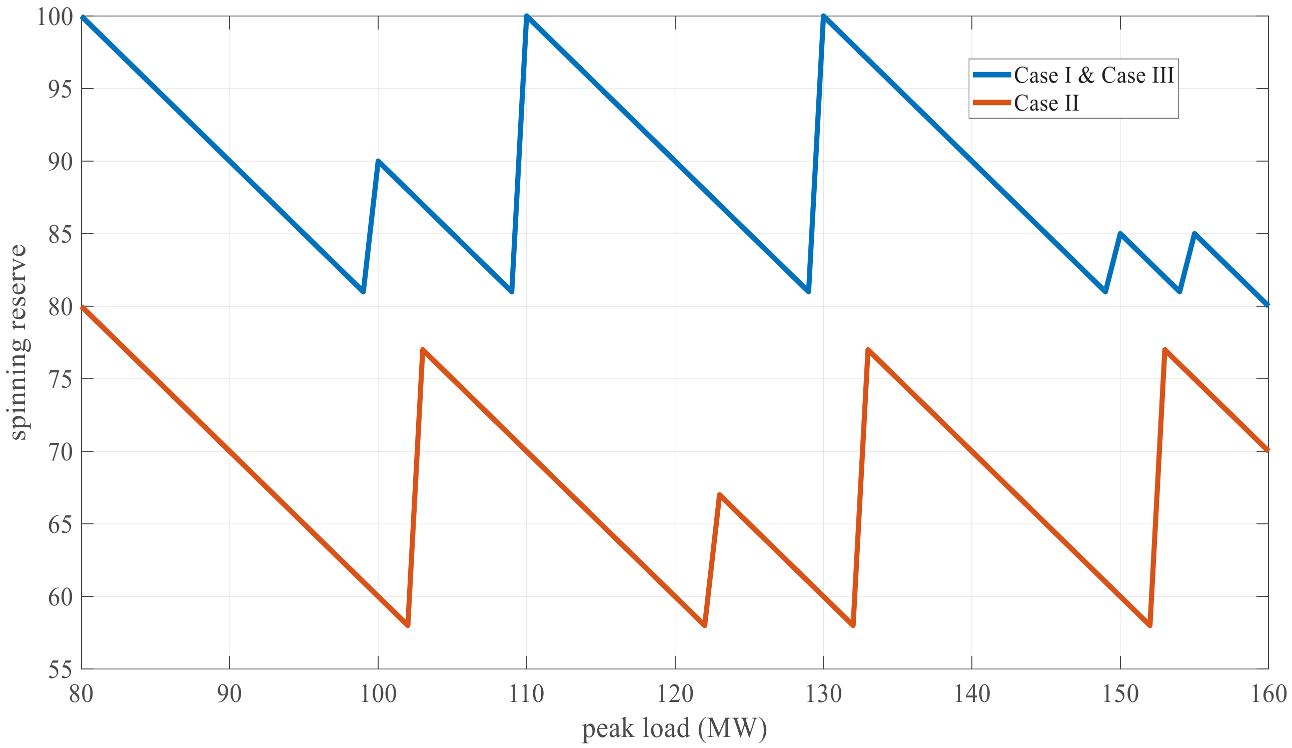

Fig. 20. The required spinning reserve value considering the peak load

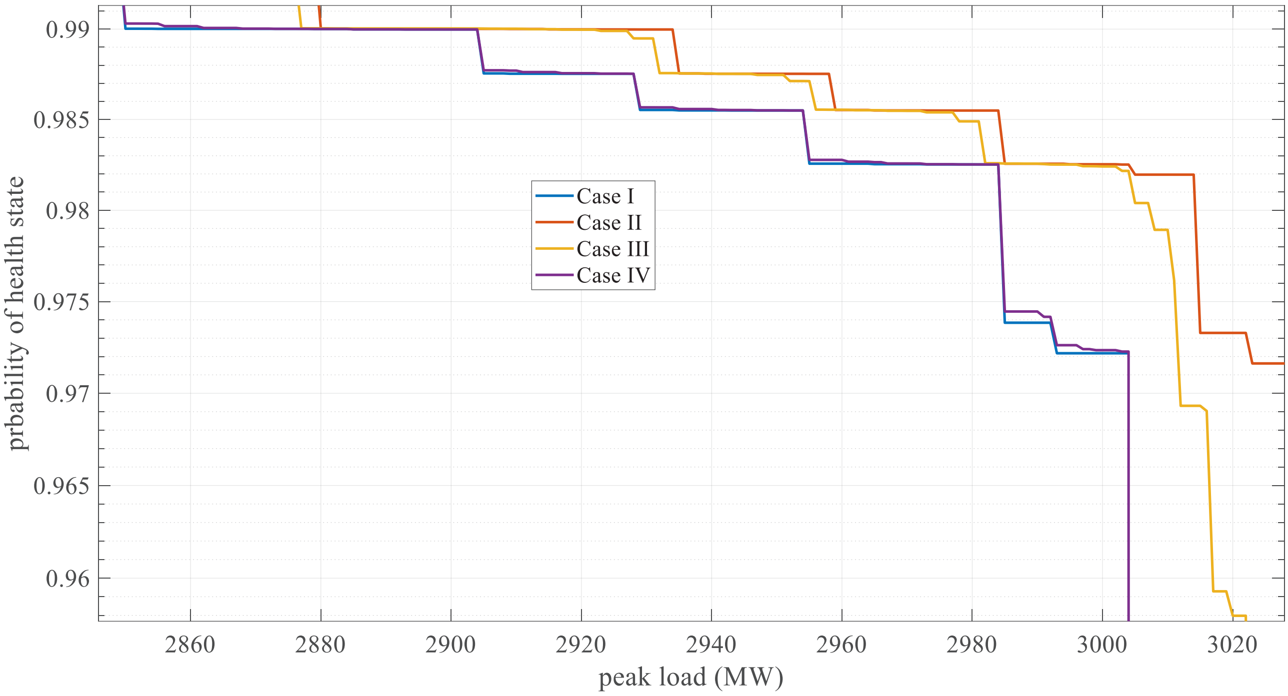

Fig. 21. The probability of health state for study time 1 hour

5- 3- IEEE-RTS case study

In this part, the well-being model of the IEEE-RTS as a reliability test system is determined. the characteristics of the IEEE-RTS generation units are given in [27]. To investigate the effect of central receiver power plant on the well-being model of the IEEE-RTS, four cases are considered. Case I is the original IEEE-RTS and in cases II to IV, respectively, a 30MW conventional generation unit with the failure rate of 5 failures per year, the understudied solar power tower with high initial solar generation and the understudied central receiver power plant with low initial solar radiation are added to the IEEE-RTS. The probabilities of health state, marginal state and risk state for the study time 1 and 4 hour considering the peak load are calculated and presented in Figs. 21 to 26. Also, the PLCC of these four cases and the IPLCC of cases II to IV provided that the probability of the health state is more than 0.998 and the risk is less than 0.00001 are calculated and presented in Tables 7 and 8. It is deduced from these results that the receiver power plants with high initial solar radiation improves the reliability-based operation indices of the IEEE-RTS based on the well-being approach. However, due to the uncertainty nature of solar power towers, the generated power of these renewable-based power plants changes and in the most of time the generated power of them is less than the rated capacity. Thus, the effect of central receiver power plant on the well-being model indices is less than the effect of conventional generation units of the same size. Also, it is deduced from the numerical results that, the addition of the central receiver power plants to the IEEE-RTS has no significant effect on the well-being model indices when the initial solar radiation is low. In this study, the capacity of the solar tower power plant integrated to IEEE-RTS compared to the test system capacity is small. If solar tower power plant with large capacity is added to test system, increase in health state probability and decrease in system risk would be significant. However, as it can be seen, despite the small capacity of solar tower power plants, integration of a central receiver power plant with high initial capacity increases the probability of a health state, decreases system risk, and increases peak load carrying capability of the system, especially at high peak loads.

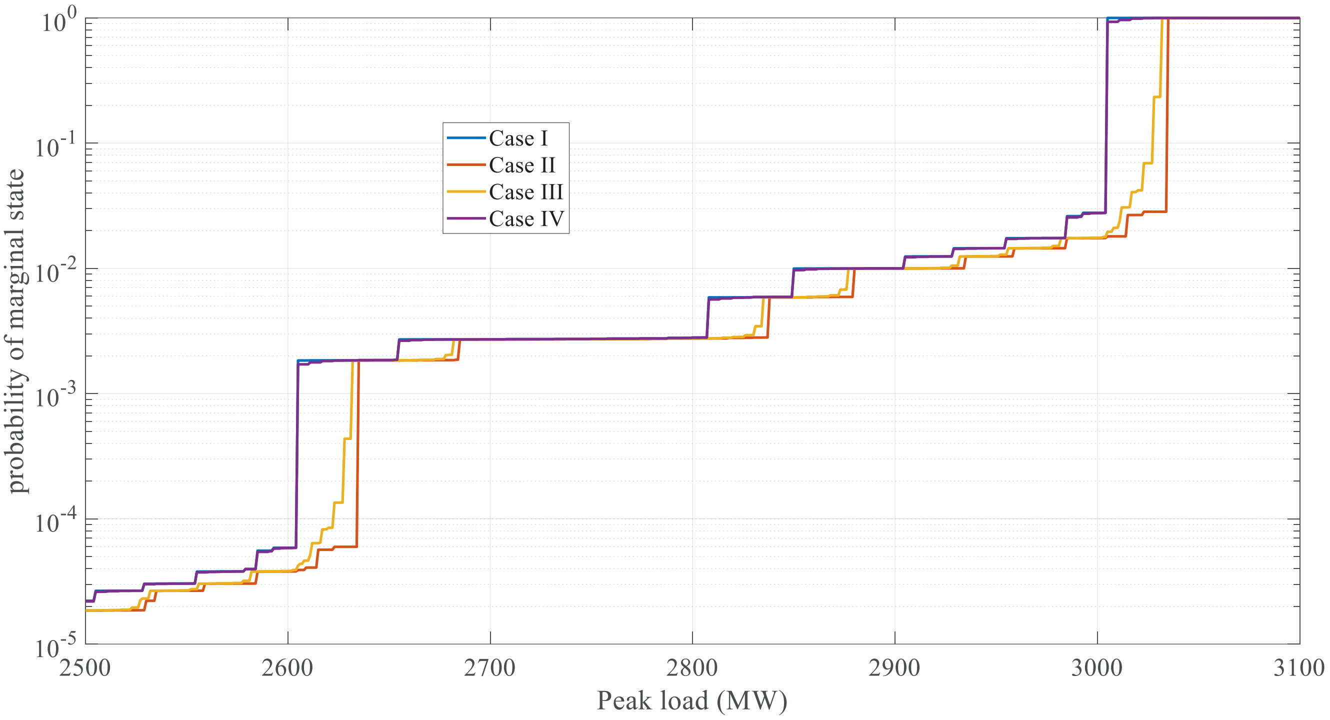

Fig. 22. The probability of marginal state for study time 1 hour

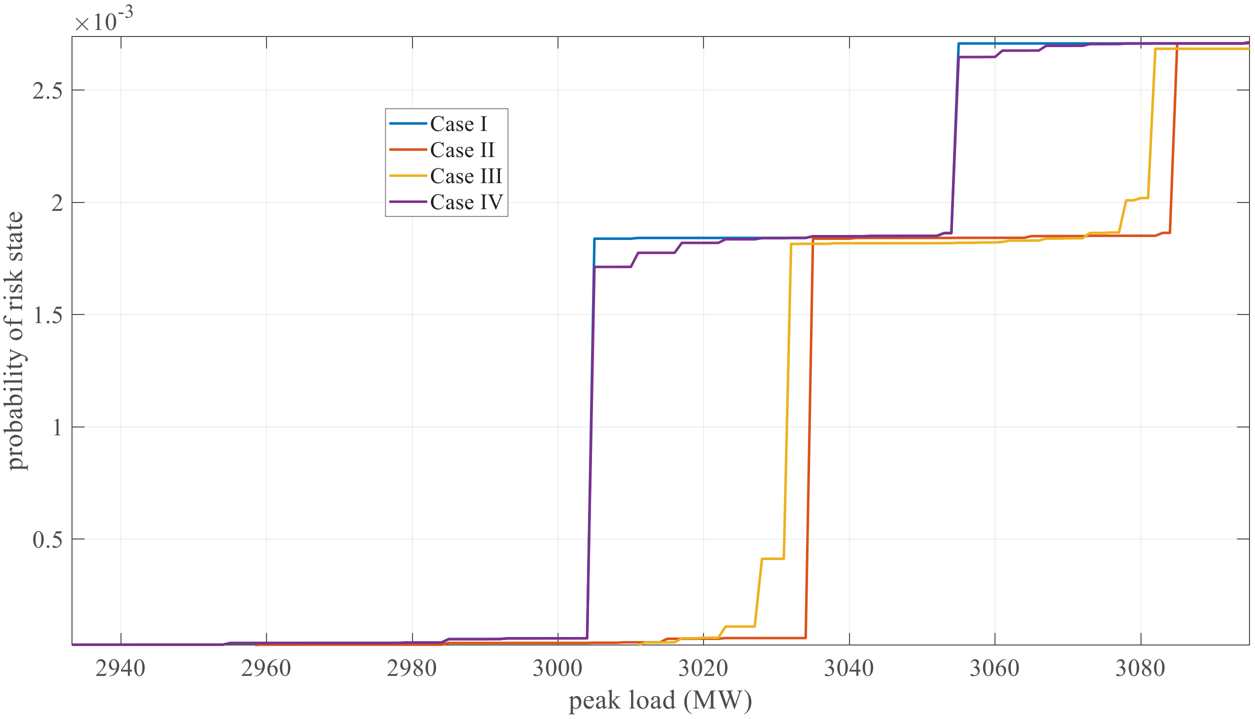

Fig. 23. The probability of risk state for study time 1 hour

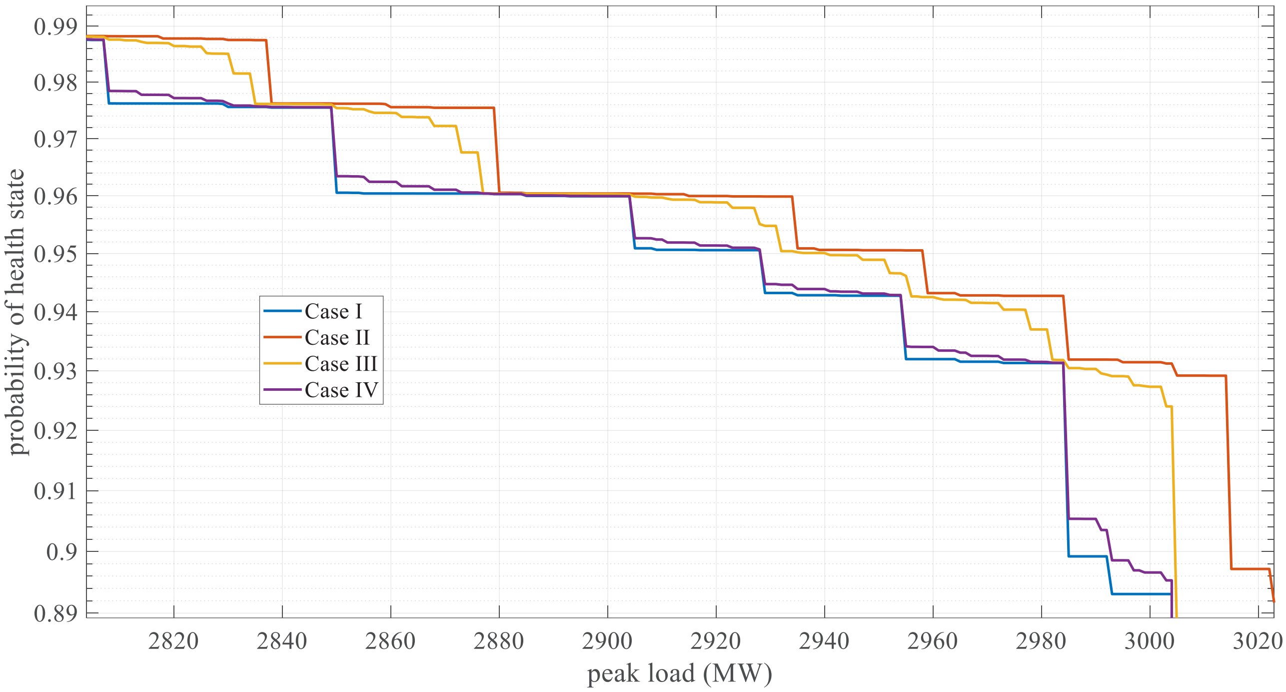

Fig. 24. The probability of health state for study time 4 hour

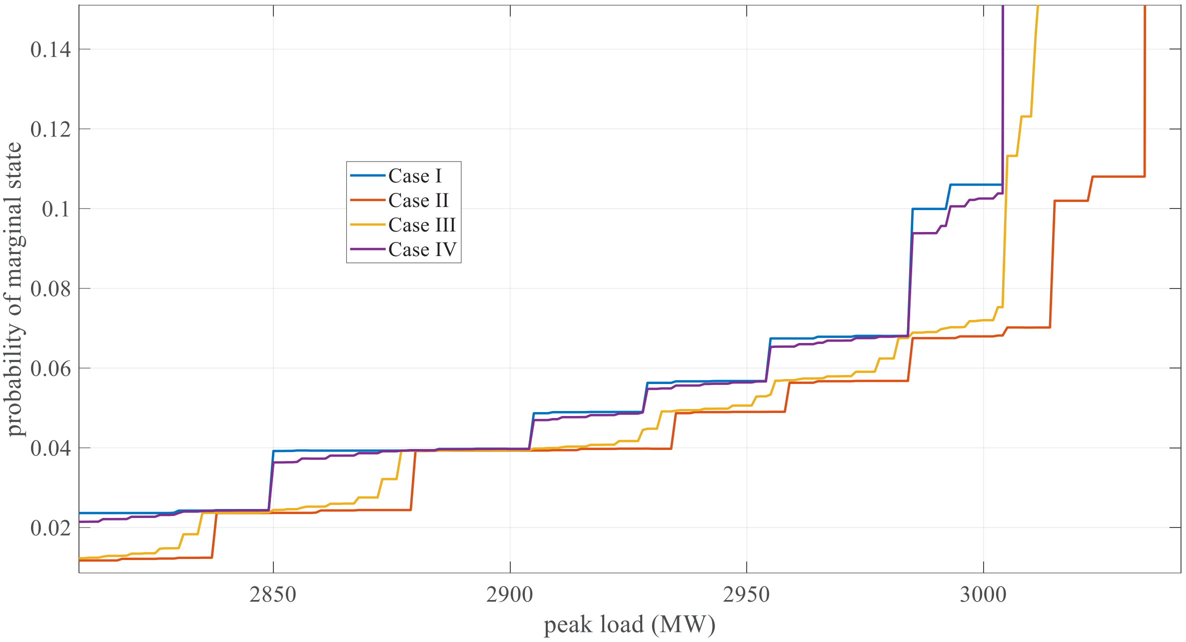

Fig. 25. The probability of marginal state for study time 4 hour

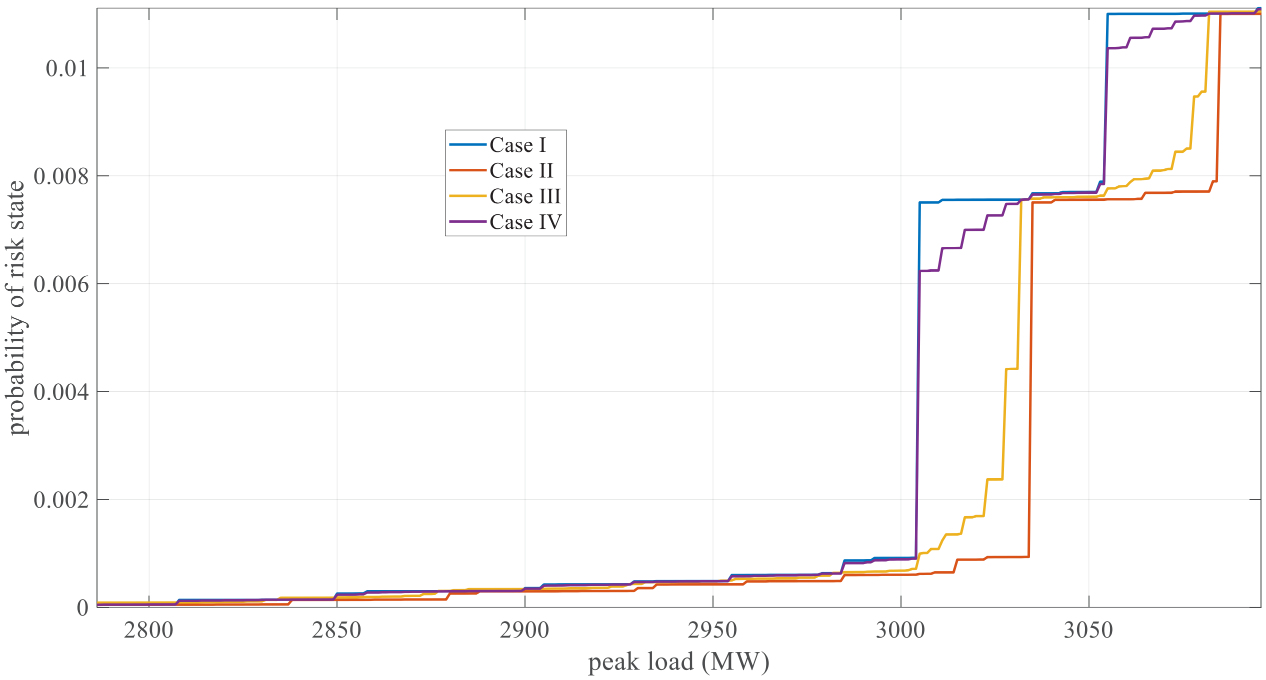

Fig. 26. The probability of risk state for study time 4 hour

Table 7. The PLCC

Cases	1 h	4 h
Case I	2654 MW	2604 MW
Case II	2684 MW	2634 MW
Case III	2681 MW	2622 MW
Case IV	2654 MW	2604 MW

Table 8. The IPLCC

Cases	1 h	4 h
Case II	30 MW	30 MW
Case III	27 MW	18 MW
Case IV	0 MW	0 MW

6- Conclusion

In this paper, the operation studies of the power systems containing large-scale central receiver power plants based on the well-being approach are performed. For this purpose, a multi-state reliability model is developed for the solar power towers taken into account both the uncertain nature of these renewable-based power plants arisen from the variation in the solar radiation and consequently the variation in the produced power and the failure of composed components including heliostats, central receiver, heat transfer fluid cycle, Rankine thermodynamic cycle components, generator, electrical converter, transformer, and cable. The study time of operation is short and so, it is neglected from the repair rate in the proposed model. In this paper, to reduce the number of states in the reliability model of solar power tower, *XB* index calculation and fuzzy c-means clustering technique are used and the transition among different states is determined to construct the stochastic transitional probability matrix of the reliability model of the central receiver power plant. The stochastic transitional probability matrix is used to determine the probabilities of different states of the reliability model of solar power towers for a certain study time through the matrix multiplication technique. Due to the uncertain nature of the central receiver power plant, the well-being approach including the health state, the marginal state, and the risk state is utilized to determine the required spinning reserve value of the power system. Based on the proposed reliability model, the well-being model of RBTS and IEEE-RTS as two well-known reliability test systems is obtained to study the effect of the central receiver power plant on the reliability-based operation indices of the power system. It is deduced from the numerical results that the receiver power plants with high initial solar radiation can improve the reliability-based operation indices of the power system containing large-scale solar power towers based on the well-being approach. However, due to the uncertain nature of central receiver power plants, the generated power of these renewable-based power plants changes, and in the most of time the generated power of them is less than the nominal capacity. Thus, the effect of solar power towers on the well-being model indices is less than the effect of conventional generation units with the same capacity. Besides, it is deduced from the numerical results that, the integration of the central receiver power plants to the power system has no significant effect on the well-being model indices when the initial solar radiation is low.

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