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Reliability Analysis of Power System Considering Renewable Resources, CHP Units, Energy Storage Devices and Demand Response Program

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Abstract— *In recent years, due to rising social welfare, the reliability has become one of most important topics of modern power network and electricity companies try to provide the electric power to the consumers with minimal interruptions. For this purpose, the electricity companies to improve the reliability of the power system can utilize different techniques. In this paper, new developments occurred in electricity industry including integration of large-scale renewable resources, integration of large capacity energy storage systems, integration of combined heat and electricity units into power network and demand side response plans are taken into account, and these events impact on power network reliability is assessed. Power networks are affected with integration of renewable resources. Multi-state reliability models for renewable generation plants are obtained, in the paper. Suitable number of states in the proposed reliability model is selected by calculating XB index. Besides, fuzzy c-means clustering approach is utilized for determining probability of states. For study impact of energy storage systems with large capacity on power network reliability, load model is modified. To investigate effect of combined heat and power plants on power network reliability, failure of composed elements and produced thermal power are considered in reliability model of these plants. To evaluate demand side response impact on reliability of power network, the load model is modified. The effectiveness of the proposed techniques on the reliability enhancement of power network is satisfied using numerical results performed on reliability test systems based on the suggested methods.*

Keywords—Reliability, renewable resources, combined heat and power plant, energy storage systems, demand response program.

1. INTRODUCTION

In recent decades, many developments occur in power industry, which have affected many power network topics. Environmental impacts of power plants with fossil fuels make renewable resources have been utilized to generate electricity in power networks. Thus, renewable power plants with large sizes including wind farms, solar power plants (photovoltaic farms and solar thermal power plants), wave energy conversion systems, barrage-kind and current-kind tidal generation units, run of the river generation units, ocean thermal energy conversion systems and so on have been integrated in modern power networks. Uncertainty nature associated to renewable generation units caused by change of output of these generation units has been affected different power network aspects such as reliability. For making best use of renewable energy sources in the power system, energy storage devices have been used to store the extra generated energy of the renewable resources (when the produced power of them is more than the required load) and to compensate the power shortage (when the required load is more than the generated power of the renewable resources). Different energy storage systems including batteries, pumped-storage power plant, capacitors, flywheel, compressed air system and the electrolyser-hydrogen reservoir-fuel cell have been used for this purpose. For increase energy efficiency of thermal power plants, combined heat and power (CHP) units are introduced, and integrated into power network. In these units, produced thermal power heats required thermal loads. Thus, efficiency of plants increases. Another method of energy management in the electricity network is the load response program that has been introduced in recent years in the power system. In this method, the flexible loads are programmed to consume the electric power at low load times, and so results in reduction peak demand of power network. Due to importance of new developments occurred in power system, many works have been performed for investigation impact of events on different power network aspects.

In [1], new approach of rescheduling plan is proposed for adjusting generation outputs of power network with renewable resources for reduction variation in power flows of branches. The proposed method prevents power congestion to balance between produced power of renewable generation units and required loads of power networks. In this research, a probabilistic approach is suggested for evaluating system uncertainty issue of power network with rescheduling plan. In [2], a comprehensive study is performed for evaluating reliability of power network with new renewable energy sources including the electric vehicles, energy storage systems, solar and wind generation units. In this research, uncertainty nature associated to renewable energy resources is considered and to study the impact of this uncertainty on generation, transmission and distribution sections, new methods are introduced. In [3], adequacy assessment of power network with wind farms, considering wind speed correlation is performed through multi-state reliability model of wind farms. In this research, correlation between wind farms located in different sites

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is considered by genetic algorithm for adjustment auto-regressive moving average time series models associated to wind speeds. In [4], reliability evaluation of the micro-grid containing the renewable generation units and prioritized loads is performed. In this paper, a hybrid analytical simulation technique according to Monte Carlo approach is proposed for considering variability of renewable generation units in the reliability performance of the micro-grids.

In [5], sequential Monte Carlo approach is suggested for adequacy study of power network incorporating energy storage systems. In this research, time series model is suggested for simulating generation unit's characteristics, energy storage devices and required loads of power network. In [6], impact of energy storage devices on distribution network reliability is investigated. This paper considers lumped and distributed methods in placement of energy storage device for determining impact of energy storage devices on feeder as well as overall system reliability. In [7], reliability and economy of distribution system containing the renewable generation units and the energy storage systems are studied. For this purpose, a method based on predictive control is proposed for minimizing cost of distribution network energy by power supplies coordination with energy storage devices, renewable generation units and external power grid. Paper [8] studies distribution network reliability with two categories of reliability indices including energy indices and frequency-expectation indices are calculated. In this research, reliability indices of distribution network are selected for determining suitable feeder by connecting energy storage devices to busbars. In [9], the failure simulation model is proposed to study the reliability of the electrical components of the combined heat and power units. In this research, impact of operation regimes on reliability of electrical equipment of combined heat and power units including the synchronous generator, the main circuit breaker and step tup power transformer, is evaluated using of the statistics and Monte Carlo method. In [10], the optimal size, place and operation of the combined heat and power plants in the multi-carrier energy systems are determined taken into account reliability, power losses and voltage profile of network. In this paper, the optimal planning of the combined heat and power plants at the arbitrary nodes in a system composed of an electrical system and a natural gas network is done through energy hub technique. Paper [11] evaluates impact of demand side response plans on short-term reliability of generating network for estimating risk of generating section during demand side response events. In this regard, multi-state continuous Markov chain model is suggested for demand response capacity. Besides, classification of response capacity states is performed by mean-standard deviation approach. In this research, estimation of transition matrix associated to demand response capacity is done by Lz-transform. In [12], a novel method is proposed for reliability enhancement of power network considering impact of demand response plans such as interruptible or curtail-able load programs. In this research, a load curtailment model according demand-price elasticity is suggested for demand response programs to modify the load curve characteristic of the system taken into account both customer benefits and penalties.

Paper [13] studies reliability performance of wind units through new approach by sequential Monte Carlo methodology. In this paper, random property of wind with operational data of wind turbines such as hazard and repair rates are combined in the reliability model of wind units. In [14], amount of spinning reserve required to satisfy reliability criteria of electric network containing CHP plants is determined. In this research, PJM method is modified to consider CHP units in the operation studies of electric network. Paper [15] general algebraic modelling system software is used to obtain optimal solutions for economic dispatch, emission dispatch and multi-objective economic emission dispatch problems in an islanded microgrid. In this research, the islanded microgrid includes wind turbines, photovoltaic systems, conventional units and battery energy storage systems. In [16], demand response program is implemented to improve the impact of electric vehicle charging on imbalance index of unbalanced distribution system. For this purpose, data mining methods including hierarchical and k-means clustering techniques are used for identifying behavioural patterns of imbalance index. Paper [17] optimal operation of coastal energy hub including energy storage devices and seawater desalination system is performed through risk averse strategy. The energy hub studied in the paper contains wind unit, photovoltaic system, combined cooling-heat- and power unit and seawater desalination. Paper [18] studies stochastic planning of distribution network containing interruptible loads, renewable generations and capacitors. In this paper, simultaneous allocation and sizing of interruptible loads, wind units, photovoltaic systems and capacitors are determined in the radial distribution systems considering different load levels.

In [19], optimal design of hybrid microgrid is performed by mixed integer linear programming method taking account statistical wind estimation and demand response. In this paper the hybrid microgrid located in Iran-Khalkhal includes photovoltaic units, wind turbines and energy storage devices. Paper [20] proposes multi-objective demand side management strategy for improving economic and environmental issues of smart microgrids. The grid-connected smart microgrid includes wind units, photovoltaic panels, diesel generators, micro turbine, fuel cell device and energy storage systems. In [21], information gap decision theory is proposed for optimal scheduling of virtual power plant. Besides, a bi-level unit commitment strategy is suggested to study the impact of virtual power plant and demand response program on operation cost of electric network. Paper [22] proposes a sampling method based on system state transition to study reliability of distribution network containing distributed generation units. In this paper, through Monte Carlo simulation approach, adequacy of radial distribution networks is evaluated to compute well-being indices of power system including probabilities, frequency and duration of healthy, marginal and risk states. In [23] probabilistic optimal allocation of charging stations of electric vehicles as flexible loads and energy storage devices in the power network is performed by Monte Carlo simulation method. Besides, the probabilistic and uncertain behaviour of the loads and their daily variation in the distributed network is considered, in the paper. Paper [24] proposes generation scheduling methodology applied in active distribution networks containing renewable energy resources considering demand response program. In this paper, Monte Carlo simulation method is used to schedule understudied active distribution system includes wind turbines, photovoltaic units and energy storage devices. Table 1 presents summary of literature review performed in the paper.

It is deduced from literature review performed in this section that in modern power systems, renewable resources, combined heat and power units, energy storage devices and demand side program are integrated that affects various aspects of electric networks such as reliability. Considering that little work has been done in this field, in the current research, a comprehensive study is performed on the modern power systems and the impact of new developments occurred in these networks on the reliability indices is investigated. For this purpose, the effect of the renewable generation units, the energy storage systems, the CHP plants and demand response program on power network adequacy is studied. Thus, the main contributions of the paper are as follow:

- A multi-state reliability model is developed for all renewable resources considering both failure of composed components and variation in produced power of them caused by variation in renewable resources.
- To achieve a reliability model with appropriate states for renewable resources, fuzzy c-means clustering method and Xie & Beni (XB) index are proposed.
- The influence of energy storage system on reliability indices of electric network is studied.
- A reliability model for CHP units is developed to study

Table 1. Literature review summary.

References	Description	Drawback
[1]	Operation of renewable resources	
[2–4]	Reliability evaluation of renewable resources through Monte Carlo simulation approach is performed	The lack of analytical method for adequacy analysis of renewable resource
[5]	Adequacy assessment of energy storage systems through sequential Monte Carlo method is performed	The lack of analytical method for adequacy assessment of energy storage devices
[7]	Reliability analysis of distribution network containing renewable resources and energy storage system is performed	The lack of adequacy assessment of power system in generation level
[9, 10]	Operation and optimal sizing studies of combined heat and power units are performed	The lack of reliability assessment studies
[11, 12]	Impact of demand response program on reliability analysis of distribution network through Markov chain and load curtailment methods is studied	The lack of reliability assessment of power system in generation level
[13]	Reliability assessment of power system containing wind farms through Monte Carlo simulation method is carried out	The lack of analytical method for adequacy analysis of renewable resources such as wind farms
[14]	Determination of spinning reserve in the power system containing combined heat and power units by PJM method is done	The lack of reliability assessment of power system containing combined heat and power units
[15]	Economic dispatch of islanded microgrid containing renewable resources and energy storage devices is performed	The lack of reliability evaluation of power system containing combined heat and power plants in generation level
[16]	The impact of demand response program on imbalance index of unbalanced distribution network is studied	The lack of reliability evaluation of power system containing combined heat and power plants in generation level
[17]	Optimal operation of an energy hub containing renewable resources and energy storage device is done	The lack of reliability assessment of renewable resources and energy storage devices
[18]	Stochastic planning of distribution network including renewable units is done	The lack of reliability assessment of renewable resources
[19]	Optimal design of hybrid microgrid containing renewable resources and demand response program is done by mixed integer linear programming method	The lack of reliability studies of renewable resources and demand response program
[20, 21]	The impact of demand side response program on economic, environmental and scheduling problems is done	The lack of reliability analysis of demand side program
[22]	Adequacy analysis of radial distribution network is performed by Monte Carlo simulation method	The lack of reliability assessment
[23]	Optimal allocation of charging stations of electric vehicles as energy storage systems is done	The lack of reliability analysis of energy storage devices
[24]	Scheduling of distribution network containing renewable resources and demand response program is performed by Monte Carlo method	The lack of reliability assessment of renewable resources and demand response program

the impact of these units on reliability performance of electric networks.

- The impact of demand response on reliability indices of electric network is studied. To this end, the structure of paper is as bellows: in second part, reliability of power network is illustrated. Suitable techniques to study the impact of different developments occurred in the power system on the reliability indices are illustrated in third part. Numerical results of calculated indices obtained by proposed techniques are illustrated in fourth part. Finally, paper conclusion is presented at fifth part.

2. Power network reliability

Reliability of any equipment defines equipment ability performing task assigned to it and so, power network reliability defines ability of power network supplying required loads connected to it according to the associated standards. For calculating power network reliability indices, two approaches can be utilized including analytical and numerical approaches [25]. Analytical methods, reliability models of subsystems are developed and overall reliability indices through mathematical relations are obtained. However, in simulation-based methods that are usually performed using of the Monte Carlo technique, reliability indices are obtained through simulation of possible states of system. Reliability assessment of power network in generation level constructs capacity outage probability table (COPT) for each generation unit. In COPT, different production capacities of generation plants and related probabilities are determined. Load can be presented by the load duration curve. In power network adequacy, generation plants and system load are connected to common bus. Associated indices are calculated by convolving models of power plants and load. Important indices calculated in adequacy assessment of generation network include loss of load expectation (LOLE), expected energy not supplied (EENS), peak load carrying capability (PLCC) and increase in peak load carrying capability (IPLCC). These indices are time horizon of load curtailment, value of curtained energy, value of load supplied when reliability criterion is in permissible range and value of increased PLCC when new power plant is added to system, respectively.

3. Proposed techniques for reliability assessment

In this section, for evaluating reliability of generation system considering impact of integration of the renewable resources, energy storage systems, CHP units into power network and demand response programs, suitable techniques are proposed.

3.1. Integration of the renewable resources

Due to uncertainty nature of renewable energies, reliability model of generation plants and conventional units is different. Produced power of renewable generation units including wind farms, photovoltaic panels, wave energy conversion systems, barrage-kind and current-kind tidal generation units, ocean thermal energy conversion systems and run-of-the-river units are dependent on renewable resources including wind speed, solar radiation intensity, height and period of the waves, tidal height and tidal current speed, ocean temperature and the water flow. Since renewable resources change, generated power of renewable power plants changes. Thus, many states are in generated power of them. For developing multi-state reliability model of renewable power plants, a suitable clustering technique must be utilized to reduce number of states of model. In this research, fuzzy c-means clustering method is implemented. In this approach, number of states must be determined and for this purpose, the XB index is calculated as (1). Optimal cluster number is obtained when XB index is minimal [26]. To determine the suitable clusters and associated probabilities through fuzzy c-means clustering approach, equations (2) and (3) are used [27]:

$$XB = \frac{J_m(U,P)}{\min_{i\neq j}\left(|P_i - P_j|^2\right) \times n} \tag{1}$$

$$J = \sum_{i=1}^{c}\sum_{k=1}^{n} u_{ik}^{m} |x_k - P_i| \tag{2}$$

$$Pr_i = \sum_{k=1}^{n} u_{ik} \tag{3}$$

Where, x_k is produced power of renewable generation units associated to time k, P_i is center of i^{th} power cluster, c is number of reduced power states or clusters, n is number of initial produced power data, m is a parameter for fuzzy modelling (it is real and larger than 1) and u_{ik} is fuzzy degree between x_k and i^{th} power cluster. In this research m is 2.

For determining complete reliability model of renewable generation units, failure of plant must be considered. If the availability of the system is A, and c clusters are determined for the plant using of the clustering algorithm, complete reliability model of plant composed of k generation units would be as presented in Fig. 1. In the model, λ is failure rate, μ is repair rate, $P1$, $P2$, . . . Pc are generation capacities of the clusters.

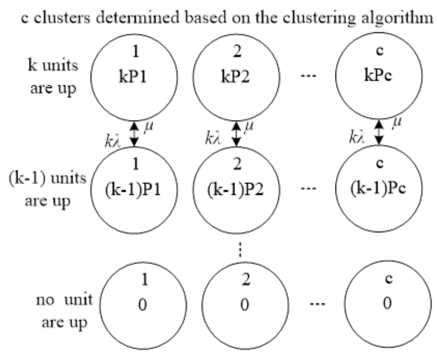

Fig. 1. Complete reliability model of renewable power plants.

For performing adequacy assessment of power network including renewable generation plants, all generation units and loads are connected to a common bus as presented in Fig. 2. The COPTs of the conventional units composed of two states are combined with the COPTs of the renewable energy-based generation units composed of multi states, and the reliability indices are determined. The flowchart of adequacy assessment of power network integrated into renewable generation units presented in Fig. 3.

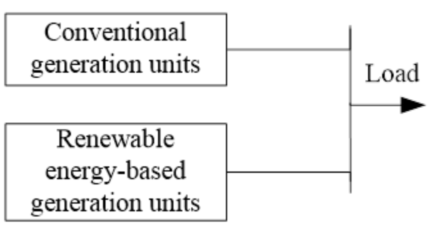

Fig. 2. The adequacy assessment of power network integrated into renewable generation plants.

3.2. Integration of the energy storage systems

In order to make optimum application of renewable resources in power network, various energy storage devices including batteries, capacitors, flywheels, compressed air systems, pumped-storage power plants and electrolyser-hydrogen reservoir-fuel cell are integrated into power network. For reducing uncertainty nature of renewable resources, in low load times, when produced power of renewable power plants is more than required load, the extra generated power stores in energy storage devices. At peak load times, when produced power is less than required demand, energy storage devices can compensate the shortage power required.

The other advantage of the energy storage devices is the economic benefit of them. In times with low load, electricity price is low and in peak load times, electricity is expensive. Using of the energy storage devices, the low cost power is stored in the device and the high cost power is transferred to the load or grid. For assessing impact of energy storage devices on power network reliability, load duration curve of system is modified. In this stage, it is assumed that the energy storage devices store the electricity in the minimum peak load and transfers the electric power in the maximum peak load. Based on this assumption, load duration curve of power system affected by energy storage system

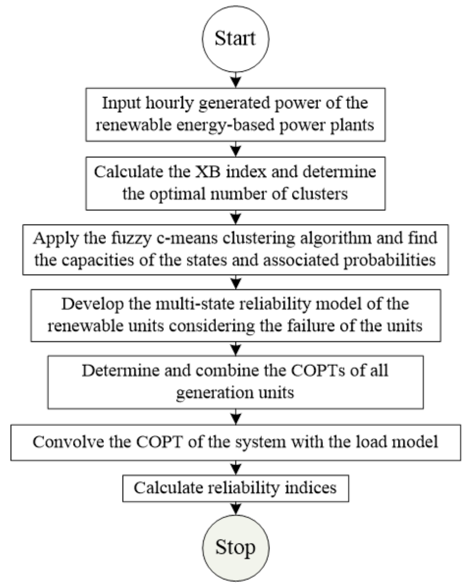

Fig. 3. Flowchart for adequacy assessment of power network including renewable resources.

is modified as presented at Fig. 4 Pc is power stored in energy storage devices and Pg is power transferred to the grid by energy storage devices. Due to the losses associated to the energy storage devices, the efficiency of store/generation is less than 100%. Thus, the Pg is less than the Pc, $i.e.Pg = \eta Pc$. The reliability indices of the generation systems including the energy storage systems can be calculated using of the modified load model.

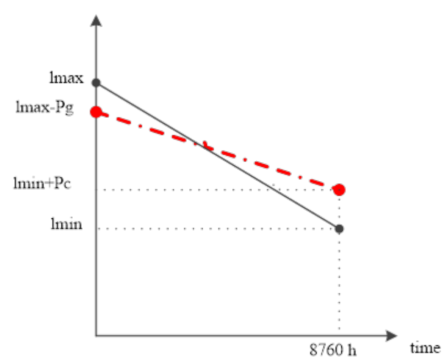

Fig. 4. The load duration curve affected by the energy storage device.

3.3. Integration of CHP

In order to make optimum use of the heat generated in the thermodynamic cycle of the thermal power plants, the CHP units are developed. Conventional thermal generation units dissipate thermal power generated in thermodynamic cycle in cooling tower or other equipment and the efficiency of the power plant is low. However, in the CHP units, the thermal power generated in the plants is conducted to the heat exchangers to produce steam or hot waters used in heating purposes. For this reason, efficiency of CHP plants is high. To study impact of CHP unit on power network reliability, reliability models considering both the electrical and the thermal powers generated in the plant are developed for these units as illustrated in Fig. 5. P and Q presented in the model are electrical and thermal powers generated by the unit. Transition rates between proposed states are summation of failure rates of elements resulted in the associated transition. Probabilities associated to states are obtained by equation (4):

$$\begin{array}{l} P_1(\lambda_{12}+\lambda_{13}+\lambda_{14}) = P_2\lambda_{21}+P_3\lambda_{31}+P_4\lambda_{41} \\ P_2(\lambda_{24}+\lambda_{23}+\lambda_{21}) = P_3\lambda_{32}+P_1\lambda_{12}+P_4\lambda_{42} \\ P_3(\lambda_{31}+\lambda_{32}+\lambda_{34}) = P_1\lambda_{13}+P_2\lambda_{23}+P_4\lambda_{43} \\ P_4+P_3+P_2+P_1 = 1 \end{array} \quad (4)$$

To calculate reliability indices of power network containing CHP units, in addition to electrical power produced by CHP unit, impact of thermal power Q generated by the unit is considered with the equivalent electrical power PQ, $i.e.$ a power plant is integrated to the power system with the capacity of the $PQ = Q/\eta$, where, is the energy conversion efficiency (the efficiency of a device that converts the electrical power PQ to the thermal power Q). For determining reliability indices of power network containing CHP plants, COPTs related to conventional plants are combined with COPTs of the CHP plants and the total COPT is constructed. Then, the reliability indices are obtained.

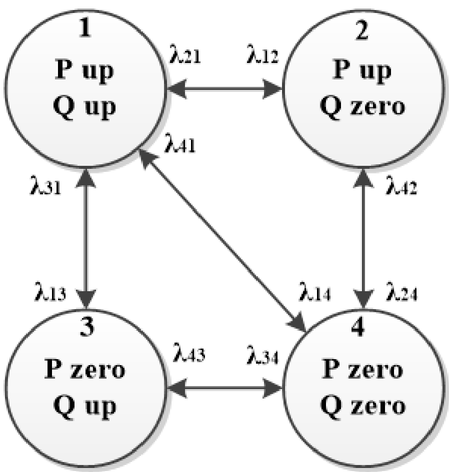

Fig. 5. Reliability model associated to CHP plants.

3.4. Impact of demand response program

Demand response program is a demand-side management method to reduce peak demand of network. According to the program, electricity customers are encouraged to shift their flexible load consumption from the peak load times to the low load times. The reason that causes customers shift related consumption from peak times to low load times is economic advantage of this because electricity prices are cheaper during low loads than during peak loads. For assessing impact of demand response program on power network reliability, load duration curve is modified as illustrated in Fig. 6. The figure presents due to participation of customers in demand response program of PDR, peak demand of network reduces by PDR and minimum load of network increases by PDR. In this figure, PDR is the power of loads participated in demand response program.

4. Numerical Results

Impact of new development in power system on reliability indices of test networks including Roy Billinton test system (RBTS) and IEEE reliability test system (IEEE-RTS) is investigated, in this part.

4.1. The characteristics of the understudied systems

The RBTS composed of the 11 generation units with $240MW$ generation capacity. Characteristics of power plants are illustrated in [28]. IEEE-RTS is a large-scale network that characteristics of its generation units are given in [29]. Load duration curve is a

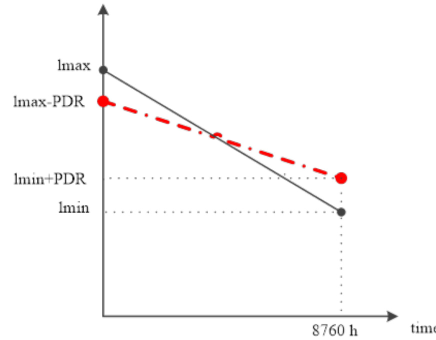

Fig. 6. The load duration curve affected by the demand response program.

Table 2. The clustering result.

Capacity (MW)	4.7	14.3	27.9
Probability	0.3989	0.3610	0.2401

straight line extends from one hundred to sixty percent of peak demand. One $30MW$ renewable energy-based generation unit with availability 0.98 is considered in the research. Output power of the unit is considered to be as presented in Fig. 7.

According to the proposed technique, XB index for different number of states is illustrated in Fig. 8. The figure presents that XB index is minimal at 3 clusters and so, the optimal number of clusters for this generation unit would be 3. The capacities of these three states and the associated probabilities are calculated and presented in Table 2. Considering the availability of the renewable energy-based generation unit, the complete reliability model of the understudied renewable generation unit is determined and Table 3 presents it.

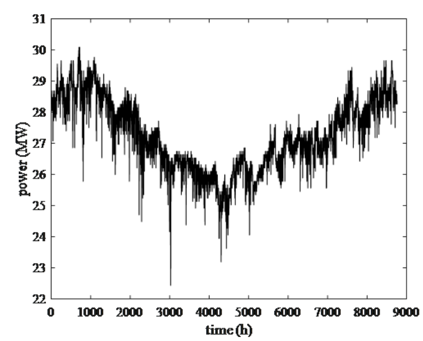

Fig. 7. Hourly output of renewable energy-based power plant.

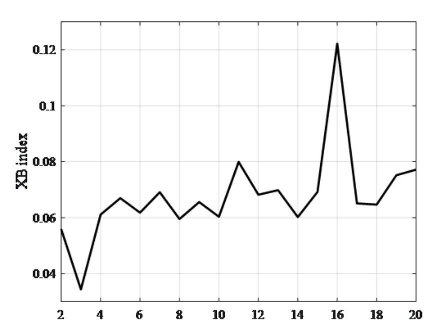

Fig. 8. XB index considering number of states.

Table 3. The reliability model of the renewable generation unit.

Capacity (MW)	0	4.7	14.3	27.9
Probability	0.02	0.3909	0.3538	0.2353

Table 4. Transition rates among states of understudied CHP unit.

Transition rate	Amount (number per hour)	Transition rate	Amount (number per hour)
State 1 to state 2	0.000114	State 2 to state 3	0
State 2 to state 1	0.01	State 3 to state 2	0
State 1 to state 3	0.000114	State 2 to state 4	0.000456
State 3 to state 1	0.02	State 4 to state 2	0.0180
State 1 to state 4	0.000342	State 3 to state 4	0.000456
State 4 to state 1	0.0174	State 4 to state 3	0.0147

In this stage, an energy storage device based on the pumped-storage power plant is taken into consideration. Output of unit, when water of upper reservoir is released, is considered to be $30MW$ and due to the plant efficiency of 80%, the consumed power of the plant for pumping water from lower reservoir to upper basin would be $37.5MW$. For study effect of CHP units on power system reliability, a $30MW$ CHP plant is taken into consideration. The generated thermal power of the plant is considered to be equivalent to a $24MW$ power plant. transition rates among different states of model are considered to be as presented in Table 4. Based on the relation (4), probabilities of states associated to reliability model are calculated and presented in Table 5.

4.2. The results of the simulations

According to the proposed techniques, reliability evaluation of test systems is performed and impact of renewable resources, energy storage devices, CHP units and demand response programs on reliability indices is assessed. In this regard, five case studies are taken into consideration: case study I is original RBTS and cases II to IV, respectively the understudied renewable generation unit, the understudied CHP and the understudied energy storage device are integrated to the RBTS. In case V, it is assumed that 10% of the loads are participated in the demand response program. LOLE and EENS related to these case studies with different demands are obtained and illustrated in Figs. 9 and 10. The figures present all developments occurred in power network result in enhancement of reliability indices of power network. PLCC of case studies are determined and illustrated in Table 6. Besides, IPLCC related to case studies II to V are determined and presented in Table 7.

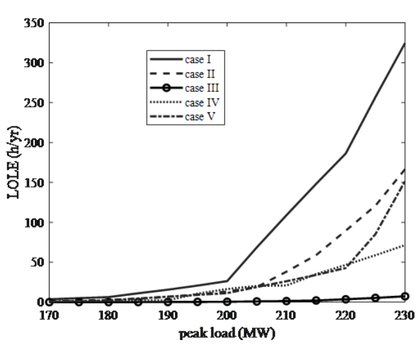

Fig. 9. LOLE at different peak demand.

Fig. 9 and 10 present increase in peak demand leads to increase in LOLE and EENS as reliability indices of power system. However, addition of renewable unit, CHP plant and energy storage device to the RBTS results in reduction of LOLE and EENS.

Table 5. Reliability model of understudied CHP unit.

States	1	2	3	4
Probability	0.9605	0.0223	0.0103	0.0069

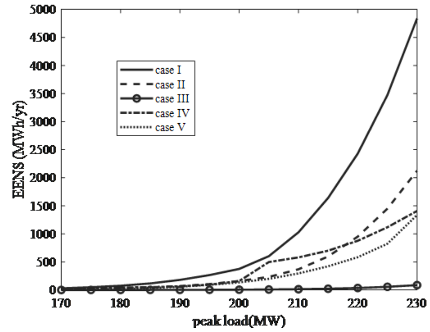

Fig. 10. EENS at different peak demand.

Table 6. PLCC of different cases.

Cases	I	II	III	IV	V
PLCC (MW)	180	190	230	195	195

Besides, as can be seen in the figures, demand response program reduces LOLE and EENS indices. Among these cases, addition of CHP units to the power system make significant reduction of LOLE and EENS comparing to other three cases. It is clearly seen from Tables 6 and 7. These tables present according to the reliability criteria, the peak load that can be provided by case III is $230MW$, while the value for other cases is less than this amount. In order to further investigate the impact of demand response program on reliability of power system, in this stage, various percent of loads are considered to participate in demand response program and PLCC and IPLCC of them are computed and presented in Table 8. As can be seen from this table, increase in loads that participate in demand response program leads to increase in PLCC and IPLCC of the electric network.

In this part, the adequacy assessment of IEEE-RTS with impact of renewable energy-based resource, the pumped-storage power plant, the CHP plant and the demand response program is performed. For this purpose, five cases are taken into consideration: case study I is original IEEE-RTS, and at case studies II to IV, understudied renewable generation unit, the understudied CHP and the understudied energy storage device are integrated to the RBTS. In case V, it is assumed that 10% of the loads are participated in the demand response program. LOLE and EENS related to these five cases for peak load of $2850MW$ are determined and illustrated in Table 9. This table presents new developments in power network results reliability of power network improves. As can be seen from this table that integration of renewable resources, CHP units and energy storage devices leads to reduction of LOLEE and EENS indices. Besides, participation of loads in demand response program reduces the LOLE and EENS indices. However, among different cases, addition of CHP unit to IEEE-RTS significantly improve the reliability indices of power system.

4.3. Comparison with Monte Carlo method

In this section, to verify the analytical methods proposed to determine reliability indices of power system containing renewable resources, CHP units, energy storage devices and demand response

Table 7. The IPLCC of different cases.

Cases	II	III	IV	V
PLCC (MW)	10	50	15	15

Table 8. PLCC and IPLCC related to demand response program.

Percent of loads participated in demand response program	10	15	20	25	30
PLCC (MW)	195	202	209	215	220
IPLCC (MW)	15	22	29	35	40

Table 9. Reliability indices of IEEE-RTS.

Cases	I	II	III	IV	V
LOLE (h/yr)	112.9	104.4	82.6	100.3	31.9
EENS (MWh/yr)	16984	15548	11884	14756	3807

Table 10. PLCC of different cases of RBTS calculated by two methods.

Cases	I	II	III	IV	V
Proposed method	180	190	230	195	195
Monte Carlo method	176	185	221	188	187
Error %	2	3	4	4	4

program, a comparison between the proposed method and Monte Carlo simulation approach is carried out. For this purpose, at each time, in MATLAB software, a random number is generated for each unit to determine the condition (up or down states) of the unit. The hourly data associated to generated power of renewable resource presented in Fig. 7, and IEEE pattern of load [presented in Fig. 11, are applied. By 1000 times repetition the Monte Carlo simulation for RBTS and 100 times for IEEE-RTS, the reliability indices are calculated and presented in Tables 10 and 11. In these tables, also, the reliability indices calculated by proposed method and the error between Monte Carlo method and analytical approach are given. It is concluded from these tables that the reliability indices calculated by analytical and Monte Carlo methods are almost the same, and thus, the accuracy of the proposed method is verified.

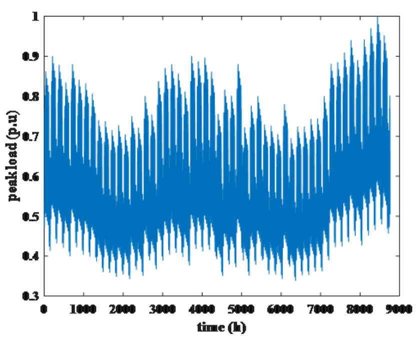

Fig. 11. Hourly peak load in per unit.

5. Conclusion

This research studies the impact of recent developments occurred in electric network including integration of renewable power plants, the use of energy storage devices, utilization of combined heat and electricity plants and demand response programs, on reliability of modern power network. A multi-state reliability model considering failure of assembled components and variation of output power is developed for renewable resources through fuzzy c-means clustering and XB index. Besides, to study impact of energy storage devices and demand response program, load duration curve of system is modified. Thus, minimum demand increases and peak demand is decreased according to function of energy storage system or demand response program. A reliability model composed of 4 states is constructed for CHP units and participation of these plants in thermal power generation is considered in the model. To evaluate effect of these developments on reliability indices of power network, analytical approach based on COPT is utilized.

According to reliability evaluation of RBTS and IEEE-RTS, all four developments have a positive impact on reliability indices of power networks and lead to improvement of reliability indices of modern power networks including PLCC, EENS, LOLE and IPLCC improve. Numerical results presents integration of renewable resources, CHP units, energy storage devices and demand response program enhances reliability indices of electric network. However, addition of CHPM units to the power network significantly improves the reliability indices comparing to other cases. For verification the proposed analytical method, a comparison between this method and Monte Carlo simulation approach is performed. It is deduced from this comparison that the proposed method with good accuracy can compute reliability indices of power system containing renewable resources, CHP units, energy storage devices and demand response program. Comparing to the Monte Carlo method, the proposed analytical approach has several advantages including less computation volume, less required memory and less calculation time.

Table 11. EENS (MWh) of IEEE-RTS calculated by two methods.

Cases	I	II	III	IV	V
Proposed method	16984	15548	11884	14756	3807
Monte Carlo method	16302	15258	11478	14109	3675
Error %	4	2	3	4	4

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