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Operation Studies of the Power Systems Containing Combined Heat and Power Plants

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Abstract- *In today's power systems, the use of methods that can increase the energy efficiency and reduce the cost of the generated energy has received much attention. One of these methods is the use of the combined heat and power (CHP) plants that simultaneously can generate the electric and thermal powers. In the conventional thermal power plants, the thermal energy of the working fluid coming out from the turbine is dissipated that result in low efficiency. However, it can be used for the heating purposes in the CHP units that result in the high efficiency of these plants. Due to the wide use of the CHP units in the power system, different aspects of the power system such as operation may be affected that must be studied. In this paper, the study of the power system operation integrated with the CHP plants is performed. For this purpose, the PJM method that considers the reliability-based indices such as unit commitment risk is utilized. Moreover, a four-state reliability model is developed different types of the CHP units including gas turbine, steam turbine, reciprocating engine, micro-turbine and fuel cell technologies. In the proposed model, both the failure of composed components and the participation of the CHP units in the thermal power generation are considered. To determine the probabilities of different states of the proposed model, matrix multiplication technique is used. Based on the PJM technique, the numerical results associated to the operation studies of the RBTS and IEEE-RTS that are given and the unit commitment risk and the required spinning reserve of these systems calculated considering the effect of the CHP units.*

Keyword: Combined heat and power, reliability, operation, PJM method, spinning reserve.

1. INTRODUCTION

Attention made to use different techniques that can improve the energy efficiency and consequently decrease the cost of generated electricity due to the emergence of electricity markets and the competitiveness of electricity companies in producing cheaper electricity.

The CHP plants simultaneously are increasingly used in the power system and they can produce the electricity and thermal energy. They may affect different aspects of this system such as operation. Thus, in this research, the operation studies of the power system considering the impact of different types of the CHP units including gas turbine, steam turbine, reciprocating engine, micro-turbine and fuel cell technologies are performed. To study the impact of these plants on the power system because of the importance of the CHP units in that, earlier researches have been made. In Ref. [1], optimal allocation of CHP units in the urban energy distribution systems is performed using of the integrated system dispatch model. In this paper, the models of the electricity, water and gas networks are developed individually and the CHP-based distributed generation model is constructed to couple these energy distribution networks. In Ref. [2], the time-domain model of grid-connected CHP units is developed for interconnection of these plants with the power grid. In this paper, a nonlinear dynamic model based on the mass and energy balance theorem that can effectively simulate the thermodynamic interaction of the CHP units is developed for these units and the effect of the CHP plants on the power system is investigated. The main components of the CHP plants including gas internal combustion engine, synchronous generator, waste heat exchanger, water storage tank, exhaust-heat boiler and gas fired boiler are studied in this paper. In Ref. [3], the energy management technique based on the game theory approach for joint operation of the CHP units and the

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photovoltaic systems associated to a grid-connected micro-grid is introduced. In this paper, a multiparty energy management structure based on Stackelberg game is proposed to optimally perform the operation of the micro-grid considering the internal price-based demand response. In this method, micro-grid operator acts as the leader and the photovoltaic prosumers are the followers. To solve the obtained problem, the heuristic algorithm based on differential evolution is proposed and the nonlinear constrained programming is adopted by each prosumer to reach the Stackelberg equilibrium. In Ref. [4], the operational flexibility constrained intraday rolling dispatch strategy is proposed to study the operation of the CHP plants in the micro-grids including the renewable resources such as wind power and photovoltaic cell. In this paper, an operational flexibility metric to quantify the ability of the CHP units-based micro-grid to overcome the uncertainties associated to the renewable resources in the operation phase is proposed that consists of a dispatch decision stage and a real-time adjustment stage based on the nonlinear programming model. In Ref. [5], different technologies associated to the CHP units caused by wide integration of renewable resources in the power system, feed-in tariffs for the renewable energies, the implementation of market mechanism and the incremented requirement in the energy efficiency and flexibility of the power plants, are introduced. In this paper, new opportunities and conditions associated to the district heating and power system cooperation through the use of district heating flexible technologies including power to heat technologies such as electric boilers and heat pumps are discussed. In Ref. [6], the operational strategies for a portfolio of CHP units and wind farms in a two-price balancing market are proposed. In this paper, to increase the overall profit of the portfolio, the imbalances and their implicit penalty in a two-price balancing market for the electricity are reduced. A comprehensive mathematical model is developed to describe the different heat and power generation plants of the CHP unit and propose different methods to determine its operation in setup with day-ahead and balancing markets. In Ref. [7], a new operation optimization model of the CHP units is suggested in the deregulated energy markets considering real time energy prices. In this paper, both overall efficiency of the CHP units and the heat to electricity ratio that are closely linked with the loading level are dynamically determined. To determine the optimal real-time operation strategies of the CHP units, a discrete optimization method is proposed and solved by the interior point method with discrete time intervals. In Ref. [8], the CHP units model composed of three main components including generator, turbine and absorption chiller is developed in Simulink. In this study, to provide zero steady-state error frequency regulation and the impact of the ambient temperature on the maximum electrical output is investigated and a new isochronous governor control strategy is suggested. In Ref. [9], the optimal configuration of the CHP units based on the reliability criteria is determined using of the stochastic programming approach. In this paper, the number and size of the composed components of the CHP units including CHP units, auxiliary boilers and heat-storage tanks are optimally determined using of the scenario tree method based on the Monte Carlo sampling approach. In Ref. [10], the online energy management of the grid-connected micro-grids including the CHP units and the energy storage systems is performed. The micro-grids are considered to include renewable resources, local c-generators with CHP supply, the electricity and heat energy storage systems such as battery and thermal tank, the centralized power grid and external natural gas station. In this paper, the operation cost of the aggregate micro-grid is minimized using the stochastic non-convex optimization programming method.

In Ref. [11], based on the improved prepared power demand table and λ-logic algorithm, a fast and new analytical non-iterative method is proposed to solve the unit commitment and the economic dispatch problems of the power system. The proposed method results in the simplification of the unit commitment problem and obtaining minimum operation cost. However, in this paper, the CHP units are not considered in the operation studies of the power system. In Ref. [12], the impact of demand response program on the operation studies of the multi-carrier micro grid is considered. In the proposed model, a micro grid containing the electricity and natural gas networks is considered and to perform the operation studies of this grid, a novel demand side management which the energy tariff for flexible loads are correlated to the energy input of the network and changes instantly is proposed. In this paper, the impact of the energy storage system, small-scale energy resources such as photovoltaic arrays and CHP units, flexible loads and the natural gas network on the operation of the micro grid is considered. However, in the proposed operation studies of the micro grid, the reliability criteria are not considered. In Ref. [13], the resilient operation scheduling of the micro grids including the electric vehicles and flexible loads is performed using of the stochastic programming method.

In this paper, to model the uncertainties associated to the renewable resources, responsive loads and electrical vehicles, the scenario based framework as stochastic programming method is proposed to anticipate and limit the risks of the system under changing conditions. However, the impact of the CHP units on the operation studies of the understudied micro grid is not considered. In Ref. [14], to optimally perform the operation studies of the distribution networks including the retailers and micro grids, a new approach based on the bi-level optimization method is proposed. In this paper, the multi-objective particle swarm optimization algorithm, is used to optimize the profit of retailers and the cost of micro grids as two aims of the upper level and lower level problems of the understudied distribution networks. However, in this paper, the large-scale CHP units and the reliability criteria of the power system are not considered.

In Ref. [15], a copula-based uncertainty modelling approach is used to perform the optimal energy management of the micro grids in day-ahead and intra-day markets. In this paper, to model the uncertainty nature associated to the renewable resources such as wind and photovoltaic units, mathematical formulation of a grid-connected micro grid containing wind turbine, photovoltaic system, micro turbine, fuel cell and energy storage system is presented. The objective function of the paper is considered to be the operational cost and environmental pollution of the micro grid and the impact of the CHP units and the reliability criteria are not investigated. In Ref. [16], a new method based on the mixed integer programming is suggested to perform the stochastic short-term hydro thermal scheduling in a power system including volatile wind power generation. In this paper, different uncertainties including energy price, spinning and non-spinning reserve prices and variation in the renewable resources such as the generated power of wind turbines are taken into account. However, the impact of the CHP plants and also the reliability-based operation studies are not considered in this paper. In Ref. [17], an approach based on the interval type-2 fuzzy is used to model the uncertainties associated to the operation planning of the wind farms with pumped storage plants. In this paper, different uncertainties including load, operating reserve and the output power of wind farms are taken into account using of the proposed stochastic and fuzzy method. However, the reliability-based operation studies of the power system including the CHP units are not performed in the reviewed papers.

In this paper, the operation studies of the power systems including large-scale CHP units are performed using the PJM method. For this purpose, a four-state reliability model of different types of the CHP plants suitable for short-term studies is developed considering the failure of composed components and the participation of the CHP units in the thermal power generation. Matrix multiplication method is proposed to determine the probabilities of different states of the CHP units. Thus, the contributions of this paper as follows:

A four-state model is developed for different types of the CHP units including gas turbine, steam turbine, reciprocating engine, micro-turbine and fuel cell technologies. In the proposed model, the failure of composed components and the participation of the CHP units in the thermal power generation are considered.

The proposed reliability model is modified to be suitable for operation studies of the power system.

To determine the probabilities of different states of the reliability model of the CHP units, the matrix multiplication technique is utilized.

To calculate the unit commitment risk of the power system including CHP units, the PJM approach is modified to consider the multi-state reliability model of the CHP units.

The impact of the CHP units on the operation studies of the power system and reliability-based indices such as unit commitment risk and spinning reserve is investigated.

The aim of this paper, is to organize as below: in the second section, different types of the CHP units and the reliability model of these plants is developed. The proposed method based on the PJM technique and matrix multiplication approach, for operation studies of the power system including the CHP units is introduced in the third section. The numerical results associated to the operation studies of the RBTS and IEEE-RTS containing the CHP units are given in the fourth section. The paper is summarized in the fifth section.

2. RELIABILITY MoDELING OF THE CHP PLANTS IN THE OPERATION STUDIES

In the CHP plants electrical and thermal energy are simultaneously produced and so, the efficiency of these units is more than the efficiency of the traditional thermal power plants that the thermal energy of the working fluid coming out from the turbine is dissipated. Because of the energy efficiency of the CHP units, the greenhouse gas emission such as CO2, SO2 and NOX, of these units is less than the conventional thermal power plants with the same size. Thus, the energy efficiency, low greenhouse gas emission and the low cost of the generated energy result in the wide installation of different types of the CHP units in the power system. The different prime movers of the CHP pants are steam turbine, gas turbine, micro-turbine, reciprocating engine and the fuel cell technologies. In this part, the structure and the composed components of these technologies are described. The structure of the CHP units based on the steam turbine is similar to the steam thermal power plant, the difference is that in the CHP plants, instead of wasting steam heat coming out from the turbine, it is used for heating purposes and so, the efficiency of the CHP units are improved. In Fig. 1, the structure and the composed components of the CHP units based on the steam turbine including boiler, turbine, generator, transformer, heat exchanger and control system are presented. The water enters the boiler and is converted to the steam. Then, the steam enters the turbine and rotates the turbine and the generator connected to the turbine and generates the electricity. The steam coming out from the turbine can be used in the heat exchanger for the heating purposes.

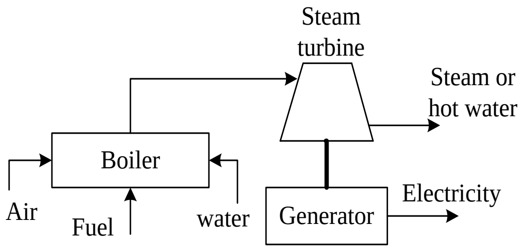

Fig. 1. The structure of the CHP units based on the steam

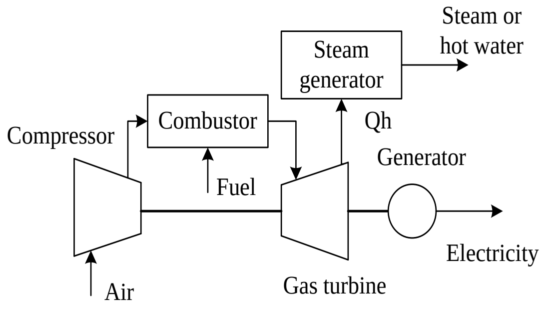

Fig. 2. The structure of the CHP units based on the gas turbine

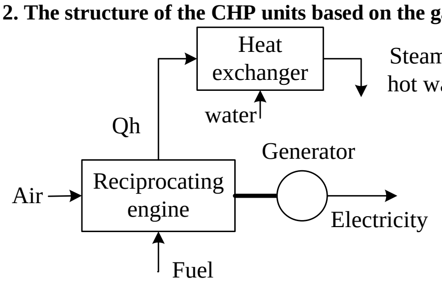

Fig. 3. The structure of the CHP units based on the reciprocating engine

The structure of the CHP units based on the gas turbine is similar to the gas power plant, the difference is that in the CHP plants based on the gas turbine, instead of the wasting the outlet turbine heat, it is used to generate steam or hot water for the heating purposes. Thus, the energy efficiency of the CHP units is more than the gas power plants and consequently the gas emission and the cost of the energy of the CHP units are less than the traditional gas power plants. The structure and the composed components of the CHP plants based on the gas turbine including compressor, combustion chamber, gas turbine, heat exchanger, generator, transformer and control system are presented in Fig. 2. In these units, the air is compressed in the compressor and then, the high-pressure air enters the combustion chamber with the fuel and the combustion is occurred results in the hot and high-pressure mixture that enters the turbine and generates the electricity. The turbine outlet heat enters the heat exchanger and can be used for the heating purposes.

The structure of the CHP units based on the reciprocating engine is similar to the reciprocating engine, the difference is that in the CHP units based on the reciprocating engine, the engine outlet heat enters the heat exchanger and is used for the heating purposes. Thus, the energy efficiency of the CHP units based on the reciprocating engine is more than the traditional reciprocating engine. The structure and the composed components of the CHP units based on the reciprocating engine including reciprocating engine, generator, transformer, heat exchanger and control system are presented in Fig. 3. In these units, the air enters the reciprocating engine with the fuel and the combustion is occurred. Thus, the piston moves I the cylinder and a reciprocating motion is produced that is converted to the rotational motion results in the rotation of the generator to generate the electricity. The engine outlet heat enters the heat exchanger and is used for the heating purposes.

The structure of the CHP units based on the micro-turbines is similar to the traditional micro-turbines, the difference is that in the CHP units based on the micro-turbine, the turbine outlet heat enters the heat exchanger and is used for the heating of the compressor outlet air and the other heating purposes such as generating the steam or hot water. In Fig. 4, the structure and the composed components of the CHP units based on the micro-turbine including compressor, turbine, generator, transformer, heat exchanger, combustion chamber and control system are presented.

The structure of the CHP units based on the fuel cell technology is similar to the fuel cell, the difference is that in the CHP units based on the fuel cell, the heat produced in the fuel cell is used for the heating purposes. The structure and the composed components of the CHP plants based on the fuel cell including water electrolysis device, hydrogen reservoir, fuel cell, electrical converter and heat exchanger are presented in Fig. 5. In the CHP units based on the fuel cell, the electric power generated by different renewable resources such as photovoltaic system or wind turbines, or the power of the grid enters the water electrolysis system that leads the water is decomposes into oxygen and hydrogen. The hydrogen can be stored in the hydrogen reservoir and, when required it enters the fuel cell with the air, which includes the oxygen. In the fuel cell, the combination of the hydrogen with the oxygen is occurred and so, the electricity and the thermal energy are produced. The generated thermal energy can be used for the heating purposes.

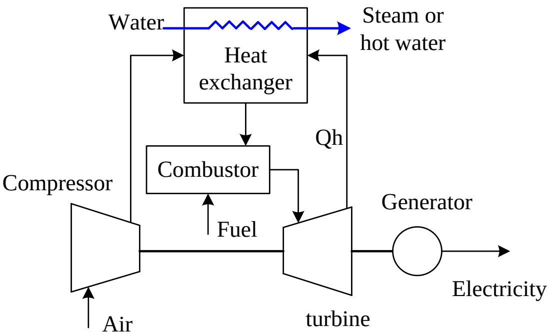

Fig. 4. The structure of the CHP units based on the micro-turbine

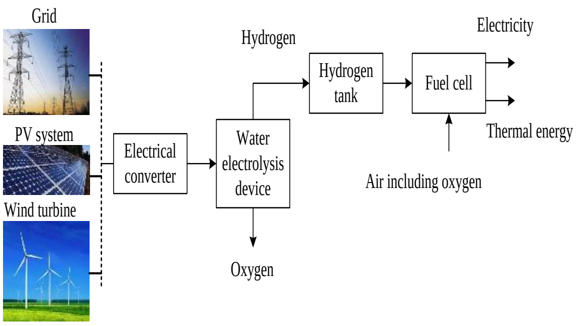

Fig. 5. The structure of the CHP units based on the fuel

To perform the operation studies of the power systems including the CHP plants, a four-state reliability model is developed for these units considering the failure of composed components and the participation of CHP units in the thermal power generation. A Markov model with two states including up and down states (presented in Fig. 6) is considered for each component of the CHP units. The transition rate from the up state to the down state is presented by the failure rate (λ) and the transition rate from the down state to the up state is presented by the repair rate (μ) [11].

To present the effect of the CHP plants that generate both electrical (P) and thermal (Q) powers, a four-state reliability model can be used to describe these units that are presented in Fig. 7. As can be seen in the figure, in the state 1, the unit can generate both electrical and thermal power and all components are perfect. In the state 2, the unit can generate and transfer the electrical power, but, the thermal generated power is zero or the unit cannot transfer the thermal power to the load. In this state, the components of the electrical part are perfect, but, one or more of the components of the thermal part are failed. In the state 3, the unit can produce the thermal power and transfer it to the load, but, the generated electrical power is zero or the unit cannot transfer the electrical power to the grid. In this state, one or more of the components of the electrical part are failed and all components of the thermal part are perfect. In the state 4, both the electrical and thermal power are zero or cannot be transferred to the load or grid. In this state, one or more components of the system that are common in electrical and thermal parts of the unit are failed or both the components of the electrical and thermal parts are failed.

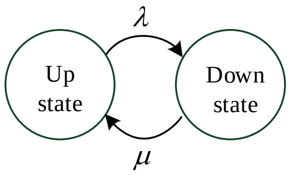

Fig. 6. The 2-state Markov model of components

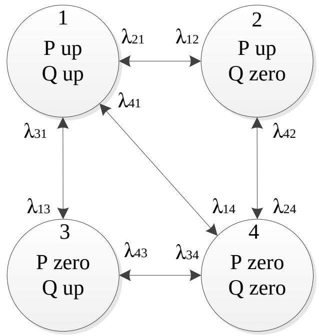

Fig. 7. The four-state reliability model of CHP plants

In the proposed model, for determination the transition rates between different states, the failure rates associated to the components that are effective in transmitting between states are added together based on the following relation:

$$\lambda_{ij} = \sum_{k=1}^{n} \lambda_k \tag{1}$$

Where, λij is the transition rate from state i to state j and the λk is the failure rate associated to the component k that leads the transition from state i to state j is occurred. If the failed components that leads the transition from state with higher capacity to the state with lower capacity is occurred, are repaired, the transition from the lower capacity state to the higher capacity state is occurred. Thus, to calculate these transition rates, the repair rate of the series components as relation (3) can be utilized:

$$\lambda_{ji} = \frac{\lambda_{ij}}{\sum_{k=1}^{n} \frac{\lambda_k}{\mu_k}} \quad (2)$$

In Table 1, the components that their failure results in the transition between different states of the reliability model of different CHP units are presented. To calculate the probabilities of different states of the reliability model of the CHP unit, the transition rates between different states are obtained and based on the following relations the associated probabilities are determined:

$$\begin{aligned} &P_1(\lambda_{12}+\lambda_{13}+\lambda_{14}) = P_2\lambda_{21}+P_3\lambda_{31}+P_4\lambda_{41} \\ &P_2(\lambda_{21}+\lambda_{23}+\lambda_{24}) = P_1\lambda_{12}+P_3\lambda_{32}+P_4\lambda_{42} \\ &P_3(\lambda_{31}+\lambda_{32}+\lambda_{34}) = P_1\lambda_{13}+P_2\lambda_{23}+P_4\lambda_{43} \\ &P_1+P_2+P_3+P_4 = 1 \end{aligned} \quad (3)$$

In the operation assessment of the power system, due to the short time of the studies, the repair cannot be performed and so, it is neglected from the repair rates in the reliability model of the CHP units. Also, at the beginning of the operation studies, all components are assumed to be perfect and so, the CHP unit is in the state 1. Based on the assumption of the Markov model, during the short time of the operation studies of the system, only one component may fail and so, the reliability model of the CHP units suitable for operation studies can be as presented in Fig. 8.

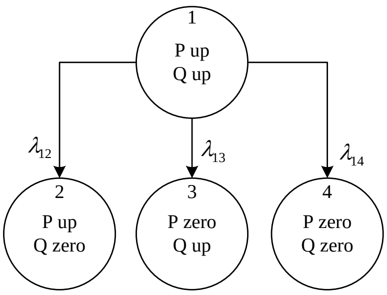

Fig. 8. The reliability model of CHP plants suitable for operation studies

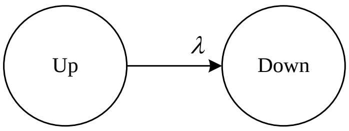

Fig.9. the reliability model of conventional unit for operation studies

3. OPERATION STUDIES OF THE POWER SYSTEMS INCLUDING THE CHP UNITS

In this part, the modified PJM method is introduced to study the operation of the power system including the CHP units. In the PJM method, the conventional generation units are presented with a two-state Markov model as presented in Fig. 9. In this model, the repair rate is neglected and the probability of down state for the study time T can be calculated as:

$$P_{down} = \lambda T \quad (4)$$

To determine the probabilities of four states of the CHP unit reliability model, matrix multiplication technique is proposed. In this method, based on the modified PJM approach, a matrix named stochastic transitional probability matrix (STPM) is constructed for the CHP unit that presents the transition between different states of the CHP unit model. For the CHP unit model presented in Fig. 8, the associated STPM for study time Δt can be determined as:

$$STPM = \begin{bmatrix} 1-(\lambda_{12}+\lambda_{13}+\lambda_{14})\Delta t & \lambda_{12}\Delta t & \lambda_{13}\Delta t & \lambda_{14}\Delta t \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

The probabilities of four states of the CHP units for the study time T are calculated based on the matrix multiplication technique as presented in follow relation:

$$[P(T)] = [P(0)][STPM]^{\frac{T}{\Delta t}} \quad (6)$$

Where, [P(T)] is a matrix including a row and 4 columns that presents the probabilities of four states of the model for study time T, [P(0)] is initial probabilities matrix including a row and 4 columns that presents the probabilities of the four states at the beginning of the study. All components are assumed to be perfect at the beginning of the study and so, this matrix would be as:

$$[P(0)] = [1\ 0\ 0\ 0] \quad (7)$$

Table. 1. The effect of composed components on the failure of different CHP units

Ttechnologies Components	Gas turbine	Steam turbine	Micro-turbine	Reciprocating engine	Fuel cell
Compressor	1-4, 2-4		1-4, 3-4	-	-
Turbine	1-4, 2-4	1-4, 2-4	1-4, 3-4	-	-
Combustion chamber	1-4, 2-4		-	-	-
Heat exchanger	1-2, 3-4	1-2, 3-4	1-4, 3-4	1-2, 3-4	1-2
Generator	1-3, 2-4	1-3, 2-4	1-3	1-3, 2-4	-
Transformer	1-3, 2-4	1-3, 2-4	1-3	1-3, 2-4	-
Water electrolysis device	-	-	-	-	1-4, 2-4
Hydrogen reservoir	-	-	-	-	1-4, 2-4
Fuel cell	-	-	-	-	1-4, 2-4
electrical converter	-	-	-	-	1-4, 2-4
Control system	1-4, 2-4	1-4	1-4, 3-4	1-4, 2-4	-
Reciprocating engine	-	-	-	1-4, 2-4	-
Boiler	-	1-4, 2-4	-	-	-

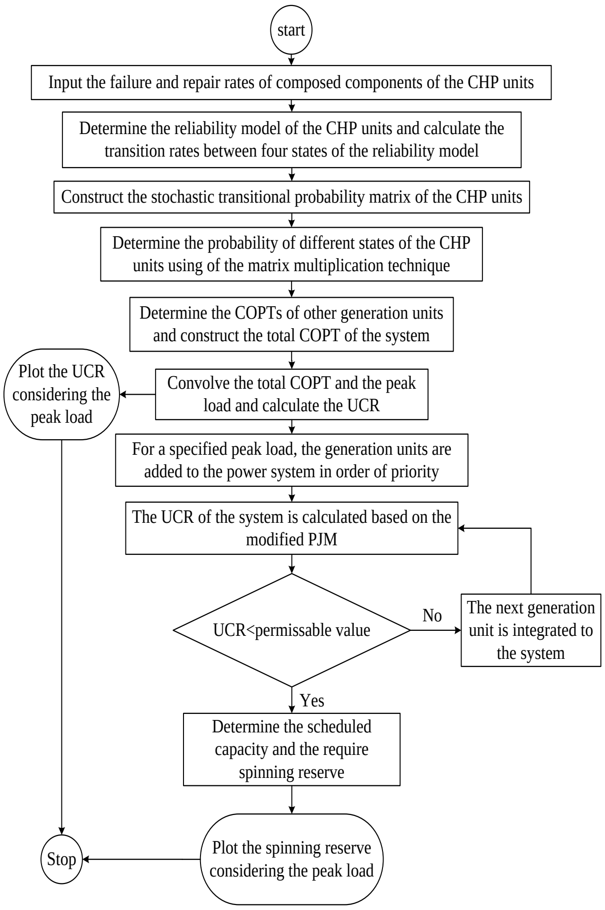

Fig.10. the flowchart of the proposed method

To determine the probabilities of the four states of the CHP unit model for the study time T, this time is divided to n time steps with duration Δt, i.e. T=n.Δt. The shorter the time steps, the greater the accuracy, but the greater the volume of the computations. In the PJM method, the capacity outage probability table (COPT) of the generation units is constructed. The COPT includes the generation capacities and associated probabilities of possible states of the power plants. The COPT of the conventional generation units has two states and the COPT of the CHP plants has four states. By combining the COPTs of different generation units of the system, the total COPT of the system is constructed. By convolving the total COPT with the load that is considered to be constant for the short study time T, the unit commitment risk (UCR) is calculated by summation of the probabilities of the states that the generation capacity is less than the required load. To determine the spinning reserve of the system for a given load, the generation units are added to the system based on the priority order. The addition of the generation units is continued until the reliability criterion is satisfied. The spinning reserve is calculated as the generation capacity of the committed units minus the load of the system. In the operation studies of the power system containing the CHP units, the participation of these plants in the thermal power generation can be considered in two approaches: in the first approach, the equivalent electric power associated to the thermal power considering the efficiency of the energy conversion is added to the generation capacity of the CHP unit. This equivalent electric power can be calculated as:

$$P_Q = \frac{Q}{\eta} \tag{8}$$

Where, PQ is the equivalent electric power, Q is the thermal power generated by the CHP plant and η is the efficiency associated to the energy conversion process. In the second method, the load is modified to determine the impact of the thermal power production of the CHP plant, i.e. the new load value is the initial load value minus the equivalent electric power. The flowchart associated to the operation studies of the power system containing CHP units is presented in Fig. 10. As can be seen in the flowchart, at first the reliability model of CHP units considering the impact of the components failure and thermal power generation is developed. The stochastic transitional probability matrices of these units are constructed and using of the matrix multiplication technique, the capacity outage probability tables of them are determined. To determine the unit commitment risk of the power system, the total COPT is constructed and by comparing the generation capacity of different states with the peak load, the risk is calculated. To determine the required spinning reserve of the power system considering the specified peak load, the generation units are added to the power system and the UCR index is calculated. Adding generation units continues until the risk is less than the permissible value and so the spinning reserve of the system is calculated as difference between the nominal capacity of the scheduled generation units and the peak load.

4. NUMERICAL RESULTS

In this part, operation studies of the RBTS and IEEE-RTS integrated with the CHP units are performed. To investigate the effect of the CHP units on the reliability-based operation indices of the power system, a 30MW CHP unit based on the gas turbine technology is taken into consideration.

4.1. The reliability model of the understudied CHP unit

In this stage, a 30MW CHP unit based on the gas turbine technology is considered. The produced thermal power of this CHP plant is so that a 24MW conventional generation unit must be committed to the system to produce the equivalent electric power and convert it to the thermal power. The failure and repair rates of the composed components of the understudied CHP plant are illustrated in Table 2.

Considering the impact of the failure of composed components on the failure of the electrical or thermal parts of the CHP unit, the transition rates between different states for long-term studies are determined and illustrated in Table 3. The STPM of the understudied CHP unit suitable for short-term studies for time step of 10 minutes can be presented as:

$$STPM = \begin{bmatrix} 0.999905 & 0.000019 & 0.000019 & 0.000057 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

4.2. Operation studies of the RBTS

In this subsection, the RBTS including 11 generation units with 240MW installed capacity is taken into account to study the effect of the CHP plants on the reliability-based operation indices of the power systems. The characteristics of the generation units of the RBTS are given in Ref. [12]. Due to the short duration of the operation study time, the load is considered to be constant. To evaluate the operation of the RBTS including the CHP units, three cases are taken into account in this stage: case I is the original RBTS, case II is the RBTS including a 30MW conventional generation unit with the failure rate of 5 failures per year and the case III is the RBTS including the understudied CHP unit. The unit commitment risk of these cases considering different peak loads for operation study time 1 hour are calculated and presented in Fig. 11. As can be seen in the figure, the addition of the new generation units reduce the unit commitment risk. However, the CHP unit improves the unit commitment risk more than the conventional generation unit with the same size.

Table. 2. The failure and repair rates of the composed components of the CHP plant

Components	Failure rate (occ./yr)	Repair time (hour)	Electrical failure	Thermal failure
Compressor	0.75	50	Yes	Yes
Combustion chamber	1	50	Yes	Yes
Gas turbine	0.75	100	Yes	Yes
Generator	0.5	50	Yes	No
Transformer	0.5	50	Yes	No
Heat exchanger	1	100	No	Yes
Control system	0.5	20	Yes	Yes

Table. 3. The transition rates between different states of the reliability model of the CHP plant

Transition rate	Value (occ./yr)	Transition rate	Value (occ./yr)
1-2	1	2-3	0
2-1	87.6	3-2	0
1-3	1	2-4	4
3-1	175.2	4-2	157.6
1-4	3	3-4	4
4-1	152.4	4-3	128.8

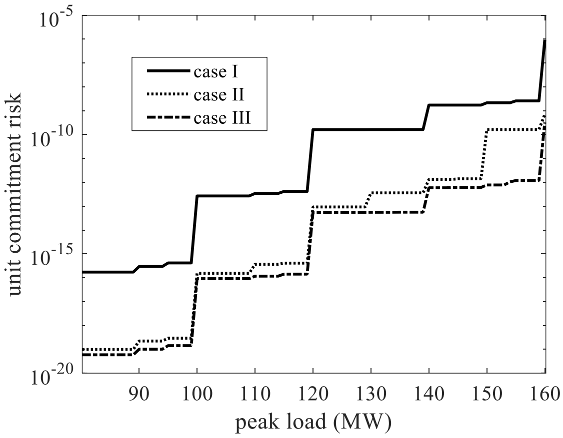

Fig.11. the unit commitment risk considering the peak load

In this stage, to validate the proposed method used for operation assessment of the power system containing CHP plants, the unit commitment risk is calculated based on the Monte Carlo simulation approach and the obtained results are compared with the results calculated from the proposed technique. To calculate the unit commitment risk based on the Monte Carlo simulation technique, for each components of the CHP units, a random number is generated and based on the availability (A) of the component in the specified study time, the condition of the associated component (up or down) is determined. If the generated number is in [0,A] the component would be healthy and of the generated number is in [A,1], the component is considered to be broken. Based on the condition of all components, the generated electrical and thermal powers of the CHP unit in the specified study time are determined. This procedure is repeated for other conventional generation units, and based on the generated random number and the availability of them, the condition (healthy or broken), and so the generation capacity of them is determined. By comparing the total production capacity of the system and the load, it is determined whether the load is curtailed or not. This procedure is repeated for adequate times and the amount of system unit commitment risk is calculated by dividing the number of states resulted in the load curtailment by the total number of repetitions. In this paper, the Monte Carlo simulation approach is repeated for 10000000 times and the unit commitment risk of the RBTS including understudied CHP unit is calculated for different peak loads. The value of the UCR calculated from the proposed method and the Monte Carlo simulation technique and the error associated to these methods are illustrated in table 4. As can be shown in the table, the error associated to the results obtained from the proposed method and the Monte Carlo simulation approach, is insignificant and it is deduced that the proposed method can accurately be used for operation studied of the power system containing CHP plants.

Table. 4. The UCR calculated from the proposed approach and the Monte Carlo simulation method

Peak load (MW)	UCR calculated from proposed method	UCR calculated from Monte Carlo method	Error (%)
220	2.09E-06	2.3E-06	10
230	2.64E-06	2.8E-06	6
240	0.000346	0.0003677	6
250	0.000348	0.0003801	9
260	0.002054	0.0020992	2
270	0.002283	0.0024010	5
280	0.003942	0.0040875	6

Table. 5. The priority order of the generation units of the RBTS

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)

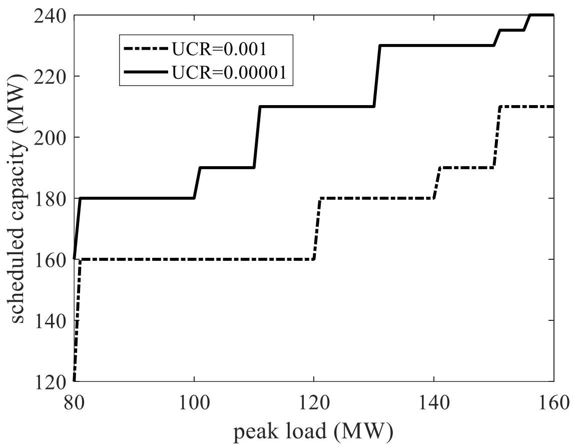

Fig.12. The scheduled capacity of the RBTS considering peak load

The order in which different generation units of the RBTS are brought into the power system is presented in Table 5. For different values of the peak load, the scheduled capacity that must be committed to the power system to satisfy the reliability criterion can be determined. In this paper, the reliability criterion is considered to be the unit commitment risk and the generation units are committed to the power system until the unit commitment risk is less than the permissible value. Two different values are considered for the unit commitment risk as low (UCR=0.00001) and high risk (UCR=0.001) level. The scheduled capacities of the RBTS and the RBTS integrated with the understudied CHP unit considering different peak loads are calculated and presented in Fig. 12 and 13, respectively.

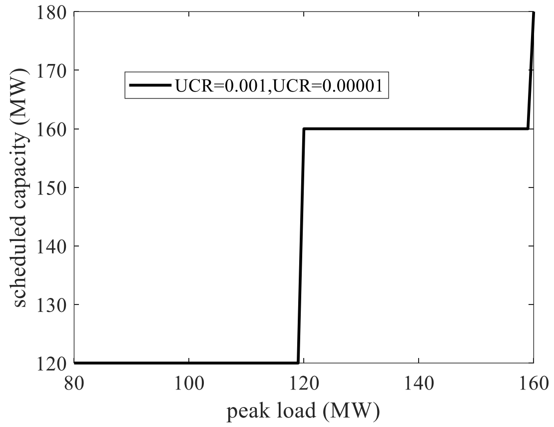

Fig.13. The scheduled capacity of the RBTS integrated with the understudied CHP unit considering the peak load

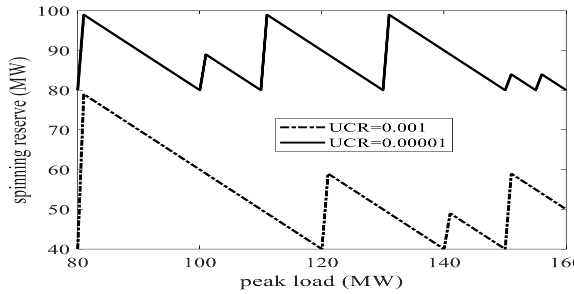

Fig.14. The spinning reserve of the RBTS considering peak load

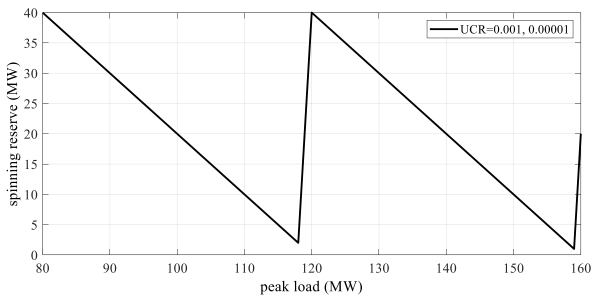

Fig.15. the spinning reserve of the RBTS integrated with the understudied CHP unit considering the peak load

The required spinning reserve of the system in cases I and II, based on the reliability criteria are determined as the scheduled capacity minus the peak load and presented in Figs. 14 and 15, respectively. As can be seen in the figures, the addition of the CHP units to the power system results in the reduction of the required spinning reserve and consequently reduction in the operation cost of the power system.

Table 6. The PLCC

Study time	1 hour	4 hours
Case I	199 MW	198 MW
Case II	239 MW	233 MW

Table 7. The IPLCC

Study time	1 hour	4 hours
Case II	40 MW	35 MW

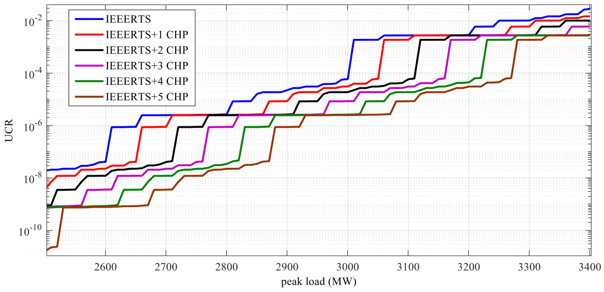

Fig.16. the UCR of the IEEE-RTS and the IEEE-RTS integrated with the different number of CHP units for study time 1 h

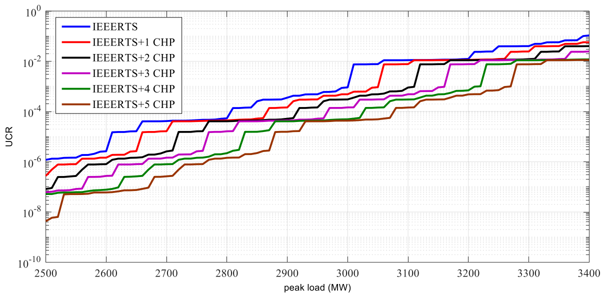

Fig.17. the UCR of the IEEE-RTS and the IEEE-RTS integrated with the different number of CHP units for study time 4 h

In this stage, the peak load carrying capability (PLCC) of the RBTS and the RBTS including the CHP unit are calculated for the study time 1 and 4 hours, provided that the UCR of the system remains less than 0.00001 and presented in Table 6. The increase in load carrying capability (IPLCC) of the RBTS when the CHP unit is added to it for the study time 1 and 4 hours provided that the UCR of the system remains less than 0.00001 is calculated and presented in Table 7.

4.3. Operation studies of the IEEE-RTS

In this stage, the IEEE-RTS as a large-scale power system composed of 3405MW installed generation capacity is taken into account to study the impact of the CHP plants on the reliability-based operation indices of the power systems. The characteristics of the generation power plants of the IEEE-RTS are given in Ref. [13]. Due to the short duration of the study time, the load is considered to be constant. Based on the proposed method, the unit commitment risk of the original IEEE-RTS and the IEEE-RTS integrated to the one to five CHP units for the study times 1 and 4 hours are calculated and presented in Figs. 16 and 17, respectively. As can be seen in the figure, the unit commitment risk of the IEEE-RTS decreases when the CHP units are added to the power system.

In this stage, the PLCC values of the IEEE-RTS and the IEEE-RTS integrated with different number of CHP units are determined and presented in Table 8 for the study times 1 and 4 hours provided that the UCR of the system remains less than 0.00001. The IPLCC values of the IEEE-RTS including the CHP unit for study times 1 and 4 h are calculated and presented in Table 9.

It is deduced from the numerical results obtained from the operation studies of the RBTS and IEEE-RTS including the large-scale CHP plants that:

As the peak load of the power system increases, the amount of the unit commitment risk increases and the reliability of the system reduces. Adding a new generation units, whetherconventional or CHP units, reduces the unit commitment risk and so improves the reliability of the power system.

By calculating the exact amount of the system risk, it is possible to determine when a new generation unit will be added to the system. For example, based on the UCR value presented in Fig. 11, if the permissible UCR is considered to be 10-10 , the initial RBTS can feed the load up to a peak load of 120 MW so that the UCR is less than the allowable value. However, if the peak load exceeds 120 MW, a new generation unit must be added to the power system.

Adding CHP units to the power system further reduces the UCR compared to the conventional units. It is due to the participation of the CHP units in providing the thermal power. With the addition of CHP units to the power system, the amount of required spinning reserve by the power system reduces and so, the operation cost of the system decreases. Some limitations of the proposed method that must be addressed in the future works are:

Lack of the sufficient information about the failure rate of the composed components of different types of the CHP units that results in the less accuracy of the obtained reliability model of CHP units.

Table 8. The PLCC

No. of CHP units	PLCC for study time 1 h	PLCC for study time 4 h
0	2850MW	2605MW
1	2903MW	2657MW
2	2955MW	2709MW
3	3008MW	2761MW

Table 9. The IPLCC

No. of CHP units	PLCC for study time 1 h	PLCC for study time 4 h
1	53MW	52MW
2	105MW	104MW
3	158MW	156MW

This method requires larger volume of calculation due to the proposed four-state model of the CHP units comparing to the two-state model of the conventional generation units.

The proposed multi-state reliability model of the CHP units can be used for scheduling of different generation units such as renewable resources and the CHP plants in the distribution networks or the smart micro grids. In this paper, the proposed method based on the analytical approach is used for operation studies of the power system including large-scale CHP units. In order to present the effectiveness of the proposed method, numerical results associated to the operation studies of two well-known test systems are also studied. The proposed method is examined on the RBTS with 240MW installed capacity as a small power system and the IEEE-RTS with 3405 MW installed capacity as a large power system. The proposed method is based on the analytical approach, and compared to the Monte Carlo simulation approach, it requires less computational volume and time. It is deduced from the numerical results that the proposed method has had a good performance in calculating the operating indices of the large-scale IEEE reliability test system including five CHP units.

5. CONCLUSION

In this paper, based on the PJM method, reliability-based operation studies of the power systems containing the CHP units are performed. For this purpose, a four-state reliability model considering the effect of the composed components of the electrical and thermal parts of the CHP units is developed. The proposed reliability model is developed for different types of the CHP units including gas turbine, reciprocating engine, steam turbine, fuel cell and micro-turbine technologies. The effect of the composed components such as compressor, combustion chamber, turbine, heat exchanger, water electrolysis system, electrical converter, control system, hydrogen tank, fuel cell, reciprocating engine, generator and transformer on the overall failure of the CHP plants is investigated. The modified model is suitable for short-term operation studies of the power system integrated with the CHP units. In this model, the repair rate is neglected and at the beginning of the study, all components are considered to be up. In addition, only the failure of one component considered to occur due to the short duration of operation studies. To perform the operation studies of the power system containing the CHP units based on the PJM method, the capacity outage probability tables of different generation units including conventional power plants and the CHP units are constructed and the total COPT of the system is developed. To determine the probabilities of different states of the CHP units, the matrix multiplication technique isutilized. For this purpose, the stochastic transitional probability matrix of the CHP units that presents the transition rates between different states of the reliability model of the CHP units is determined. Then, the multi-state reliability model of CHP units is resulted and used for operation assessment of the power systems including these plants. The proposed technique is implemented on RBTS and IEEE-RTS to investigate the effectiveness of the method and the CHP units on the reliability-based operation indices of the power system. It is concluded from the numerical results that the CHP units can improve the reliability-based operation indices of the power system. The addition of the CHP units to the power system, the unit commitment risk, the scheduled capacity required to satisfy the reliability criterion, the required spinning reserve and consequently the operation cost of the system is reduced and the peak carrying capability of the power system is increased. Moreover, due to the participation of the CHP units in the thermal generation, the CHP plants can improve the reliability-based operation indices of the power system more than the conventional generation units with the same size. In order to continue this research, it is suggested that the developed reliability model of the CHP units to be used to study the operation of the power system by minimizing operating and reliability costs. As well as, it is proposed to study the operation of the power system in the presence of the transmission system to examine the impact of the transmission network on the reliability-based operation indices.

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