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Adequacy Assessment of the Power Systems Containing Combined Heat and Power Plants

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Abstract

In recent years, energy efficiency and related solutions to enhance the efficiency of power plants have been the focus of attention. For this purpose, the combined heat and power (CHP) plants are increasingly used to generate the required electrical and thermal powers, simultaneously. On the other hand, the reliability of the power system has become one of the important studies of the power system, so that today the consumers expect the electricity provided them with least possible interruption. For this purpose, in this paper, the reliability of the power system including CHP plants from adequacy point of view is evaluated. To study the effect of the CHP units on the adequacy indices of the power system, a reliability model is developed for CHP units that considers both the failure of composed components and the effect of this unit from thermal power generation point of view. To consider the heat generation of the CHP units in the related reliability model, a four-state reliability model is developed for each unit based on the electrical and thermal power of the CHP plant. In this paper, the reliability modeling of different CHP technologies including the CHP units based on the gas turbine, reciprocating engine, micro-turbine, steam turbine, and fuel cell is studied. To investigate the effectiveness of the proposed model, the adequacy assessment of the Roy Billinton test system (RBTS) and IEEE reliability test system (IEEE-RTS) including the CHP units is performed and the impact of the CHP units on the reliability indices is evaluated.

Keywords: Combined Heat And Power (CHP), Reliability, Thermal Energy, Adequacy, Power Generation.

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1. INTRODUCTION

In recent years, the energy efficiency and the related solutions to enhance the efficiency of the power plants have been the focus of attention. In conventional thermal power plants, based on a thermodynamic cycle such as Rankine, the water is first pumped and then heated in the boiler to evaporate. The high-pressure steam is passed through the turbine to rotate the generator connected to the turbine and produce the electricity. In conventional power plants, the heat of the steam is dissipated in the cooling tower that causes the efficiency of thermal power plants to be low (in the range of 25% to 50%). To enhance the efficiency of thermal power plants, the heat of the steam can be utilized for heating needs in hospitals, universities, large apartments, and so on. The combined heat and power (CHP) plants are the power plants that the produced thermal power is used for heating purposes. Thus, the efficiency of the CHP units is high (60%-80% and sometimes more) which has caused these units to be widely installed in the power system. As the number of CHP units installed in the power system increases, many aspects of the power system such as reliability may be affected that must be studied. For this purpose, in this paper, the effect of CHP units on the reliability of the power system is investigated. Due to the importance of the CHP units in the power system, many pieces of research have studied the CHP units and their effects on the power system. In [1], the short-term scheduling of the CHP generation units considering the effect of demand response programs is performed. In this paper, the industrial and commercial customers with cogeneration facilities, conventional power plants, and heat-only units are considered and the short-term hourly scheduling considering the impact of demand response program to serve the power and heat demands of the customer with minimum cost is performed. In [2], a CHP dispatch is formulated to coordinate the operation of the electrical power system and district heating network. In this paper, an iterative technique is proposed to solve the CHP dispatch model considering the temperature dynamic of district heating system for exploiting energy storage as a solution to manage the variability associated with the wind energy. In [3], the effect of CHP plants on the thermal and electrical energy supply associated with the small and medium-size enterprises is investigated. In this paper, the impact of the CHP units on the power system including reduction of greenhouse gas emission, increase in reliability, improved electrical power quality, enhanced energy efficiency, and other environmental benefits are studied. In [4], the frog leaping-based intelligent search algorithm is used to minimize the operation cost of the CHP system. In this paper, due to the nonlinearity and non-convexity nature of the optimization problem associated with the CHP economic dispatch, the frog leaping heuristic algorithm is proposed in a way that is capable to attain the optimal solution even in the case of non-convex optimization problems. In [5], the fuzzy Shannon entropy and fuzzy technique for order of preference by similarity to the ideal solution approach are proposed to evaluate the CHP systems. In this paper, a fuzzy multi-criteria method is used to assess five CHP commercial technologies including the CHP units based on the reciprocating engine, steam turbine, gas turbine, micro-turbine, and fuel cell. In [6], the available reserve capacity of the CHP plants and the district heating network are analyzed and the components-coupling and heating-dependency features of the CHP units are evaluated. In this paper, the regulating region technique is used to describe the heating-restricted reserve capacity of the CHP plants based on this proposed approach, an integrated power and heat dispatch method is proposed to utilize the regulating region for formulating the available CHP reserve capacity. In [7], a subsidy-based bi-level optimal model is proposed to optimize the operation of the power system including combined heat and power units and the wind farms. In this paper, the objective of the upper problem is to minimize the operating cost and the objective of the lower problem is to maximize the benefits of CHP and electrical boilers based on the subsidy signals sent by the power system operator. In [8], an electric boiler is used to coordinate the heating system and electrical power network to reduce wind curtailment during the heating supply season in the northern area. In this paper, an optimal economic dispatching model of CHP energy systems is proposed to minimize the total operation cost and wind curtailment by using the electrical boilers. In [9], a detailed CHP dispatch model based on the principles of the heat transfer is proposed to develop a joint dispatch model considering the CHP plants, conventional thermal power plants, and the heating process. In this paper, a three-stage heat transfer model of the extraction steam is used to describe the heating process and analyze the impacts of different factors on this heat transfer process. In [10], the modeling and deep peak regulation control of CHP units are investigated. In this paper, a nonlinear dynamic model of a CHP plant including an absorption heat pump and bypass system is proposed and associated unknown parameters are determined based on design data and perturbation test. In [11], the reliability evaluation of a power system with customer-operated CHP systems is performed using Monte Carlo simulation method. In this research, the hourly generated power of different power plants, hourly required load, hourly operational state of CHP units, and hourly state of distribution network are determined by random number generation in MATLAB software. However, high computational volume and duration of calculations and also the need for more memory are some of the disadvantages of numerical methods compared to analytical approaches. Paper [12] studies the adequacy assessment of power systems containing building cooling, heating, and power plants. In this paper, a two-state reliability model is developed for building cooling, heating, and power plants. In the proposed reliability model of these plants, failure of the compressor, combustor, gas turbine, generator, and transformer is considered. From a reliability point of view, these five components are considered to be series in the proposed model.

In [13], reliability evaluation of integrated heat and power units in the operational phase is performed. In this research, reliability modeling of coupling devices associated with combined heat and power units and heat pumps is done. The uncertainties of the model including forecasting and data errors are considered by fuzzy multi-state models and scenario-based dispatch techniques. Paper [14] studies the impact of combined heat and power plants on reliability of micro-grids. In this paper, types, capacity size, and locations of distributed energy resources used in micro-grids are studied. The understudied micro-grid includes micro-turbines, combustion turbines, diesel generators, combined heat and power units that for optimal benefit to cost ratio of micro-grid, the location and capacity size of units are determined by particle swarm optimization technique. In [15], according to the network constrained unit commitment framework, a two-state hybrid stochastic information gap decision approach is proposed to study the impact of combined heat and power units in energy systems considering market clearing of joint energy and flexible ramping reserve. In this paper, Monte Carlo simulation approach is used to investigate the uncertain nature of load demands and wind powers. In [16], an artificial bee colony algorithm is used to optimize the capacity size of CHP units and energy cost in a residential building. In this paper, two optimization methods including the genetic algorithm and the artificial bee colony method are used for problem optimization. It is concluded from numerical results that the artificial bee colony is better than the genetic algorithm for the optimal determination of the capacity of CHP units. In [17], distributed energy management of a micro-grid containing combined heat and power units considering demand response programs is studied. For this purpose, the system model of operational cost including combined heat and power units, demand response, renewable distributed units, and diesel generators is developed. Then, the optimal scheduling method based on the sub-gradient dynamic search technique is used for energy management of the micro-grid.

According to the knowledge of the authors, so far, a comprehensive reliability model that considers both failure of composed components and the operation of CHP units is not developed. For this purpose, in the current paper, a multi-state reliability model of the CHP units based on the failure of composed components and thermal power generation performance is developed and used for adequacy assessment of the power system including large-scale CHP units. The proposed reliability model can be used for reliability modeling of combined cool and power units and also combined cool, heat, and power units. Thus, the contributions of the paper would be as:

- All types of CHP units based on their actuator are studied.
- A comprehensive reliability model taken into account both failure of composed components and thermal performance of the units is developed for all types of CHP plants.
- The reliability model of combined cool and power units and also combined cool, heat, and power units is developed.
- The impact of CHP units on the adequacy indices of the power system is studied.

For this purpose, the organization of the paper would be as follows: in the second section, different types of CHP units and composed components of them are explained. In the third section, the reliability modeling of the CHP units is performed. The proposed technique for adequacy assessment of the power system including CHP plants is introduced in the fourth section. The numerical results associated with the adequacy assessment of the RBTS and IEEE-RTS are given in the fifth section. The conclusion of the paper is summarized in the sixth section.

2. CHP PLANTS

The CHP unit or cogeneration, is the concurrent generation of the electricity and thermal energy from a single source of energy. The CHP plants improve the efficiency of the system in a way that results in the lower consumption of the fossil fuels. Thus, the energy efficiency, reduction in the greenhouse gas emission, and reduction in the generated energy cost are some advantages of the CHP units that results in the wide use of the CHP plants in the power system for electric and thermal power generation. Various prime movers or technologies have been developed to generate the electrical and thermal power, simultaneously, in the CHP units including steam turbine, gas turbine, reciprocating engine, micro-turbine, and fuel cell. The produced thermal energy of the CHP units can be used in direct process applications or indirectly used for the production of steam, hot water, and hot air. In this section, different types of the CHP units are explained.

2.1. The Steam Turbines

In the CHP plants based on the steam turbines, the electricity is generated from the mechanical or kinetic energy of the hot steam generated in a boiler that results in the rotation of the turbine and the generator connected to the turbine shaft. This type of the CHP unit is one of the most versatile and oldest prime mover technologies for driving generators. The thermal energy generated in the boiler is transferred to the turbine using the high-pressure steam that converts to the kinetic energy of the turbine and the generator. The outlet steam from the turbine that has high thermal energy can be used for heating purposes. In the conventional thermal power plants, the thermal energy of the outlet steam from the turbine is dissipated in the cooling tower that results in the low efficiency of these power plants. The structure and the composed components of the CHP units based on the steam turbine are presented in Fig. 1. The main components of the CHP units based on the steam turbine are the boiler, turbine, generator, transformer, heat exchanger, and control system.

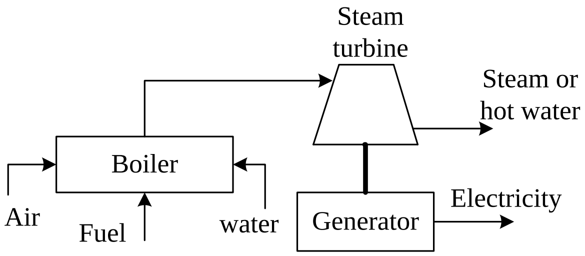

Fig. 1. The structure of the CHP units based on the steam turbine.

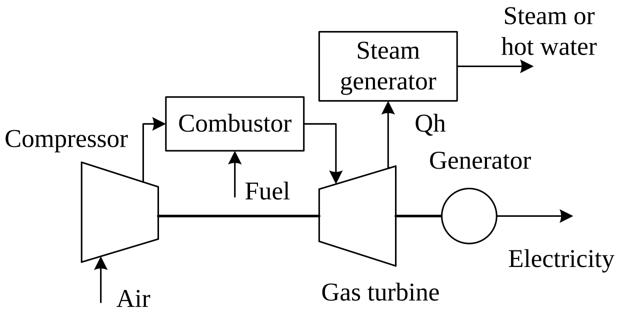

Fig. 2. The structure of the CHP units based on the gas turbine.

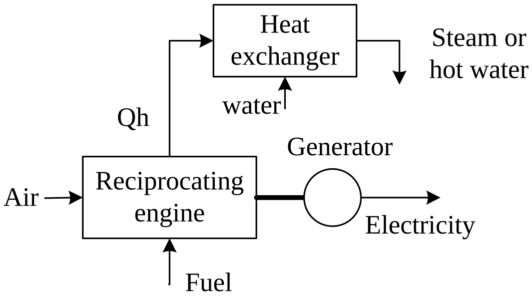

Fig. 3. The structure of the CHP units based on the reciprocating engine.

2.2. The Gas Turbines

The structure and the composed components of the CHP plants based on the gas turbine technology are presented in Fig. 2. In these units, the air is compressed through the compressor and enters the combustion chamber with the fuel. Then, the combustion occurs and the compressed air with high temperature enters the turbine leading to turbine rotation. The generator connected to the turbine through a shaft is rotated and the electricity is generated. The outlet thermal energy from the turbine enters the steam generator to produce steam of hot water for heating purposes. The main components of the CHP units based on the gas turbine are the compressor, combustion chamber, gas turbine, heat exchanger, generator, transformer, and control system.

2.3. The Reciprocating Engines

The structure and the composed components of the CHP plants based on the reciprocating engine technology are presented in Fig. 3. In these units, the fuel such as natural gas and the air enter the reciprocating engine and a combustion is occurred that results in the reciprocating motion of the piston in the cylinder. This motion is converted to the rotational motion that results in the rotation of the generator and production of the electricity. The outlet thermal energy from the reciprocating engine which enters the heat exchanger contains water and steam or hot water is generated. The main components of the CHP units based on the reciprocating engine are the reciprocating engine, generator, transformer, heat exchanger, and control system.

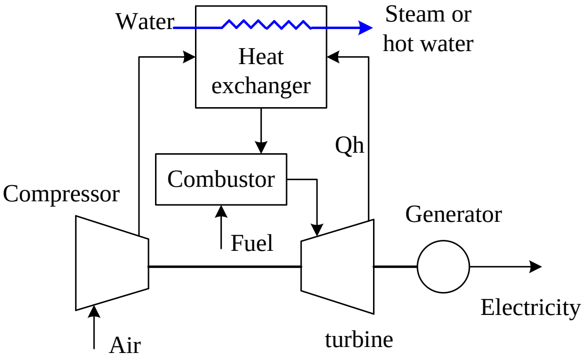

Fig. 4. The structure of the CHP units based on the micro-turbine.

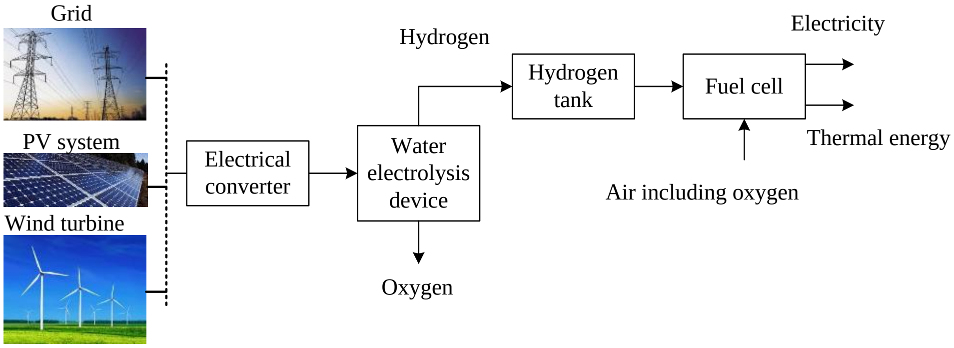

Fig. 5. The structure of the CHP units based on the fuel cell.

2.4. The Micro-Turbines

In the CHP plants based on the micro-turbines technology, a heat exchanger transfers thermal energy from the hot exhaust of the turbine to hot water or low-pressure steam. The produced heat can be used for different heating purposes such as water heating, absorption chillers, process heating, and other applications. In these units, the air is compressed by the compressor and enters the heat exchanger to raise its temperature. Then, the high-pressure and hot air enters the combustion chamber with the fuel. The combustion occurs and the high-pressure and very hot outlet air enters the turbine and rotates it. The generator connected to the turbine is rotated and the electricity is produced. The main components of the CHP units based on the micro-turbine technology are a compressor, turbine, generator, transformer, heat exchanger, combustion chamber, and control system.

2.5. The Fuel-Cell

In the CHP plants based on the fuel cell, the electric power produced by different technologies such as photovoltaic systems or wind turbines enters the water electrolysis device that leads water decomposition into oxygen and hydrogen. The hydrogen is stored in the hydrogen tank and when required it enters the fuel cell with the air, which contains the oxygen. In the fuel cell, the hydrogen and the oxygen are combined to produce electricity and thermal energy. The produced thermal energy can be used for the

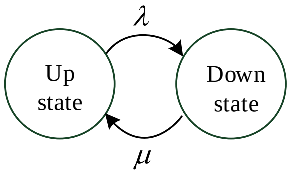

Fig. 6. The 2-state Markov model of devices.

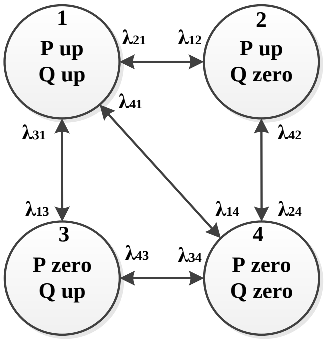

Fig. 7. The 4-state reliability model of CHP units.

heating purposes. The main components of the CHP units based on the fuel cell are water electrolysis device, hydrogen reservoir, fuel cell, electrical converter, and heat exchanger.

3. RELIABILITY MODEL OF CHP PLANTS

In this part, a multi-state reliability model is developed for different types of CHP plants considering the failure of composed components and their participation in thermal power generation. The reliability model of each component is considered as a two-state Markov model including up and down states as presented in Fig. 6. The transition rate from the up state to the down state is the failure rate (λ) and the transition rate from the down state to the up state is the repair rate (μ). The availability (A) and unavailability (U) of each device can be calculated as [18]:

$$A = \frac{\mu}{\lambda + \mu}, U = 1 - A \tag{1}$$

In a CHP unit, both electric (P) and thermal (Q) powers are generated and a four-state reliability model is developed for this plant in this paper, as presented in Fig. 7. In the state 1, all composed components are up and the unit can generate the electrical and thermal powers and transfer them to the loads or grid. In the state 2, the failure of one or more components occurs that results in the zero production of the thermal power or results in no heat transfer to the load. In this state, the electric power is generated and transferred to the grid. In the state 3, the failure of one or more components occurs that results in zero production of the electrical power or results in no electric power transfer to the grid. However, in this state, the thermal power is generated and transferred to the load. In the state 4, the failure of one or more components occur that results in the zero production of electric and thermal powers or results in no electrical and thermal powers transfer to the loads or grids. In the 4-state reliability model λ_{14} is the common mode failure rate that causes the electrical and thermal powers of the CHP unit to be zero.

To determine the transition rates between different states, the failure rates related to components that are effective in transmitting between modes must be added together according to the following relation:

$$\lambda_{ij} = \sum_{k=1}^{n} \lambda_k \tag{2}$$

where, λ_{ij} is the transition rate from state i to state j and the λ_k is the failure rate of the component k that results in the transition from state i to state j. If the failed components that result in the transition from state with higher capacity to the state with lower capacity are repaired, the transition from lower capacity state to the higher capacity state is occurred. Thus, to determine the associated transition rate, the repair rate of the series components as equation (3) can be used:

$$\lambda_{ji} = \frac{\lambda_{ij}}{\sum_{k=1}^{n} \frac{\lambda_k}{\mu_k}} \tag{3}$$

In this part, the components that their failure leads to the transition of the CHP unit from the state 1 to the states 2, 3, and 4 are introduced for different types of CHP plants. In the CHP units based on the gas turbine, the failure of heat exchanger results in the transition from state 1 to 2, the failure of generator or transformer results in the transition from state 1 to 3, the failure of compressor or combustion chamber, gas turbine or control system results in the transition from state 1 to 4, the failure of compressor or combustion chamber, gas turbine, generator, transformer, or control system results in the transition from state 2 to 4, and the failure of the heat exchanger results in the transition from state 3 to 4. In the CHP units based on the reciprocating engine, the failure of heat exchanger results in the transition from state 1 to 2, the failure of generator or transformer results in the transition from state 1 to 3, the failure of reciprocating engine or control system results in the transition from state 1 to 4, the failure of reciprocating engine or generator, transformer, or control system results in the transition from state 2 to 4, and the failure of the heat exchanger results in the transition from state 3 to 4. In the CHP units based on the steam turbine, the failure of heat exchanger results in the transition from state 1 to 2, the failure of generator or transformer results in the transition from state 1 to 3, the failure of boiler or turbine or control system results in the transition from state 1 to 4, the failure of boiler or turbine, generator, transformer, or control system results in the transition from state 2 to 4, and the failure of the heat exchanger results in the transition from state 3 to 4. In the CHP units based on the micro-turbine, the failure of generator or transformer results in the transition from state 1 to 3, the failure of compressor or turbine, heat exchanger, or control system results in the transition from state 1 to 4, and the failure of the compressor or turbine, heat exchanger, or control system results in the transition from state 3 to 4. In this CHP unit, the probability of state 2 would be zero. In the CHP units based on the fuel cell, the failure of heat exchanger results in the transition from state 1 to 2, the failure of water electrolysis device, hydrogen reservoir, fuel cell and electrical converter results in the transition from state 1 to 4, the failure of water electrolysis device, hydrogen reservoir, fuel cell, and electrical converter results in the transition from state 2 to 4. In these CHP units the probability of state 3 is zero.

To determine the probabilities associated with different four states of the CHP reliability model, the transition rates between different states are determined and using the following relations the probabilities are calculated:

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

To determine the reliability indices of the power system including the CHP units, the conditional probability approach can be used. The reliability indices of the power system for each state of the CHP unit is calculated as table 1, and based on the conditional probability approach as relation (5), the reliability indices such as *S* are determined.

$$S = S_{00}\times P_{00} + S_{01}\times P_{01} + S_{10}\times P_{10} + S_{11}\times P_{11} \tag{5}$$

Table 1. ***The four states of the CHP units and the associated indices and probabilities.***

States	Electrical energy not generated		Electrical energy generated	
	Index	**Probability**	**Index**	**Probability**
Thermal energy generated	S_{01}	P_{01}	S_{11}	P_{11}
Thermal energy not generated	S_{00}	P_{00}	S_{10}	P_{10}

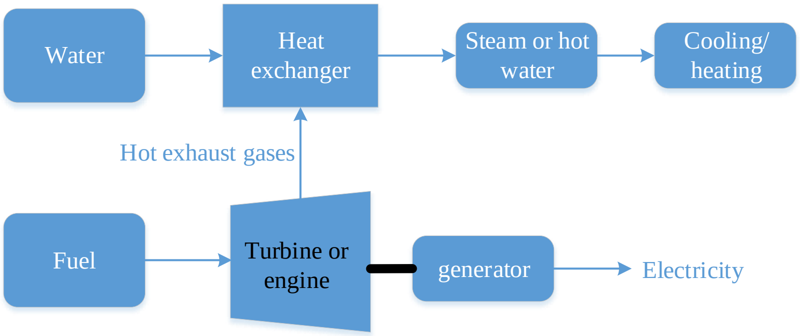

Fig. 8. The structure of typical CCHP.

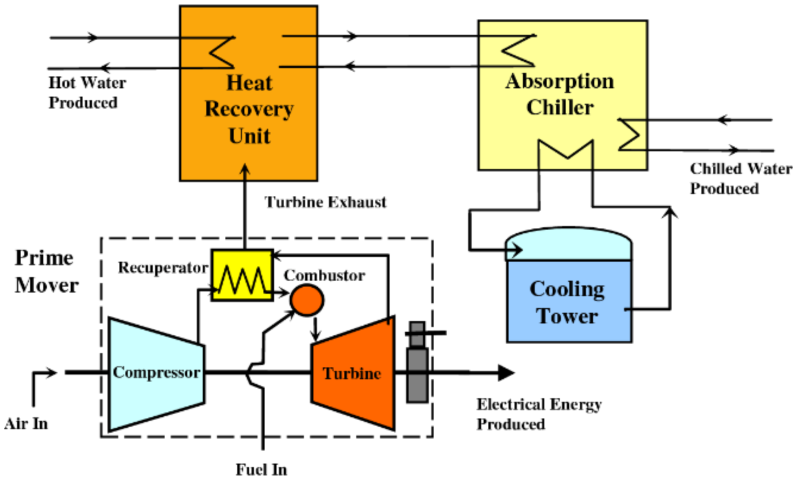

Fig. 9. The components of CCHP [19].

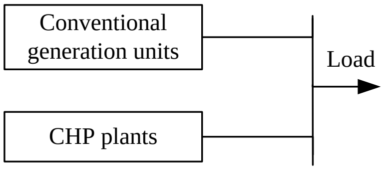

Fig. 10. Adequacy assessment of power system containing the CHP plants.

4. RELIABILITY MODEL OF COMBINED COOL, HEAT AND POWER UNITS

The structure of a typical combined cool, heat and power (CCHP) unit is presented in Fig. 8. In Fig. 9, the other components required for heating or cooling purposes are presented in a typical CCHP unit [19]. As can be seen in the figure, the high-temperature gas of turbine exhaust can be used for heating or cooling purposes. In the CHP unit, the outlet gas of the turbine is used for heating purposes, and in the combined cool and power (CCP) unit, the outlet gas of the turbine is used for cooling purposes.

The reliability model of these CCP and CCHP units is similar to the reliability model of CHP unit. In the CHP unit, the thermal power (Q) of turbine exhaust gas is used for heating, while the CCP and CCHP are used for cooling and cooling/heating purposes. Since, the electric (P) and thermal (Q) powers generated in CHP, CCP, and CCHP are the same, the 4-state reliability model developed for the CHP unit can be used for the reliability modeling of CCP and CCHP units.

5. ADEQUACY STUDIES OF THE POWER SYSTEMS CONTAINING THE CHP UNITS

Reliability of the power system is the ability of this system for supplying the required loads that is categorized in two aspects including adequacy and security. The adequacy of the power system studies the adequate facilities that must be established to supply the required load and the security studies the response of the power system to different disturbances such as generation unit outages. In this paper, the adequacy of the power system including the CHP units is performed. For this purpose, it is neglected from the transmission network and all generation units and the load are connected to a common bus as presented in Fig. 10.

For adequacy studies of the power systems integrated with the CHP units, a capacity outage probability table (COPT) including the possible generation capacities and associated probabilities is developed for each conventional power plant. The conventional generation units can be presented with two-state reliability model including up (with rated capacity) and down (with zero capacity) states and so, the COPT of these conventional power plants has two states. The CHP units can be modeled with 4 states and so, the COPT of these CHP units with 4 states can be obtained as section 3. The COPT of the generation system is obtained by combining all COPTs, and by convolving the generation system model (total COPT) and load model, the reliability indices such as loss of load expectation (*LOLE*), expected energy not supplied (*EENS*), peak load carrying capability (*PLCC*), and increase in peak load carrying capability (*IPLCC*) are calculated. In this paper, the load duration curve is considered as a straight line extended from the maximum yearly peak load to the minimum yearly peak load. The *LOLE* is the days or hours of a year that part or all of the system load is curtailed and based on the load duration curve presented in Fig. 11, can be calculated as:

$$LOLE = \sum_{i=1}^{n} t \times P_i \quad hours / year \tag{6}$$

where t is the time of the year that the system load is curtailed when the generation capacity i of the system COPT with the probability of P_i is considered to be analyzed. Based on this load duration curve, the expected energy not supplied in MWh per year can be calculated as:

$$EENS = \sum_{i=1}^{n} ENS_i \times P_i \tag{7}$$

where ENS_i is the energy not supplied associated with the generation capacity i of the system COPT. The *PLCC* of the system is the value of the load that can be supplied, provided that the reliability criterion is satisfied. The *IPLCC* is the value added to the *PLCC* when a new generation unit is integrated to the system.

The participation of the CHP units in the thermal power generation can be considered in two methods: in the first method, the equivalent electric power associated with the thermal power, i.e. the electric power required to supply the thermal load that is supplied by the CHP unit is added to the generation capacity of the CHP unit. This equivalent electric power can be considered as:

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

where P_Q is the equivalent electric power, Q is the thermal power produced by the CHP unit and η is the efficiency associated with a system that converts the electric power to the thermal power. In the second method, the load duration curve is modified as Fig. 12 to determine the effect of the thermal power generation of the CHP unit. The results of the two methods are the same. In this paper, the first method is used to investigate the adequacy of the power system including CHP units. The flowchart associated with this approach is presented in Fig. 13.

6. NUMERICAL RESULTS

In this section, the adequacy studies of the RBTS and the IEEE-RTS that are modified by the addition of the CHP units are performed and the effect of the CHP units on the reliability indices of these power systems is investigated.

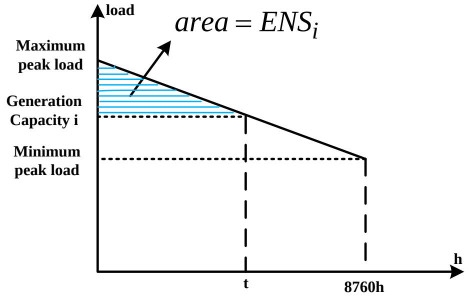

Fig. 11. The load duration curve of the system.

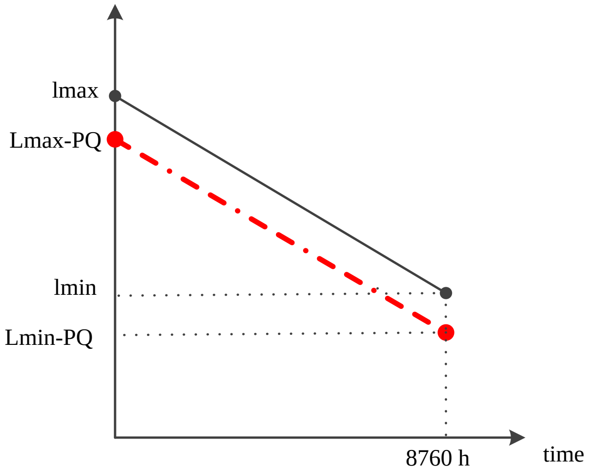

Fig. 12. The load duration curve of the system considering the effect of the CHP unit.

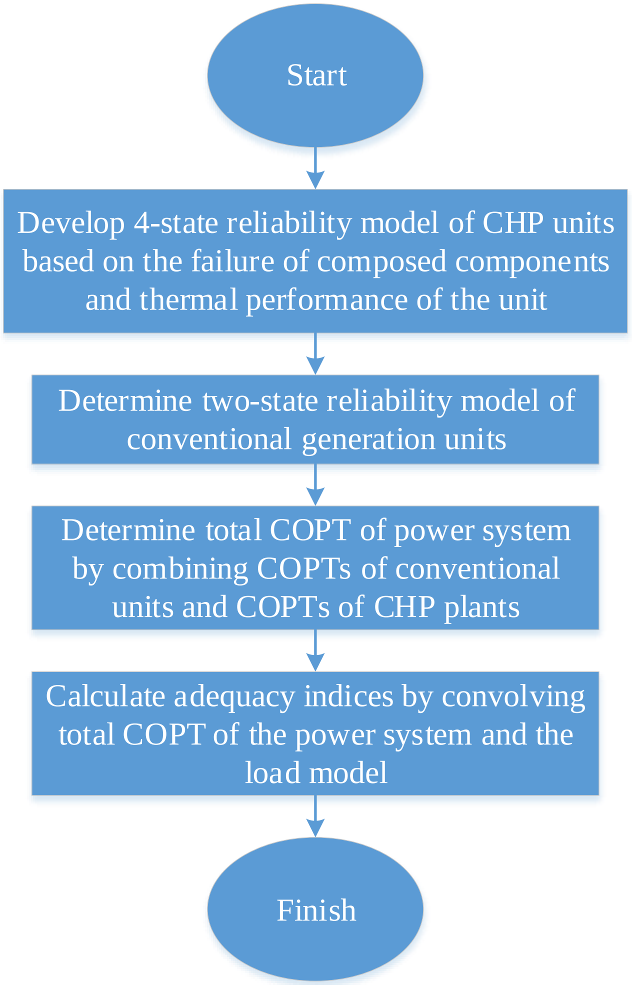

Fig. 13. The flowchart of adequacy assessment method.

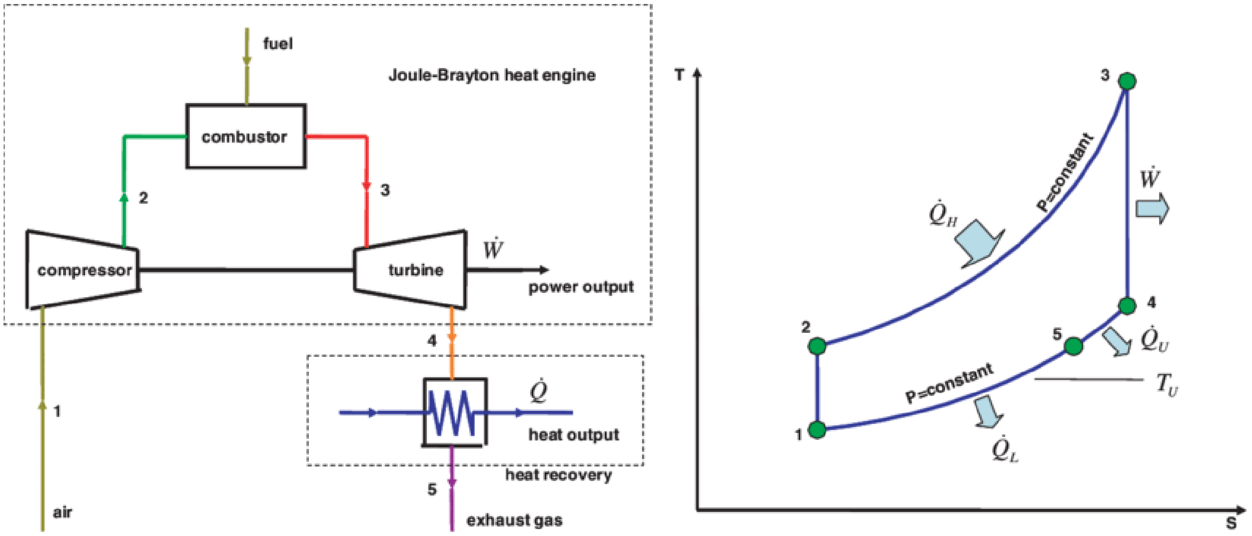

Fig. 14. The thermodynamic cycle of understudied CHP unit [20].

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

Components	Failure rate (occ./yr)	Repair time (hour)	State 2	
			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

6.1. The Reliability Model of the Understudy CHP Unit

In this paper, a 30MW CHP plant based on the gas turbine is considered. The thermodynamic cycle of this CHP unit is based on Brayton cycle and is presented in Fig. 14 [20]. As can be seen in the temperature-entropy (T-S) diagram of the plant, the air is compressed in the compressor as a constant-entropy process. Then, in a constant-pressure process, combustion occurs and the temperature of high-pressure gas is increased and it is entered into the turbine and generates electricity in a constant-entropy process. After it, the low-pressure gas with high thermal energy is entered into the heat exchanger and its thermal energy is used for heating purposes in a constant-pressure process. The generated thermal power of this CHP unit is so that a 24MW power plant must be committed to the system to generate the equivalent electric power and convert it to the thermal power.

The failure and repair rates of the composed components of this CHP unit are presented in table 2.

Based on the effect of the failure of these components on the failure of the CHP unit in the electrical or thermal parts, the transition rates between different states are calculated and presented in table 3. The probabilities of 4 states of the reliability model of the understudied CHP unit are calculated based on the relations (4) and presented in table 4.

6.2. Reliability Evaluation of the RBTS

In this part, the RBTS with 240MW installed capacity is considered to investigate the impact of the CHP units on the reliability indices of the power systems. The characteristics of the generation units of the RBTS are given in [21]. The load duration curve is considered as a straight line extended from 100% to 60% of the peak load. To investigate the reliability of the RBTS integrated with the CHP units, three cases are considered in this stage: case I is the original RBTS, case II is the RBTS integrated with a 30MW conventional generation unit with the availability of 0.95, and case III is the RBTS integrated with the understudies CHP unit. The loss of load expectation and expected energy not supplied associated with these cases considering the peak load are calculated and presented in Fig. 15 and 16, respectively. The values of the peak load carrying capability of these three cases provided that the *EENS* of the power system remains less than the permissible values and are calculated and presented in table 5. Based on the values obtained for the PLCC, the IPLCC of the power system for cases II and III, i.e. with addition of the conventional generation unit and the understudied CHP unit to the power system are calculated and presented in table 6. It is concluded from the numerical results that the addition of the new generation units improves the reliability indices of the power system. However, the CHP units due to the participation in the thermal power generation improve the reliability indices more than the conventional units of the same size.

Table 3. ***The transition rates between different states of the CHP unit model.***

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

Table 4. ***The reliability model of the understudied CHP unit.***

States	**1**	**2**	**3**	**4**
Probability	0.9605	0.0223	0.0103	0.0069

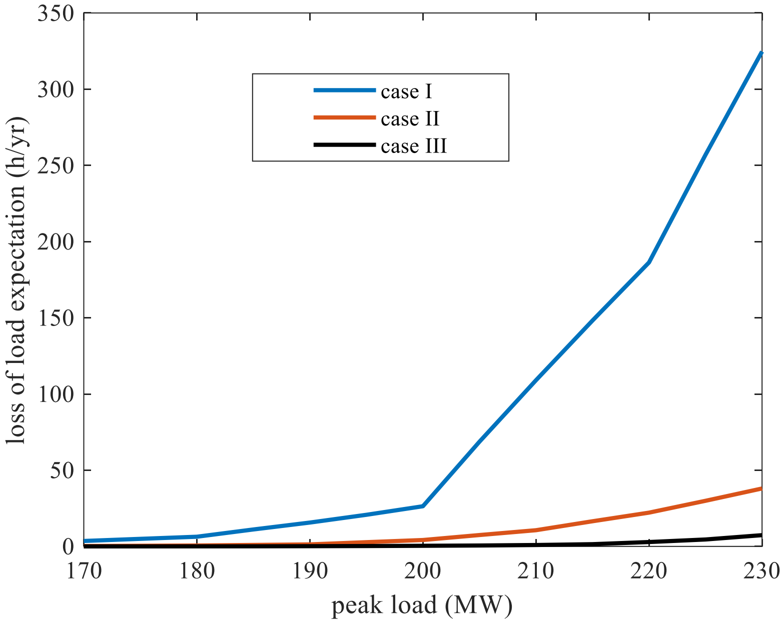

Fig. 15. The loss of load expectation considering the peak load.

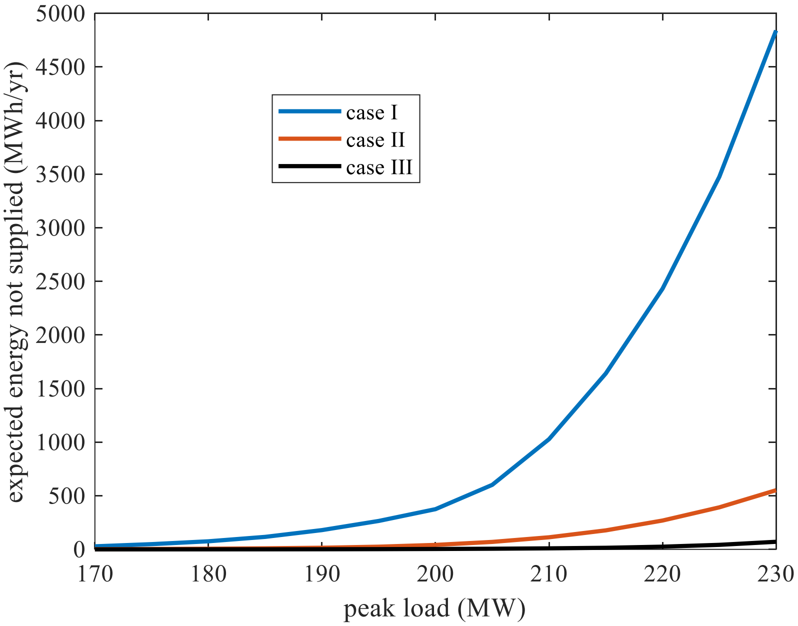

Fig. 16. The expected energy not supplied considering the peak load.

Table 5. ***The PLCC associated to three cases.***

Permissible EENS	50 MWh/yr	80 MWh/yr
Case I	175 MW	180 MW
Case II	200 MW	205 MW
Case III	225 MW	230 MW

Table 6. ***The IPLCC associated to cases II and III.***

Permissible EENS	50 MWh/yr	80 MWh/yr
Case II	25 MW	25 MW
Case III	50 MW	50 MW

6.3. Reliability Evaluation of the IEEE-RTS

In this part, the IEEE-RTS with 3405MW installed generation capacity is considered to evaluate the effect of the CHP units on the reliability of large-scale power systems. The characteristics of the generation units of the IEEE-RTS are given in [22]. The load duration curve is considered as a straight line extended from 100% to 60% of the yearly peak load. The loss of load expectation, disprovide of expected energy, peak load carrying capability, and increase in peak load carrying capability of the original IEEE-RTS and the IEEE-RTS integrated to the one to five CHP units are calculated and presented in figs. 17 to 20, respectively. As can be seen in these figures, the reliability indices of the IEEE-RTS significantly improve, when the CHP plants are added to this system.

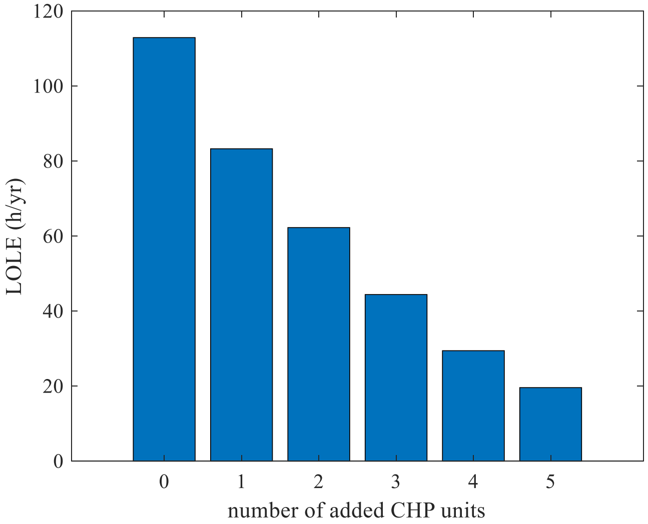

Fig. 17. Loss of load expectation considering the number of added CHP units.

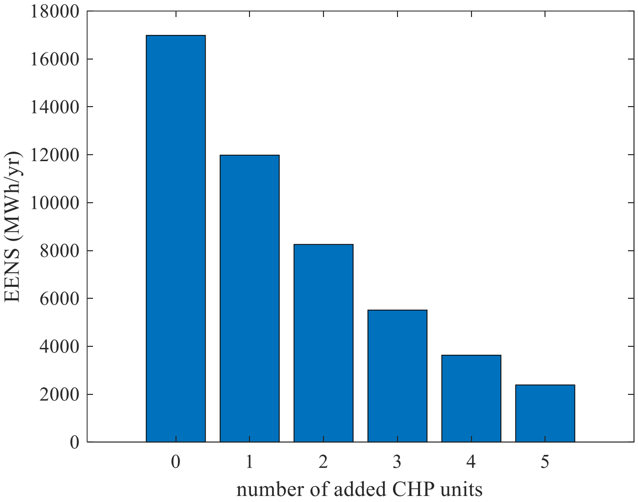

Fig. 18. Expected energy not supplied considering the number of added CHP units.

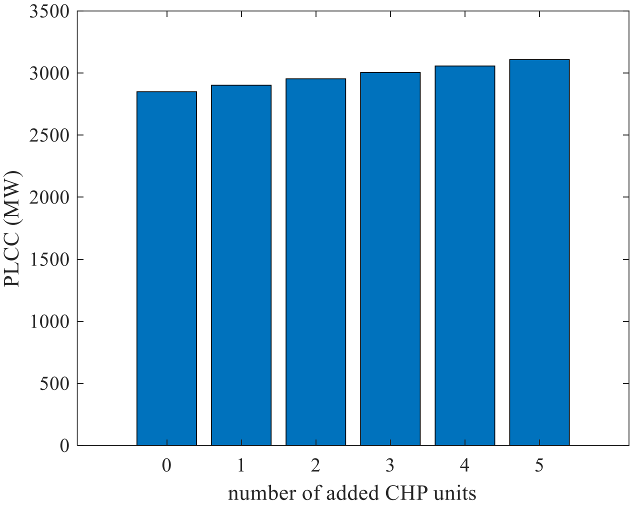

Fig. 19. Peak load carrying capability considering the number of added CHP units.

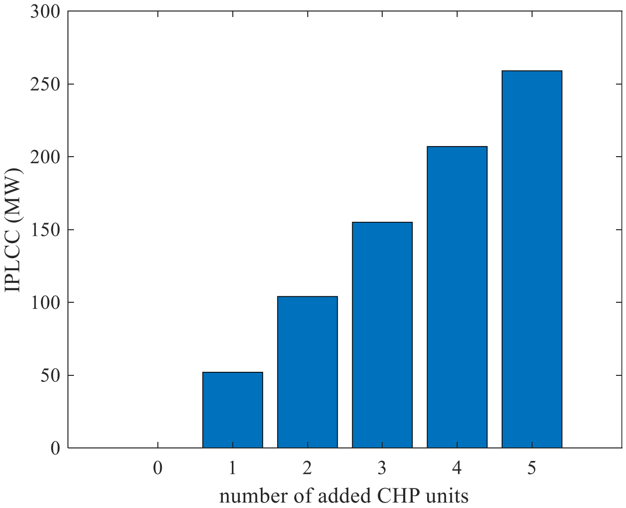

Fig. 20. Increase in peak load carrying capability considering the number of added CHP units.

7. CONCLUTION

In this paper, a four-state reliability model is developed for different types of the CHP units that considers the failure of composed components and the participation of these units in the thermal power generation. Five CHP units that are based on the steam turbine, gas turbine, reciprocating engine, micro-turbine, and fuel cell technologies are studied and composed components of them are introduced. The effect of the main components of the CHP units on the overall failure of electrical and thermal parts of different CHP units is investigated and the multi-state reliability model of the CHP plants is determined. To obtain the probabilities of these four states, the conditional probability approach is proposed and based on the analytical approach the adequacy studies of the power system including CHP units are performed. The main components of the CHP units including compressor, combustion chamber, heat exchanger, turbine, generator, transformer, control system, reciprocating engine, water electrolysis device, electrical converter, fuel cell, and hydrogen reservoir are considered in different types of the CHP units and the effect of these components on the overall performance of the CHP plants are investigated. It is concluded from the numerical results associated with the adequacy assessment of the RBTS and IEEE-RTS integrated with the CHP units that the addition of the CHP units and also conventional generation units result in the improvement in the reliability indices of the power system. However, the addition of the CHP units to the power system improves the reliability indices of the power system more than the addition of the conventional generation units with the same size. It is due to the participation of the CHP units in the thermal power generation and high efficiency of these units.

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