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Reliability Assessment of Integrated Electricity and Heat Systems Considering Multi-State Units

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Abstract: *In order to solve the problem that the traditional two-state reliability theory cannot be applied to the reliability assessment of integrated electricity and heat systems (IEHS), an IEHS reliability assessment method suitable for multi-state units considering the uncertainty of wind, solar and wind loads was proposed. Firstly, the steady-state probability model of multi-state units is analyzed based on the Markov process, and then, considering the uncertainties in the case of wind power and photovoltaic access in IEHS, the optimal load reduction model of IEHS is established with the goal of minimizing load reduction, and the Monte Carlo simulation method is used to solve the model. Finally, the effectiveness of the model and solution method is verified by example simulation, and the influence of multi-state units and electric heat pump (EHP) capacity on system reliability is analyzed.*

Keywords: *Reliability Assessment; Integrated Electricity and Heat Systems (IEHS); Multi-State Units; Monte Carlo Simulation*

1. Introduction

In traditional reliability analysis, a two-state probabilistic model is generally used, that is, components are considered to have only two states, "running" and "faulting", however, there may be multiple states between "running" and "failure" due to the aging of components, local faults, or other external factors. On the basis of the two-state model, the developed multi-state shutdown model can describe the state characteristics of components in more detail. Therefore, the study of the component multi-state model is conducive to more accurate analysis and assessment of the reliability level of IEHS [1].

At present, there have been many research results on the energy flow calculation of IEHS, but there are few studies on the reliability assessment of IEHS. In reference [2], based on the Markov process Monte Carlo method, the reliability of the integrated energy system was quantitatively evaluated by the value of the importance index. In reference [3], a comprehensive energy system reliability assessment method based on the sequential Monte Carlo simulation method is proposed, and the influence of PV output correlation, load reduction strategies considering users' thermal comfort, and demand response and coupling operation on the reliability assessment results are analyzed. In reference [4], a method for evaluating the operational reliability of the grid-connected wind power system of Markov chain considering the uncertainty factors of source-grid-load is proposed, and the influence of random variable fluctuations on the reliability of the system is quantitatively analyzed and compared.

In order to solve the problem that the traditional two-state reliability theory cannot be applied to IEHS reliability assessment, this paper proposes an IEHS reliability assessment method suitable for multi-state units and wind-solar load uncertainty. Firstly, the steady-state probability model, the IEHS optimal load reduction model and the calculation of reliability index of multi-state combined heat and power (CHP) units are analyzed in detail, and then an IEHS reliability assessment method suitable for multi-state units is proposed, and finally, the influence of multi-state units and EHP capacity on IEHS reliability is quantitatively evaluated through example simulation.

2. Reliability Model for Multi-State Units

In this paper, the CHP unit is mainly regarded as a multi-state unit, and its operational constraints are determined by its electrothermal characteristics, as shown in Figure 1 [5].

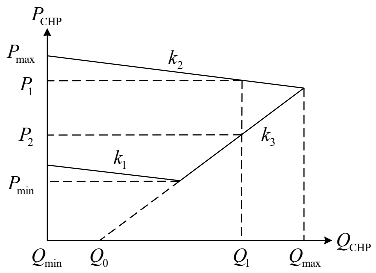

Figure 1: Electrothermal characteristics of CHP units

As Figure 1 illustrates, the power generation power of the CHP unit is determined by its heating power. After the CHP heating power is determined, its power generation capacity can be considered adjustable within a specific range, for example, with a heating power of Q_1 for the CHP unit, the power generation capacity varies between the lower limit of P_1 and the upper limit of P_2. The constraints on the thermal power and electrical power output of the CHP unit are shown in equation (1), respectively.

$$\begin{gathered} 0 \le Q_{\mathrm{CHP},i}^{\mathrm{adj}} \le Q_{\mathrm{CHP},i}^{\max} \\ \max \begin{Bmatrix} P_{\mathrm{CHP},i}^{\min} - k_{1,i} Q_{\mathrm{CHP},i}^{\mathrm{adj}}, \\ k_{3,i}(Q_{\mathrm{CHP},i}^{\mathrm{adj}} - Q_0) \end{Bmatrix} \le P_{\mathrm{CHP},i}^{\mathrm{adj}} \le P_{\mathrm{CHP},i}^{\max} - k_{2,i} Q_{\mathrm{CHP},i}^{\mathrm{adj}} \end{gathered} \tag{1}$$

where: $Q_{\mathrm{CHP},i}^{\max}$ represents the maximum heating power, while $P_{\mathrm{CHP},i}^{\max}$ and $P_{\mathrm{CHP},i}^{\min}$ correspond to the maximum and minimum generating power values of CHP unit *i*, respectively. In the feasible domain, $Q_{\mathrm{CHP},i}^{\mathrm{adj}}$ and $P_{\mathrm{CHP},i}^{\mathrm{adj}}$ represent the heating power and power supply of CHP unit *i*, respectively. $k_{1,i}$, $k_{2,i}$, $k_{3,i}$ are the slopes of the electrothermal characteristic boundary of CHP unit *i*.

A CHP unit can be divided into three subsystems according to the different functions of each unit, as shown in Figure 2. The Markov process model is used to predict the state probability of CHP units, and the state space of CHP units can be obtained according to the different states of each subsystem, as shown in Figure 3. In Figure 3, R and F in the ellipse are the operating state and fault state of each subsystem, respectively, and λ and μ are the failure rate and repair rate between different states, respectively [6].

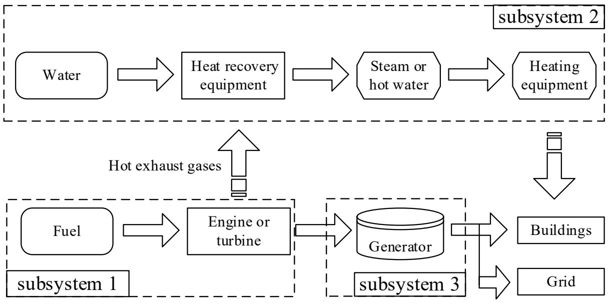

Figure 2: Subsystems in the CHP unit

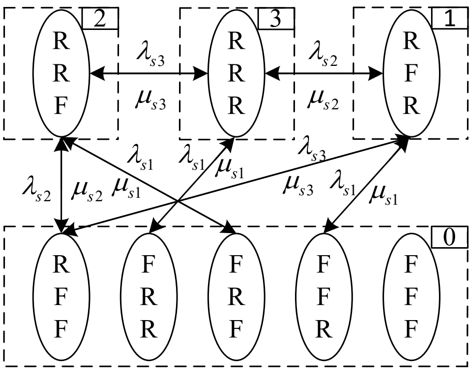

Figure 3: State space of CHP units

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The probability of the CHP unit in each state can be calculated according to the state space diagram, as shown in Equation (2).

$$\begin{cases}(\lambda_{s1}+\lambda_{s2}+\lambda_{s3})p_{i,3}=\mu_{s3}p_{i,2}+\mu_{s2}p_{i,1}+\mu_{s1}p_{i,0}\\(\lambda_{s1}+\lambda_{s2}+\mu_{s3})p_{i,2}=\lambda_{s3}p_{i,3}+(\mu_{s2}+\mu_{s1})p_{i,0}\\(\lambda_{s1}+\lambda_{s3}+\mu_{s2})p_{i,1}=\lambda_{s2}p_{i,3}+(\mu_{s3}+\mu_{s1})p_{i,0}\\p_{i,3}+p_{i,2}+p_{i,1}+p_{i,0}=1\end{cases} \tag{2}$$

where: $p_{i,3}$, $p_{i,2}$ and $p_{i,0}$, respectively, are the steady-state probabilities of CHP unit *i* in states 3, 2, 1, and 0, respectively.

In state 0, the performance level can be represented as (0,0) if it is in the fault state and does not produce any energy. In state 1, the performance level can be represented as (0, $P_{\mathrm{CHP},i}^{\max}$). In state 2, the performance level can be represented as ($Q_{\mathrm{CHP},i}^{\max}$,0). In state 3, it can output both thermal power and electrical power, its performance level can be represented as ($Q_{\mathrm{CHP},i}^{\mathrm{adj}}$, $P_{\mathrm{CHP},i}^{\mathrm{adj}}$). Therefore, the state distribution of CHP units is shown in equation (3).

$$(Q_{\mathrm{CHP},i},P_{\mathrm{CHP},i})=\begin{cases}(Q_{\mathrm{CHP},i}^{\mathrm{adj}},P_{\mathrm{CHP},i}^{\mathrm{adj}}) & ,\ \text{state 3}\\(Q_{\mathrm{CHP},i}^{\max},0) & ,\ \text{state 2}\\(0,P_{\mathrm{CHP},i}^{\max}) & ,\ \text{state 1}\\(0,0) & ,\ \text{state 0}\end{cases} \tag{3}$$

3. IEHS Optimal Load Shedding Model

When the IEHS is insufficient due to failure, it is necessary to reduce the electricity and heat load to ensure the safe operation of the system.

3.1. Objective Function

Based on the constraints of the IEHS optimal energy flow calculation, the goal is to minimize the sum of the electrical and thermal loads, which can be expressed as:

$$\min\ f=\sum_{i=1}^{\mathrm{N_e}}\omega_{\mathrm{e}}\Delta P_i+\sum_{n=1}^{\mathrm{N_h}}\omega_{\mathrm{h}}\Delta Q_n \tag{4}$$

where: ΔP_i and ΔQ_n are the load shedding of the power system node i and the thermal system node n, respectively. $\mathrm{N_e}$ and $\mathrm{N_h}$ are the number of nodes of the power system and the thermal system, respectively. ω_{e} and ω_{h} are the weights of electrical and thermal energy in the total energy in the system, respectively.

3.2. Constraints

The constraints of IEHS mainly include thermal system constraints, power system constraints, and coupling element constraints.

3.2.1. Thermal System Constraints

Thermal system constraints include hydraulic and thermal model constraints [7]:

$$\begin{aligned}\sum_{q\in\psi_{\mathrm{T},n}}m_q^{\mathrm{SU}}+m_n^{\mathrm{G}}&=\sum_{q\in\psi_{\mathrm{F},n}}m_q^{\mathrm{SU}}+m_n^{\mathrm{L}}\\\sum_{q\in\psi_{\mathrm{T},n}}m_q^{\mathrm{RE}}+m_n^{\mathrm{G}}&=\sum_{q\in\psi_{\mathrm{F},n}}m_q^{\mathrm{RE}}+m_n^{\mathrm{L}}\end{aligned} \tag{5}$$

$$\begin{aligned} \Delta p_q^{\mathrm{SU}} &= K_q m_q^{\mathrm{SU}} \left| m_q^{\mathrm{SU}} \right| \\ \Delta p_q^{\mathrm{RE}} &= K_q m_q^{\mathrm{RE}} \left| m_q^{\mathrm{RE}} \right| \end{aligned} \tag{6}$$

$$\begin{aligned} \sum_{q \in \psi_{\mathrm{loop}}} \boldsymbol{B} \Delta p_q^{\mathrm{SU}} &= 0 \\ \sum_{q \in \psi_{\mathrm{loop}}} \boldsymbol{B} \Delta p_q^{\mathrm{RE}} &= 0 \end{aligned} \tag{7}$$

$$\begin{aligned} QG_n &= \mathrm{C_P}\, m_n^{\mathrm{G}} (TS_n^{\mathrm{G}} - TR_n^{\mathrm{G}}) \\ Q_{\mathrm{LD},n} - \Delta Q_n &= \mathrm{C_P}\, m_n^{\mathrm{L}} (TS_n^{\mathrm{L}} - TR_n^{\mathrm{L}}) \end{aligned} \tag{8}$$

$$\begin{aligned} TS_q^{\mathrm{OUT}} &= (TS_q^{\mathrm{IN}} - \mathrm{T}_{q,\mathrm{a}}) \mathrm{e}^{-\lambda_q L_q / (\mathrm{C_P}\, \boldsymbol{m}_q^{\mathrm{SU}})} + \mathrm{T}_{q,\mathrm{a}} \\ TR_q^{\mathrm{OUT}} &= (TR_q^{\mathrm{IN}} - \mathrm{T}_{q,\mathrm{a}}) \mathrm{e}^{-\lambda_q L_q / (\mathrm{C_P}\, \boldsymbol{m}_q^{RE})} + \mathrm{T}_{q,\mathrm{a}} \end{aligned} \tag{9}$$

$$\begin{aligned} \sum_{q \in \psi_{\mathrm{F},n}} m_q^{\mathrm{SU}} TS_q^{\mathrm{OUT}} + m_n^{\mathrm{G}} TS_n^{\mathrm{G}} &= TS_n \Big(\sum_{q \in \psi_{\mathrm{T},n}} m_q^{\mathrm{SU}} + m_n^{\mathrm{G}} \Big) \\ \sum_{q \in \psi_{\mathrm{F},n}} m_q^{\mathrm{RE}} TR_q^{\mathrm{IN}} + m_n^{\mathrm{L}} TR_n^{\mathrm{L}} &= TR_n \Big(\sum_{q \in \psi_{\mathrm{T},n}} m_q^{\mathrm{RE}} + m_n^{\mathrm{L}} \Big) \end{aligned} \tag{10}$$

where: $\psi_{\mathrm{T},n}$, $\psi_{\mathrm{F},n}$, ψ_{loop} are respectively the collection of pipes flowing into node *n*, the collection of pipes flowing out of node *n*, the collection of pipes forming a loop. m_q^{SU} and m_q^{RE} are the water flow rate supplying pipeline *q* and the water flow returning pipeline *q*. m_n^{G} and m_n^{L} are the flow rate of water required for the supply and load of the heat source at node *n*, respectively. Δp_q^{SU} and Δp_q^{RE} are pressure losses for the supply loop and return loop of pipeline *q*. K_q is the resistance coefficient of pipeline q. ***B*** is the loop correlation matrix. QG_n is the output power of the heat source at node *n*. $\mathrm{C_P}$ is the specific heat capacity of water. λ_q is the thermal conductivity of pipe *q*. L_q is the length of the pipe *q*. TS_q^{IN}, TS_q^{OUT}, TR_q^{IN}, TR_q^{OUT} are the inlet temperature and outlet temperature of the supply pipeline *q*, and the inlet temperature and outlet temperature of the return pipeline *q*, respectively. $\mathrm{T}_{q,\mathrm{a}}$ is the ambient temperature of pipe *q*.

3.2.2. Power System Constraints

In the reliability assessment of IEHS, the power system usually adopts the optimal power flow based on DC power flow as the power constraint to reduce the amount of computation in the simulation process. The model is:

$$P_{\mathrm{w},i} + P_{\mathrm{pv},i} + P_{\mathrm{CHP},i} + P_{\mathrm{G},i} - P_{\mathrm{EHP},i} - P_{\mathrm{LD},i} + \Delta P_i - \sum_{j=1}^{N_{\mathrm{c},i}} P_{ij} = 0 \tag{11}$$

$$P_{ij} = (\theta_i - \theta_j) / X_{ij} \tag{12}$$

$$0 \le \Delta P_i \le P_{\mathrm{LD},i} \tag{13}$$

$$P_{ij,\min} \le P_{ij} \le P_{ij,\max} \tag{14}$$

$$P_{\mathrm{G},i}^{\min} \le P_{\mathrm{G},i} \le P_{\mathrm{G},i}^{\max} \tag{15}$$

where: $P_{\mathrm{G},i}$, $P_{\mathrm{EHP},i}$, P_{ij} are respectively the output power of the conventional unit at node *i*, the electrical power required by the EHP unit, and the transmission power from the transmission line node *i* to node *j*. $N_{\mathrm{c},i}$ is the number of nodes connected to node *i*. θ_i is the voltage phase angle of node *i*. X_{ij} is the reactance of the transmission line from node *i* to node *j*.

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3.2.3. Coupling Component Constraints

The coupling elements are mainly CHP units and EHP units. The constraints of the CHP unit are shown in equation (1), and the EHP unit is a device that consumes electricity to generate heat, and its constraint is:

$$Q_{\mathrm{EHP},k} = \alpha_{\mathrm{EHP},k} P_{\mathrm{EHP},k} \tag{16}$$

where: $Q_{\mathrm{EHP},k}$ and $\alpha_{\mathrm{EHP},k}$ are the thermal power and power-to-heat efficiency of EHP unit *k*.

4. Method and Indicators of IEHS Reliability Assessment

In this paper, a reliability evaluation method for considering the uncertainty of wind, solar and load for multi-state units is proposed, and the definitions and calculation formulas of IEHS reliability indicators Loss of Load Probability (LOLP) and Expected Energy Not Suppled (EENS) are given.

4.1. IEHS Reliability Assessment Method

Based on the optimal load reduction model and the multi-state model of CHP units, considering the uncertainty of the output and load of wind power and photovoltaic units, the reliability assessment of IEHS is carried out by Monte Carlo simulation method, and the specific steps are as follows, as shown in Figure 4.

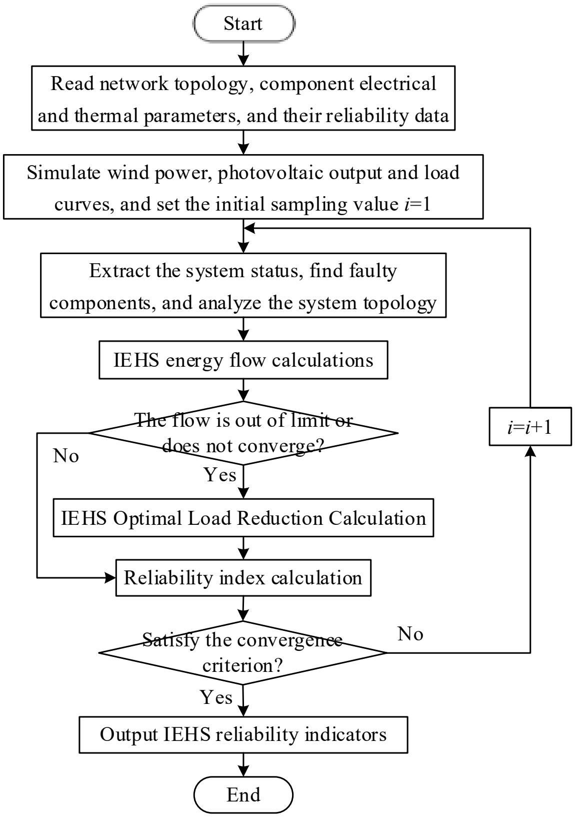

Figure 4: Reliability assessment process of IEHS

4.2. LOLP

The meaning of this metric is the probability that the system will experience load shedding on average per year, and its formula is as follows:

$$LOLP_{\mathrm{e,s}} = \frac{1}{N}\sum_{i=1}^{N}\left(\sum_{x\in\Omega_x} p(x)\cdot If(\Delta P_{\mathrm{e,s}}(x) > 0)\right) \tag{17}$$

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$$LOLP_{\mathrm{h,s}} = \frac{1}{N}\sum_{i=1}^{N}\left(\sum_{x\in\Omega_x} p(x)\cdot If(\Delta Q_{\mathrm{h,s}}(x) > 0)\right) \tag{18}$$

$$LOLP_{\mathrm{s}} = \frac{1}{N}\sum_{i=1}^{N}\left(\sum_{x\in\Omega_x} p(x)\cdot\left(If(\Delta P_{\mathrm{e,s}}(x) > 0) \,\|\, If(\Delta Q_{\mathrm{h,s}}(x) > 0)\right)\right) \tag{19}$$

where: *N* is the total number of sampling years. Ω_x is a collection of all scenes. $p(x)$ is the probability of scenario *x*. $LOLP_{\mathrm{e,s}}$, $LOLP_{\mathrm{h,s}}$ and $LOLP_{\mathrm{s}}$ are the probability of power grid power loss load, heat network heat loss load probability and system load loss probability respectively.

4.3. EENS

The meaning of this indicator is the expected value of the system's average annual energy supply shortfall, and its calculation formula is:

$$EENS_{\mathrm{e,s}} = \frac{8760}{N}\sum_{i=1}^{N}\left(\sum_{x\in\Omega_x} p(x)\cdot\Delta P_{\mathrm{e,s}}(x)\right) \tag{20}$$

$$EENS_{\mathrm{h,s}} = \frac{8760}{N}\sum_{i=1}^{N}\left(\sum_{x\in\Omega_x} p(x)\cdot\Delta Q_{\mathrm{h,s}}(x)\right) \tag{21}$$

$$EENS_{\mathrm{s}} = \omega_{\mathrm{e}} EENS_{\mathrm{e,s}} + \omega_{\mathrm{h}} EENS_{\mathrm{h,s}} \tag{22}$$

where: $EENS_{\mathrm{e,s}}$, $EENS_{\mathrm{h,s}}$ and $EENS_{\mathrm{s}}$ are expected to be insufficient for the total energy supply of electricity, heat and the system, respectively.

5. Case Simulation

5.1. Summary of the Example

The IEHS constructed in this paper is composed of a 24-node power system and a 32-node thermal system, and its topology is shown in Figure 5. Among them, the power grid data comes from the Matpower toolbox, and the heat network data comes from the reference [8].

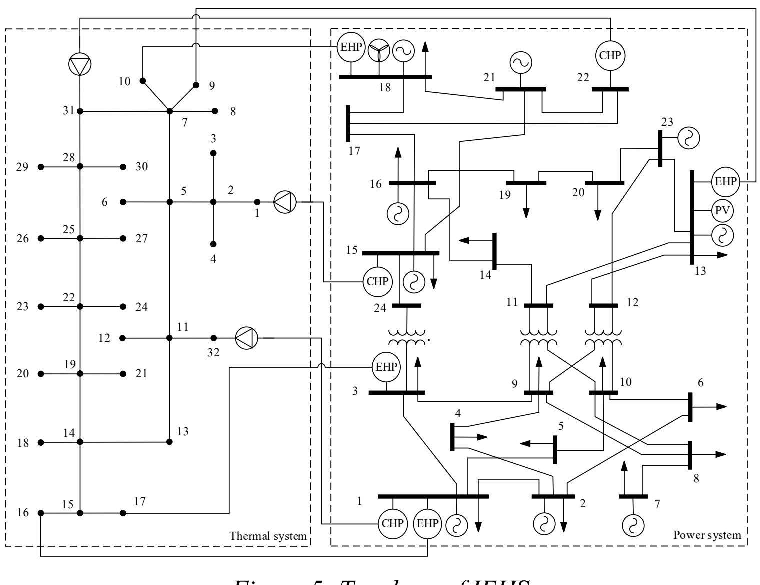

Figure 5: Topology of IEHS

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5.2. The Impact of Multi-State Units on IEHS Reliability

The reliability assessment of the case is carried out by the two-state model and the multi-state model of the CHP unit, and Figure 6 displays the simulation results, whereas Figure 7 illustrates the outputs of the CHP unit across various feasible domains.

It can be seen from Figure 6 that the convergence of the reliability index LOLP and EENS is fluctuating, and with the increase of the number of sampling, the reliability index will eventually fluctuate up and down a certain value; When some components such as the waste heat boiler fail, the operation mode of the unit is adjusted to continue to ensure the supply of electric load or heat load, thereby improving the reliability of the system.

As depicted in Figure 7, it is evident that the electric and thermal output of the CHP unit under the two-state model and the multi-state model is basically on the boundary of the feasible domain, and the output of the CHP unit is basically the same, because the states 1 and 2 of the multi-state CHP unit can ensure the normal power supply and heat supply of the unit in the case of failure, while the two-state CHP unit can only increase the output of the unit or reduce the load to meet the normal operation of the system.

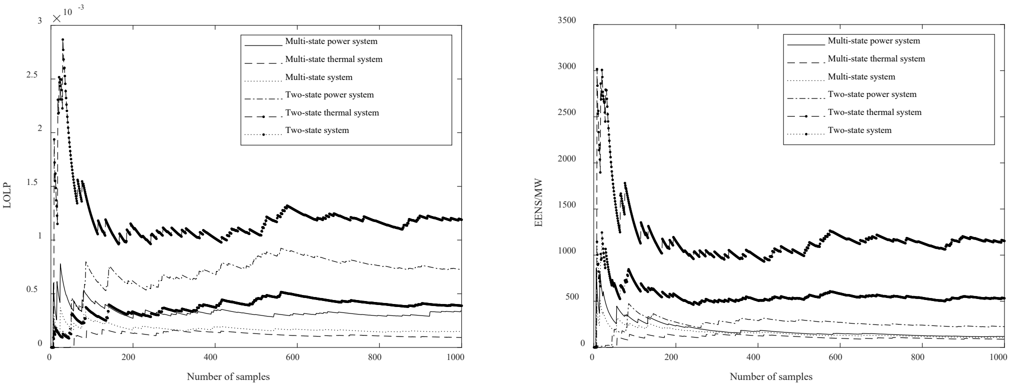
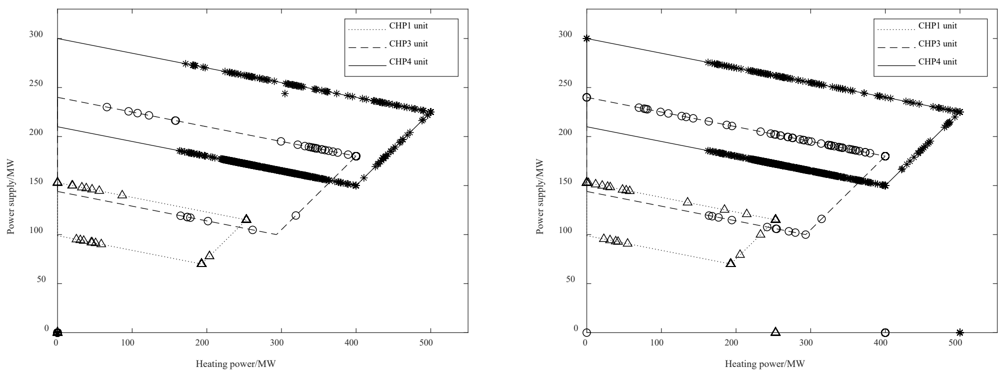


Figure 6: LOLP and EENS for each system in different states



(a) Two state CHP units *(b) Multi-state CHP units*

Figure 7: Feasible region for units CHP 1, 3, 4

5.3. Effect of EHP Capacity on IEHS Reliability

In order to reduce the influence of uncertainty on the reliability of IEHS, the change of reliability index of EHP capacity analysis system can be adjusted, and the outcomes of the simulation are depicted in Figures 8 and 9.

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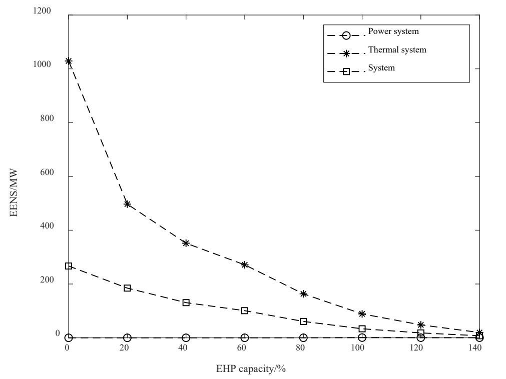

Figure 8: EENS for each system

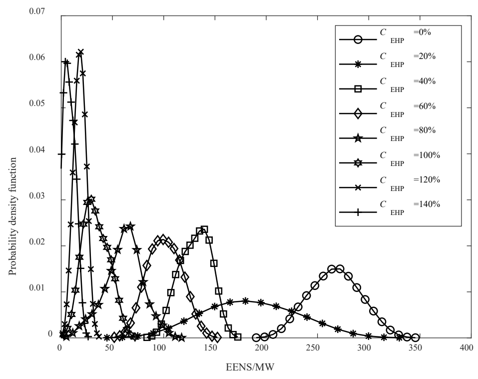

Figure 9: Probability density function of EENS of system

It can be seen from Figure 8 and Figure 9 that with the increase of EHP unit capacity, the system reliability index EENS decreases significantly, and the upper limit of its fluctuation range is gradually decreasing, the operational flexibility of IHES is enhanced by EHP units, as they convert electrical power into thermal power., thereby avoiding load reduction to a certain extent, therefore, reasonable adjustment of EHP unit capacity can effectively align with the peak-to-valley characteristics of wind power, photovoltaic output, and load, thereby improving the system's reliability..

6. Conclusions

In this paper, an IEHS optimal load reduction model for multi-state units is established, an IEHS reliability assessment method considering the uncertainty of wind, solar and wind loads is proposed, the influence of multi-state units and EHP capacity on IEHS reliability is quantitatively evaluated, and the effectiveness of the model and solution method is confirmed through example simulation, which provides a certain theoretical basis for the safe operation analysis of IEHS and reaches the following conclusions: 1) The reliability model of the multi-state unit reflects the more realistic output of the unit, and the multi-state unit exhibits a significantly higher system reliability level compared to the two-state unit. 2) By rationally adjusting the capacity of EHP, it can be better aligned with the peak-to-valley characteristics of uncertain factors, thereby enhancing the system's reliability.

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