

Reliability Evaluation of Electricity-heat Integrated Energy System with Heat Pump

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Abstract—Integrated energy system (IES) has the advantages of improving the efficiency of energy utilization and promoting the consumption of renewable energy. It is of great importance to evaluate the reliability of an IES. This paper proposes a novel reliability evaluation method for the electricity-heat IES with heat pump. First, the load-point reliability indices and system-level reliability indices are defined according to the characteristics of electricity-heat IES. Second, the model of maximum output heat power of heat pump at the user-side considering the safety criterion of distribution network is established, and the step-varied repeated power flow method is applied to solve the model. Third, the reliability evaluation procedure of electricity-heat IES with heat pump based on the Monte Carlo simulation is presented. Case studies are carried out on the electricity-heat IES of an industrial park, and the results show that the configuration site, capacity and coefficient of performance of heat pump as well as the security constraints of distribution network can significantly affect the reliability indices.

Index Terms—Electricity-heat integrated energy system, heat pump, Monte Carlo simulation, reliability evaluation, security constraints.

I. INTRODUCTION

WITH the worsening of the global energy crisis and environmental pollution, traditional ways of energy supply are unable to satisfy the rapidly increasing energy needs of human society. Integrated energy system (IES) has the advantages of improving the efficiency of energy utilization and promoting the consumption of renewable energy, and it is also recognized as the future direction of energy supply [1], [2]. IES is capable of coordinating and optimizing the distribution, conversion and consumption of all kinds of energy. It breaks down the traditional mode of power supply, gas supply, heat supply and cool supply, which are planned, designed and operated separately [3]. Since the reliability indices can provide valuable references to the planning and operation of IES, it is of great importance to evaluate the reliability accurately.

Several previous studies have been conducted on the reliability evaluation methods of IES. In [4], a model is established for analyzing and calculating the expected reliability of the supply and expected energy not supplied in IES considering the mutual dependence of multi-carrier energy. Reference [5] proposes a method to evaluate the reliability of IES based on smart agent communication, in which system reconfiguration is innovatively integrated into the reliability evaluation process. In [6], a gas system is combined with an electrical distribution system, and the reliability evaluation model for the combined system is proposed. In [7], the effects of the combined cooling, heating and power (CCHP) system on the reliability of energy supply are studied, and simulation results show that combining the supply of electricity, cool and heat can significantly improve the overall reliability. In [8], the positive influence of the CCHP system on the reliability of the distribution network is researched. In [9] and [10], the reliability evaluation methods based on the energy hub model are presented. Reference [11] analyzes the influence of combined power, gas, and thermal networks on the reliability of the energy supply. Reference [12] presents a sequential Monte Carlo model of the combined GB gas and electrical system, and the reliability indices such as loss of load probability and expected energy unserved are studied. In [13], a reliability model of IES considering the dynamic behavior of heat loads is proposed, and the results indicate that the dynamic behavior of the heat load should not be neglected when evaluating the energy supply reliability of IES. In [14], a reliability evaluation model of IES with energy storage considering multi-energy coupling and grade difference is proposed, and Monte Carlo simulation with the failure mode and effect analysis method are used to obtain the reliability indices.

From a review of the above references, it can be seen that some impressive achievements have been made on the reliability evaluation of IES. However, there exists three problems in the above researches: (a) the reliability indices of IES are relatively rough, which are primarily based on the traditional power supply reliability indices; (b) the influence of user-side distributed energy conversion equipment (such as heat pumps) whose input is the secondary energy on the reliability of IES is ignored; (c) the reliability evaluation model of IES which is based on the energy hub model cannot consider the security constraints of the power system, such as nodal voltage limits and branch current limits. Therefore, further research on the reliability evaluation of IES should be performed.

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This paper focuses on the electricity-heat IES when evaluating the reliability. First, the load-point reliability indices and system-level reliability indices are defined according to the characteristics of electricity-heat IES. Then, the model of maximum output heat power of heat pump at the user-side considering the safety criterion of the distribution network is established, and the corresponding solving strategy based on the step-varied repeated power flow method is applied to solve the model. On this basis, the reliability evaluation method of electricity-heat IES with heat pump based on the Monte Carlo simulation is presented. At last, case studies carried out on the electricity-heat IES of an industrial park verify the feasibility and effectiveness of the proposed reliability evaluation method.

The rest of this paper is organized as follows: the reliability indices of electricity-heat IES are defined in Section II. The calculation method of the maximum output power of heat pump considering the security constraints of the distribution network is described in Section III. Section IV presents the reliability evaluation method. And the performances of the proposed method are studied in Section V. Finally, Section VI concludes this paper.

II. RELIABILITY INDICES OF ELECTRICITY-HEAT IES

Electricity-heat IES transmits and distributes power through the electrical lines and heat pipes to meet the energy needs of different users. However, electricity and heat have different characteristics of transmission and distribution [15], [16]. The transmission and distribution of electricity can be accomplished instantaneously. Without considering the electrical energy storage devices, once a failure occurs in the distribution network, the affected customers will be powered off within an extremely short period of time. The time scale of heat transmission and distribution is longer than that of electricity. When the heat load stops being heated, the heat will not dissipate immediately, and the loss of heat will be reflected after a period of time. Moreover, different types of heat customers are distinguished in the requirement of heat quality. The customers whose heat demand quality is high do not allow intermittent heat supply, while others whose heat demand quality is not high allow short-term interruption of heat supply because of the building's thermal insulation properties [17].

In order to evaluate the reliability of electricity-heat IES accurately, it is of great necessity to take into account the differences of transmission and distribution characteristics of electricity and heat when formulating the reliability indices. This section proposes a series of load-point reliability indices and system-level reliability indices of electricity-heat IES.

A. Load-point Reliability Indices

There are three basic load-point indices for the reliability evaluation of electricity-heat IES, i.e., the failure rate of load-point (λ , times/year), the energy interrupting duration of load-point (r , hours/time), and the annual average energy interrupting duration of load-point (U , hours/year). The relationship among the three indices is shown in formula (1):

$$r = \frac{U}{\lambda} \quad (1)$$

The load-point reliability indices of the distribution network [18], [19] can be directly used in the reliability evaluation of IES in terms of the power supply system, i.e., the failure rate of the electricity load-point λ^e , the interrupting duration of the electricity load-point r^e , and the annual average interrupting duration of the electricity load-point U^e .

In heat system, not all of the failures of components will lead to the lack of heating for the heat load. The heat load can be divided into the following two categories: I-type heat load and II-type heat load. Among them, I-type heat load does not allow intermittent heating and has a higher requirement for the heating quality, such as the production process heat load; II-type heat load allows for intermittent heating and has a lower heat quality requirement, such as the heat load of civil heating. Different load-point reliability indices are selected for these two categories of heat load. For I-type heat load, the calculation method of load-point reliability indices is the same as those of the distribution network. For II-type heat load, if the repair time of the fault components (τ) is less than or equal to the allowable interruption time of heating (T), then no fault happens to the heat load; if the repair time of the fault component is bigger than the allowable interruption time of heating, then the heat system is regarded as a failure.

The allowable interruption time of heating for the II-type heat load can be obtained by using the temperature drop model [17]:

$$T = \chi \ln \frac{t_n - t_w - \frac{Q}{q_0 V}}{t_n^{\min} - t_w - \frac{Q}{q_0 V}} \quad (2)$$

where, χ is the coefficient of the heat reserve of the building; t_n is the indoor temperature of the building; t_w is the temperature of the outdoor air; $t_n^{\min}$ is the indoor minimum allowable temperature; q_0 is the heat indices of the unit heating volume of the building; V is the building's peripheral volume; Q is the capacity of the heat being supplied to the building under fault conditions, and $Q = 0$ represents the heat load being disconnected from the heat network in the event of a fault.

If the allowable interruption time of heating is determined, the number of faults and the load-point failure rate (λ^h , times/year) of the II-type heat load after correction can be calculated. And the corresponding heat interrupting duration of the load-point (r^h , hours/times) can be calculated by:

$$r^h = \max \{(\tau - T), 0\} \quad (3)$$

Furthermore, the annual average interrupting duration of the II-type heat load (U^h , hours/year) can be calculated by formula (1).

B. System-level Reliability Indices

Considering the characteristics of the combined supply of electricity and heat, the system-level reliability indices of the electricity-heat IES are defined in this section, i.e., the system interruption frequency (SIF_{IES} , times/customer/year), the system interruption duration (SID_{IES} , hours/customer/year), the system energy not supplied ($SENS_{IES}$, MWh/customer/year) and the system service availability (SSA_{IES} , %). The system-level reliability indices can be achieved according to the load-points reliability indices, and their calculation formulas are as

follows:

$$SIF_{IES} = \frac{\sum_{i \in E} \lambda_i^e N_i^e + \sum_{i \in H} \lambda_i^h N_i^h}{\sum_{i \in E} N_i^e + \sum_{i \in H} N_i^h} \quad (4)$$

$$SID_{IES} = \frac{\sum_{i \in E} U_i^e N_i^e + \sum_{i \in H} U_i^h N_i^h}{\sum_{i \in E} N_i^e + \sum_{i \in H} N_i^h} \quad (5)$$

$$SENS_{IES} = \sum_{i \in E} L_i^e U_i^e + \sum_{i \in H} L_i^h U_i^h \quad (6)$$

$$SSA_{IES} = 1 - \frac{\sum_{i \in E} U_i^e N_i^e + \sum_{i \in H} U_i^h N_i^h}{8760 \left(\sum_{i \in E} N_i^e + \sum_{i \in H} N_i^h \right)} \quad (7)$$

where, E is the set of load-points of the electricity network; H is the set of load-points of the heat network; N_i^e and N_i^h are the number of customers of the i th load-point in the electricity network and heat network, respectively; L_i^e and L_i^h represent the electricity demand and heat demand of the i th load-point in the electricity network and heat network, respectively.

III. CALCULATION OF THE MAXIMUM OUTPUT HEAT POWER OF HEAT PUMP CONSIDERING DISTRIBUTION NETWORK SECURITY CONSTRAINTS

Safety energy supply is one of the basic requirements for the planning and operation of IES, which is the precondition of reliable energy supply. Different energy supply networks (such as electricity network, gas network, heat network, cool network, etc.) in IES have their own safety guidelines. This paper focuses on the electricity-heat IES with heat pump. Due to the differences of the energy grade of electricity and heat, there are few cases where the user-side is equipped with heat-electricity conversion equipment. Therefore, only electricity-heat conversion equipment is considered at the user-side in this paper, and heat pump is selected as the energy conversion equipment. The input of heat pump is the electricity from the distribution network. Due to the security constraints of the distribution network, the output heat power of heat pump cannot increase infinitely.

A. Principle of Heat Pump

A heat pump is a device that makes heat flow from a low temperature medium to a high temperature medium. Heat pump can absorb heat from the environment through the driven of electricity and offer heat to the building, which is energy-saving and environment-friendly. According to the different sources of heat, heat pumps can be divided into air source heat pump and ground source heat pump. The heat source of air source heat pump is the outdoor air, from which it absorbs heat and raises the temperature for indoor heating. Due to the air temperature limits, overheating or cooling will reduce the efficiency of air source heat pump. The heat source of ground source heat pump is the earth. Since the earth can store heat, it is equal to an accumulator, which can improve the energy efficiency of ground source heat pump. The key index for a

heat pump is the coefficient of performance (COP), i.e., the ratio of the output heat power to the input electrical power of the heat pump [20], [21]. The COP of the heat pump will change according to the temperature differences between the heat source and the heat load.

The calculation method of the COP [20], [21] is as follows:

$$COP = \frac{P_{h,HP}}{P_{e,HP}} \quad (8)$$

where, $P_{h,HP}$ is the output heat power of the heat pump; $P_{e,HP}$ is the input electrical power of the heat pump.

B. Model of Maximum Output Heat Power of Heat Pump under the Security Constraints of the Distribution Network

The most important feature of IES is the mechanism of complementary provided by multiple energy sources. Specifically, for a given customer's demand, the energy sources are not unique, and there may be several energy supply schemes. If one type of energy supply network fails in an IES, not all of the load will be out of supply, and part of the load can still be supplied through the energy conversion equipment from other types of energy supply networks. In this way, the reliability of the IES can be greatly improved. Fig. 1 shows the schematic diagram of the user-side heat pump connecting to the electricity-heat IES. For the electricity load, its demand only can be supplied by the distribution network. But for the heat load, its demand can be satisfied not only by the heat network, but also by the distribution network through the heat pump. If the heat network fails and turns to limited heating, the heat pump can continue heating for the heat load. Therefore, the maximum output heat power of heat pump under the security constraints of the distribution network should be determined before evaluating the reliability of electricity-heat IES with heat pump.

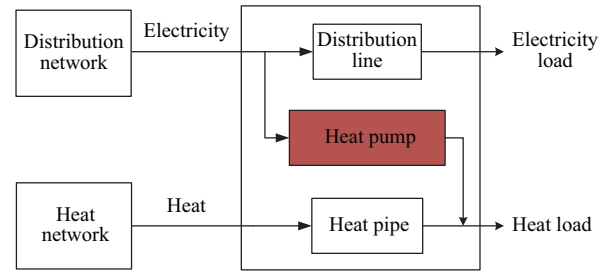


Fig. 1. Schematic diagram of user-level heat pump connecting to the electricity-heat IES.

Let $\{s_{eh}\}$ be the set of heat pumps. The devices in $\{s_{eh}\}$ play different roles in the distribution network and heat network. They can be regarded as the load in the distribution network while they can be considered as the source in the heat network. The essence of calculating the maximum output heat power is to determine the maximum input electrical power of the heat pumps in $\{s_{eh}\}$. Due to the security constraints of the distribution network, there is an upper limit to the input electrical power of the heat pump. This limited value is modeled and solved as follows.

Distribution network has the characteristics of a closed-loop design and open-loop operation, and has few dynamic

components. The N-1 static safety analysis method is usually applied to analyze it [22]. According to the type of components, N-1 can be divided into feeder N-1 verification and main transformer N-1 verification. When the feeder or the main transformer has N-1 disconnected, it is required that the distribution network can supply all the load by reconfiguration, and ensure that the nodal voltage and line power are within the restrictions. Under the security constraints of distribution network, the maximum output heat power of the heat pump can be calculated by formula (9):

$$P_{HP,i} = COP_i \times \min \{P'_i, P_i^r\} \quad (9)$$

where, $P_{HP,i}$ is the output heat power of the i th heat pump; COP_i is the coefficient of performance of the i th heat pump; P'_i is the maximum input electrical power of the i th heat pump under the security constraints of the distribution network; and P_i^r is the rated input electrical power of the i th heat pump.

To obtain the maximum output heat power of the heat pump under the security constraints of the distribution network, the key is to determine P'_i in formula (9). Determining P'_i is equal to calculating the maximum increment ratio (k) of the input electrical power of the heat pump, and the mathematical model is as shown in formula (10) and formula (11). The objective function of the model is to maximize the increment ratio of the input electrical power of the heat pump, and the constraints contain power flow equation, nodal voltage restriction, branch current restriction, and main transformer capacity restriction. Objective:

$$\max k \quad (10)$$

Subject to:

$$\begin{cases} f(\mathbf{X}) + k\mathbf{P} = 0 \\ V_{i,\min} \leq V_i \leq V_{i,\max} \\ I_l \leq I_{l,\max} \\ S_j \leq S_{j,\max} \end{cases} \quad (11)$$

where, $f(\mathbf{X})$ is the power flow equations under the basic load, $\mathbf{P}$ is the electrical power growing pattern vector of the input of the heat pumps; V_i is the nodal voltage at bus i , $V_{i,\min}$ and $V_{i,\max}$ are, respectively, the lower and upper nodal voltage at bus i ; I_l is the current at branch l , while $I_{l,\max}$ is the allowed maximum current; S_j is the apparent power of the j th main-transformer, and $S_{j,\max}$ is the maximum capacity it can supply.

C. Solving Strategy

The mathematical model described in formula (10) and formula (11) can be solved by the step-varied repeated power flow method [23]. As long as the maximum increment ratio of the input electrical power of the heat pump is determined, the maximum output heat power of the heat pump can be obtained. Fig. 2 shows the flow chart of calculating the maximum output heat power of the heat pump, and the main steps are described as follows:

Step 1: Input the structure information of the distribution network, load, set of heat pumps $\{s_{eh}\}$, etc. Determine the initial step size k and the convergence precision ε .

Step 2: Judge whether the step size k meets the convergence precision or not. If yes, stop the iteration and go to step 6; otherwise, go to step 3.

Step 3: Increase the input electrical power of the i th heat pump from the reference value P_i to P'_i by the percentage of k .

Step 4: Let P'_i be the reference value, and the main transformer N-1 and feeder N-1 are verified, respectively.

Step 5: If all the N-1 checking are satisfied, the new load is taken as the reference load, and then go back to Step 2. If any N-1 checking fails, let $k = k/2$, and go back to Step 3.

Step 6: Calculate the maximum output heat power of the i th heat pump by formula (9).

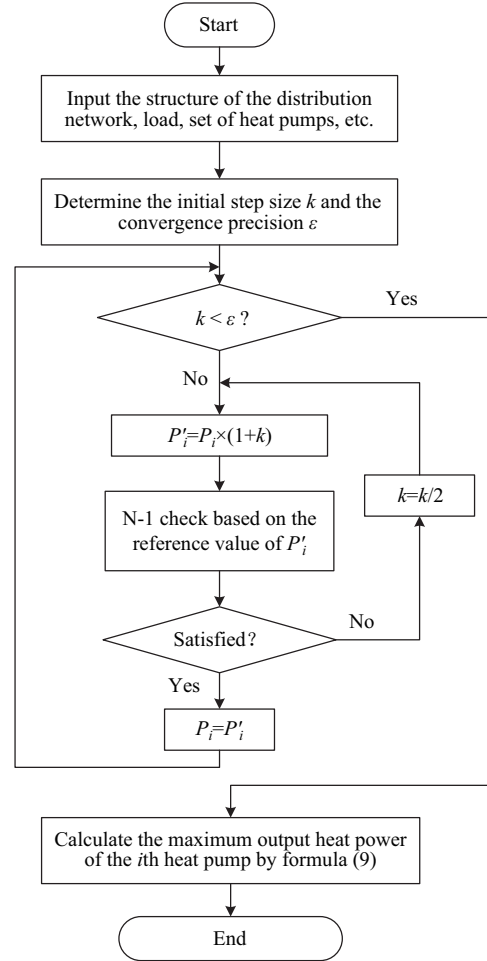


Fig. 2. Flow chart of calculating the maximum output heat power of the heat pump.

IV. RELIABILITY EVALUATION METHOD OF ELECTRICITY-HEAT IES WITH HEAT PUMP

The two-state model is applied to all the components of electricity-heat IES with heat pump, and only permanent faults of the components are considered. Monte Carlo simulation method is used to evaluate the reliability of electricity-heat IES with heat pump and the main ideas are as follows: first, the duration of the operating conditions of the components is randomly sampled; second, all the fault events of the electricity-heat IES with heat pump in the simulation period

are listed; at last, the reliability indices are calculated. The detailed procedure of evaluating the reliability of electricity-heat IES with heat pump is as follows.

Step 1: Input the parameters of the electricity-heat IES, and determine the simulation period.

Step 2: The two-state model is used to model all the components, and the i th component's two-state model is shown in Fig. 3. "Normal" indicates that the component is under normal state, and "Fault" indicates that the component is under fault state. λ_i and μ_i are the average failure rate and average repair rate of component i , respectively.

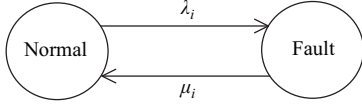


Fig. 3. Two-state model of component i .

The most widely-used exponential distribution [5], [24] is applied to describe the probability distribution of the failure rate and repair rate of all the components. The time to failure (TTF_i) and time to repair (TTR_i) of component i can be calculated by formula (12) and formula (13), respectively [5], [24].

$$TTF_i = -\frac{1}{\lambda_i} \ln U_1 \quad (12)$$

$$TTR_i = -\frac{1}{\mu_i} \ln U_2 \quad (13)$$

where, U_1 and U_2 are uniformly distributed random numbers in the interval of $[0, 1]$.

Assume that all the components are under the normal state at the starting time of the Monte Carlo simulation, the TTF and TTR of each component are sampled one by one, and the sequences of the durations of the operating states of all the components are formulated.

Step 3: Set the current simulation time as the starting point, find out the component whose state changes the quickest at the next time, and advance the simulation time.

Step 4: Judge whether the distribution network and heat network are faulty or not. If the distribution network is faulty, the load in the distribution network will be transferred. If the heat network is faulty, calculate the maximum output heat power of the heat pump considering the security constraints of the distribution network according to the description in section III.

Step 5: Calculate the load-point reliability indices λ , r and U according to the method in part A of section II.

Step 6: Judge whether the simulation period is completed or not. If yes, go to step 7; otherwise, go back to step 3.

Step 7: According to the load-point reliability indices, calculate the system-level reliability indices according to the method in part B of Section II.

In order to illustrate the procedure of evaluating the reliability of electricity-heat IES with heat pump more clearly, the above procedure are presented in the form of a flow chart, as shown in Fig. 4.

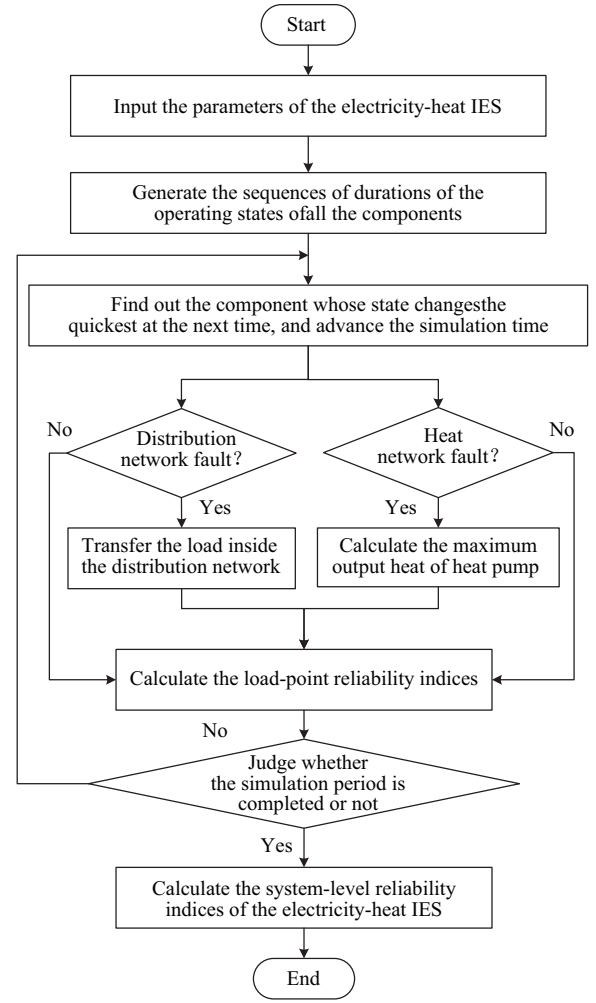


Fig. 4. Flow chart of reliability evaluation of electricity-heat IES with heat pump.

V. CASE STUDIES

Case studies are carried out on the electricity-heat IES with heat pump of an industrial park to validate the proposed reliability evaluation method. The programs for the reliability evaluation of the electricity-heat IES are developed with Matlab R2015b on a PC with Intel(R) Core(TM) i5-7200 2.5 GHz CPU and 8 GB RAM. The simulation period is set as 100,000 years, and the computing time of the evaluation algorithm is about 15 minutes.

A. Electricity-heat IES with Heat Pump

The electricity load of the electricity-heat IES is 30.4 MW. The heat load of the electricity-heat IES is 50.0 MW, and the heating period is 118 days in a year. The structures of the distribution network and the heat network are shown in Fig. 5 and Fig. 6, respectively. The distribution network and the heat network are coupled by a combined heat and power (CHP) unit on the source-side, and by heat pumps on the user-side. The CHP unit consists of a steam turbine and a waste heat boiler.

The potential fault components include distribution lines, transformers, breakers, hot water pipes, valves and heat pumps, and they are all assumed to be repairable components. The

reliability parameters are listed in Table I. The operational time of the segmented switch is 0.3 h/time, and the operational time of tie switch is 1 h/time [25]. The information of the electricity load is listed in Table II. The information of the heat load and the corresponding No. of buses in the distribution network are listed in Table III.

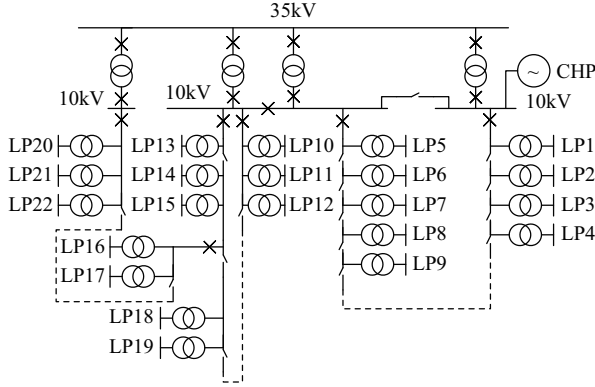


Fig. 5. Structure of the distribution network.

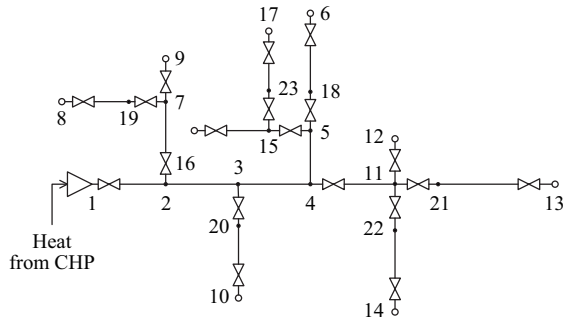


Fig. 6. Structure of the heat network.

TABLE I
RELIABILITY PARAMETER OF THE COMPONENTS

Type of component	Failure rate λ	Repair rate μ
Distribution line	0.065 times/year/km	0.2 times/hour
Transformer	0.0150 times/year	0.005 times/hour
Breaker	0.006 times/year	0.25 times/hour
Hot water pipe	0.05 times/year/km	0.05 times/hour
Valve	0.002 times/year	0.1 times/hour
Heat pump	0.5 times/year	0.1 times/hour

B. Results and Analysis

Table IV lists 8 configuration schemes of heat pumps for the electricity-heat IES. Among them, scheme No.1 is the basic case, schemes No.2 to No.4 are configured with heat pumps at the II-type heat load buses, schemes No.6 to No.8 are configured with heat pumps at the I-type heat load buses, and scheme No.5 is configured with heat pumps at both the I-type heat load buses and the II-type heat load buses. The COP of each heat pump is 3.5. The reliability evaluation method of electricity-heat IES with heat pump as described in section IV is applied to evaluate the system-level reliability indices of the 8 schemes in Table IV, and the results are listed in Table V.

TABLE II
LOAD DATA OF THE DISTRIBUTION NETWORK

No. of electricity load	Active power of electricity load(MW)	Reactive power of electricity load (Mvar)
LP1	9	4
LP2	1.2	0.5
LP3	0.6	0.2
LP4	0.6	0.2
LP5	1.8	0.7
LP6	0.6	0.2
LP7	0.6	0.2
LP8	0.4	0.1
LP9	0.6	0.2
LP10	1.8	0.6
LP11	0.6	0.2
LP12	0.9	0.4
LP13	1.5	0.6
LP14	0.6	0.2
LP15	1.5	0.5
LP16	1.8	0.8
LP17	0.9	0.4
LP18	0.9	0.3
LP19	0.9	0.4
LP20	1.8	0.7
LP21	0.9	0.4
LP22	0.9	0.3

TABLE III
LOAD DATA OF THE HEAT NETWORK

No. of heat load	Type of heat load	Heat power (MW)	Corresponding No. of bus in distribution network
6	I-type	10.8	12
8	I-type	3.5	2
9	II-type	5.5	3
10	I-type	4	4
12	II-type	5	6
13	II-type	6	19
14	II-type	4.2	15
16	II-type	3.5	21
17	II-type	7.5	17

By comparing the reliability evaluation results of schemes No.1, No.2, No.3, No.4 and No.5 in Table V, it can be seen that configuring proper heat pumps at the user-side is helpful to the improvement of the reliability of electricity-heat IES. With the increasing of the configured heat pump capacity, the system interruption frequency (SIF_{IES} , times/customer/year) is slightly increased due to the probability of the fault of the heat pump. Since the influence of the heat network fault on the heat load can be reduced by heat pumps, all the rest of the system-level reliability indices are improved after configuring the heat pumps.

TABLE IV
CONFIGURATION SCHEME OF HEAT PUMPS

Scheme No.	Location of heat pumps: bus No. in the heat network (type of heat load)	Rated output heat power of each heat pump(MW)
No. 1	/	0
No. 2	9(II-type)	1
No. 3	9(II-type), 12(II-type)	1
No. 4	9(II-type), 12(II-type), 17(II-type)	1
No. 5	6(I-type), 9(II-type), 10(I-type), 12(II-type), 17(II-type)	1
No. 6	6(I-type)	1
No. 7	6(I-type), 10(I-type)	1
No. 8	6(I-type), 8(I-type), 10(I-type)	1

TABLE V
SYSTEM-LEVEL RELIABILITY INDICES UNDER DIFFERENT
CONFIGURATIONS OF HEAT PUMPS

Scheme No.	SIF_{IES}	SID_{IES}	$SENS_{IES}$	SSA_{IES}
No. 1	1.202	6.59	543.2	0.999243
No. 2	1.208	6.56	530.4	0.999248
No. 3	1.210	6.55	521.1	0.999253
No. 4	1.216	6.47	492.4	0.999261
No. 5	1.226	6.04	442.9	0.999311
No. 6	1.206	6.49	514.5	0.999259
No. 7	1.208	6.39	497.0	0.999272
No. 8	1.213	6.17	435.5	0.999282

By comparing the reliability results of schemes No.1, No.2, No.3, No.4, No.6, No.7 and No.8 in Table V, it can be seen that compared to the II-type heat load, configuring the heat pumps at I-type heat load can result in better reliability. Fig. 7 shows the relationships of the system-level reliability indices and the number of configured heat pumps. Under the condition of configuring the same number and capacity of heat pumps, the reliability indices of schemes No.6, No.7 and No.8 are obviously better than those of schemes No.2, No.3 and No.4. This is because that the I-type heat load is more sensitive to the fault of the heat system. For the I-type heat load, it stops heating once the fault happens. But for the II-type heat load, the thermal insulation properties of the buildings can provide a buffer time to the fault. Therefore, from the view of the IES operator, the I-type heat load should have the priority to configure the heat pumps.

Additionally, it can be seen from Table V that schemes No.2 and No.7 have the same SIF_{IES} , but the other three indices are different. Scheme No.2 is configured with one 1 MW heat pump, while scheme No.7 is configured with two 1 MW heat pumps. If the types of heat load are the same for the two schemes, the SIF_{IE} of scheme No.2 will be smaller than that of scheme No.7. However, due to the different characteristics of the I-type heat load and II-type heat load, the SIF_{IE} of the two schemes are occasionally equal. Since the configured number and capacity of the heat pumps of scheme No.7 are bigger than those of scheme No.6, the other three indices of scheme No.7 are better than those of scheme No.6, which are better than those of scheme No.2 as aforementioned.

Furthermore, the influences of the capacity and COP of the configured heat pumps on the load-point reliability indices of the IES are studied. Assume that the heat pumps are installed at bus-6 in the heat network. Let the capacity of the configured heat pump increase from 0 to 4 MW with an equivalent step size of 0.5 MW and the COP of the configured heat pump increase from 2 to 5 with an equivalent step size of 0.5. The annual average energy interrupting duration of load-point (U , hours/year) is evaluated in different cases considering the security constraints of the distribution network, and the results are shown in Fig. 8.

It can be seen from Fig. 8 that if the COP of the heat pump is kept unchangeable, the annual average energy interrupting duration of the load-point decreases a lot according to the increment of capacity of the heat pump at the beginning. When the capacity of the heat pump reaches a certain value, the annual average energy interrupting duration of the load-

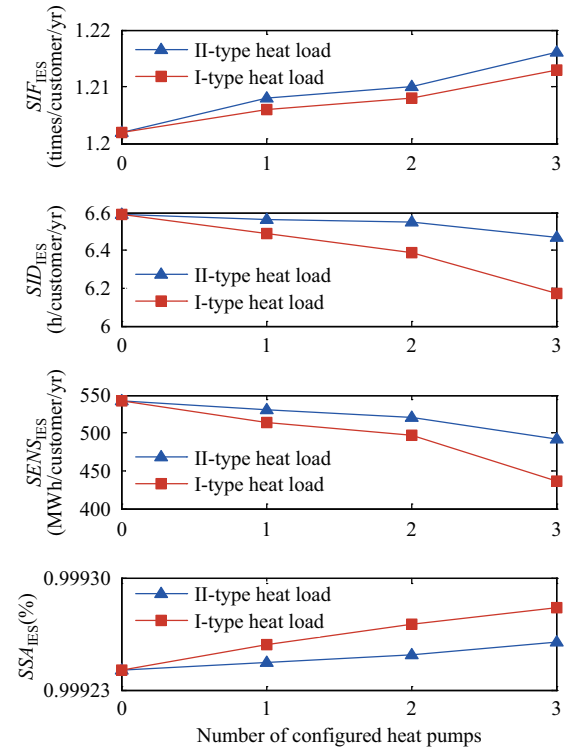


Fig. 7. System-level reliability indices versus the number of heat pumps.

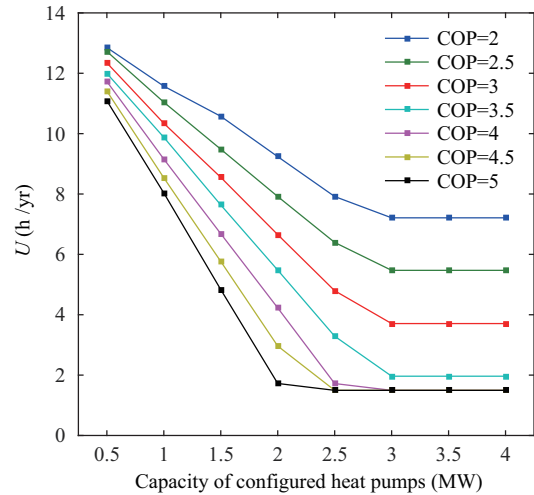


Fig. 8. The annual average energy interrupting duration of the load-point under different cases.

point will not decrease. This is because that the input electrical power of the heat pump is from the distribution network, and it cannot be infinitely increased due to the security constraints of the distribution network. If the input electrical power of the heat pump is too big, the nodal voltage and line power may be out of bounds. In this way, the output heat power of the heat pump is limited, ensuring that the load-point reliability indices cannot increase sustainably.

From Fig. 8 we can also find that if the capacity of the heat pump remains unchanged, the load-point reliability of the IES can improve a lot according to the increment of the COP of the heat pump. When the COP of the heat pump increases, the output heat power of the heat pump grows, ensuring that the

heat load can be supplied by heat pumps if faults happen in the heat network. Compared to the heat pump with low COP, the one with high COP can improve the output heat power limit of the heat pump, and this type of improvement is not at the cost of higher configuring capacity of the heat pump. In this way, the capacity limit caused by the security constraints of the distribution network can be avoided. However, when the transferred capacity of the heat pump exceeds the total heat load of the certain heat load point, the load-point reliability indices will not change any more.

VI. CONCLUSION

This paper studies the reliability evaluation method of electricity-heat IES with heat pump. First, the reliability indices are defined according to the characteristics of electricity-heat IES. Secondly, the calculation method of the maximum output heat power of the heat pump at the user-side considering the safety criterion of the distribution network is researched. On this basis, the detailed reliability evaluation procedure of electricity-heat IES with heat pump based on the Monte Carlo simulation is proposed. Case studies are carried out on the electricity-heat IES of an industrial park, and the results show that:

- 1) Compared to the II-type heat load, configuring heat pumps at the I-type heat load can result in higher reliability.
- 2) The increment of the reliability of electricity-heat IES is related to the COP of the configured heat pump. By configuring the heat pump with high COP, the higher reliability can be achieved.
- 3) Due to the security constraints of the distribution network, there is an upper limit to the improvement of the reliability of IES with heat pump. Therefore, it is of great necessity to take the safety criteria of the distribution network into account when evaluating the reliability of IES with heat pump.

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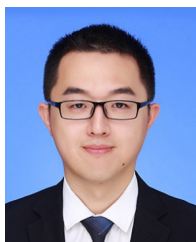
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