Energy supply reliability assessment of the integrated energy system considering complementary and optimal operation during failure

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1 | INTRODUCTION

Traditionally, gas and electrical systems operate independently, which limits the efficiency of the overall energy system. The integrated energy system (IES), coupling different types of energy technologies, is an effective solution to improve energy efficiency [1–4]. A representative IES architecture is introduced in [1], and the interdependencies and interactions in the IES are discussed in [2]. Cheng et al. [3] proposed a novel concept of IES cyber-physical systems. Hu et al. [4] improved the energy efficiency of IES through the proposed ‘exergy efficiency’. Compared to the traditional independent planning and operation of each energy system, IES realises the coordination and optimisation of the production, distribution, conversion, storage, and consumption of multiple energy sources. Therefore, it can be regarded as the physical carrier of the Energy Internet [5, 6]. However, the energy coupling of the IES is complex and the energy characteristics are different, making its reliability assessment more complicated than the traditional energy system. Therefore, there is an urgent need to carry out research on the reliability assessment methods of IES to provide a more scientific and reasonable decision reference for planning, construction, and safe operation.

As a key technology in the operation and planning process, the research on reliability assessment methods has been widely conducted. The reliability assessment can be summarised as the following three basic steps [7]: Obtaining the random state of the system; analysing and evaluating the random state; calculating the system reliability indices. In order to obtain the random state of the system, two main methods [8, 9] are adopted in the previous studies: The analytical method and the Monte Carlo method. The analytical method has a clear physical concept and high model accuracy, but it is difficult to deal with the random failure and simulate the actual large-scale system operation [10]. Monte Carlo method belongs to statistical experimental methods. Compared to analytical methods, it can simulate the random variation characteristics of the system and also obtain the probability distribution of some variables of interest,
but it often takes a long time to obtain high accuracy [11, 12].

Since the failure occurrence and the failure device are uncertain in the IES, the Monte Carlo method is more suitable for the evaluation of the IES. To analyse and evaluate the random state, failure model and effectiveness analysis (FMEA) is widely used by traversing the impact of device fault on load in the system. Moeinighaie et al. [13] used the FMEA method to evaluate the electrical supply reliability of distribution network, and Che et al. [14] and Xu et al. [15] applied the same method for the reliability assessment of microgrids with distributed energy resource. However, there are few studies about the impact of device fault on the energy supply of the IES. Chaudry et al. [16] proposed the objective operation function of the system aiming at minimising the total operational costs based on a reliability assessment model of the combined GB gas and electricity network (EN) during the device failure. Qadrdan et al. [17] built a Monte Carlo model of the combined gas and EN and minimised the combined costs. These two studies realised the calculation of electricity and gas losses, but they do not consider the cooling and the heating, ignoring the diversity of loads. In the process of calculating system reliability indices, most of the existing reliability indices are only used for single energy systems with traditional reliability indices. Oh et al. [18] used the indices to evaluate the reliability of the electrical system considering wind generators. Shan et al. [19] proposed the structural and functional indices to evaluate dynamic reliability of heating networks. However, few reliability indices have been proposed specifically to evaluate the IESs. Mohammad-Hossein et al. [20] considered the dynamic characteristics of the heating load and uses ‘unavailability’ as the reliability indicator of IES. Zhe et al. [21] proposed a new approach based on hierarchical decoupling optimisation and uses the probability of load curtailments to assess the reliability of IES. In addition, the current reliability indices of IES are mainly based on electrical systems, and research studies on the reliability index of cooling and heating system have rarely been conducted [22, 23]. Moreover, Liu et al. [24], proposed an operational reliability assessment method for an electricity-gas integrated energy distribution feeder with traditional reliability indices such as system average interruption frequency index and expected energy not supplied (EENS). Yang et al. [25] proposed an analytical method that can incorporate the uncertainty of the natural gas pipeline network system into the reliability assessment of IES, and it uses the loss of load probability, loss of load expectation and EENS as the reliability evaluation indices. The main contributions of this study are as follows:

1. In order to make full use of the complementary characteristics of various energy sources, a mathematical model for the optimal operation of the IES during the failure period is established, and three optimal operation objectives are proposed. The three different operation objectives are proposed based on different perspectives to minimise the user's energy loss, to minimise the economic loss of the energy supply station, and to obtain the best energy supply indices, respectively. So the operation state can be optimised during failure based on the model established in the study.

2. Three new indices are proposed to evaluate the reliability of the IES system collectively, considering the cooling, heating and electricity supply at the same time, and the energy value differences among the three types of energy are taken into account. The index system established in this study is more suitable for the evaluation of the energy supply reliability of the IES.

3. The rest of the study is organised as follows. An IES with multiple energy supply stations is constructed in Section 2. The structure of the system and the key devices inside are introduced. To take the advantage of the multi-energy complementary characteristics of IES, a mathematical model with three operational objectives during the device failure period is established in Section 3, which optimises the output of remaining devices and realises the optimal scheduling of energy flow. In Section 4, an energy reliability assessment method for IES is proposed, including specific reliability assessment processes and the detailed reliability indices; in Section 5, simulations are performed to verify the effectiveness of the proposed method and indices.

2 | THE STRUCTURE OF IES

2.1 | Inter-station and intra-station structure of energy supply stations

IES with multiple energy supply stations has been used to replace the existing model of traditional energy systems that divides production and supply, which realises the centralised coordination of resources. The structure of the IES constructed in this study is shown in Figure 1. The system realises the exchange of various energy sources such as cooling, heating, electricity and gas. During the normal operation, the system can meet the load demands, including cooling, heating and electricity. In Figure 1, the EN and the gas network (GN) are connected.
to energy supply stations. The inter-station connection network is built to achieve energy interaction among different stations. It includes the electrical connection network (ECN) and the thermal connection network (TCN), which achieves the energy interaction of the cooling and heating systems. The gas required by the energy supply station can only be supplied through the GN, and there is no gas connection network among stations. Each energy supply station is responsible for supplying energy to cooling, heating and electricity demands in their respective areas.

The internal structure of the energy supply station is shown in Figure 2, where the system is comprised of energy input, conversion, output, and so forth. Energy is converted through the gas turbine (GT), the electric boiler (EB), the electric refrigerator (ER), the absorption chiller (AC), the gas boiler (GB) and other devices in the system. This figure can clearly show the energy flow and conversion inside the system, as well as the connection of devices. To simplify the analysis, all load nodes in the downstream network are collectively equivalent to cooling, heating and electricity load nodes as shown in Figure 2.

2.2 Mathematical model of devices

In this study, the sequential Monte Carlo method is used to simulate the system timing state over a time span, and then to evaluate the reliability of the energy supply when a device fails. When failures happen, the specific energy flow path, energy conversion mode and energy balance in the system are reflected by input and output of devices. Therefore, in this section, the mathematical model of each device in the system is established to determine its input and output during the failure, further to judge the system’s ability to supply various types of loads and evaluate the system’s energy supply reliability.

1. Electric boiler

EBs are essential electricity-heat coupling devices, and its model is given as follows:

$$P_{EB}^h = \eta_{EB}(1 - \mu_{LOSS})P_{EB}^e$$

where $P_{EB}^h$ represents the heat power output of the EB at time $t$, $P_{EB}^e$ represents the electrical power consumed by the EB at time $t$, $\eta_{EB}$ denotes the electricity-heat conversion efficiency; $\mu_{LOSS}$ represents the heat loss at time $t$, which is assumed to be zero in this study.

1. Gas boiler

GBs are the key devices of gas-heat coupling, which is modelled as

$$P_{GB}^h = \frac{V_{GB}L_{NG}\eta_{GB}}{\Delta t}$$

where $P_{GB}^h$ represents the heat power output of the GB at time $t$, $V_{GB}L_{NG}$ represents the natural gas consumption of the GB; $\eta_{GB}$ represents the heating efficiency of the GB.

1. Electric refrigerator

ERs convert electrical energy for cooling energy, and its model is

$$P_{ER}^c = \eta_{ER}P_{ER}^e$$

where $P_{ER}^c$ represents the cooling power output of the ER; $\eta_{ER}$ represents the refrigeration coefficient of the ER; $P_{ER}^e$ represents the electrical power input of the ER.

1. Absorption chiller

ACs are used to convert heat energy for cooling energy, which is typically modelled as

$$P_{AC}^c = C_{AC}P_{AC}^h$$
where $P^e_{AC,d}$ represents the cooling power output of the AC at time $t$; $C_{AC}$ represents the heat power input of the AC at time $t$. The energy conversion efficiency of the device is shown in Table 4 of the Appendix, and the failure rate and repair time of devices is shown in Table 6 of the Appendix.

3 COMPLEMENTARY AND OPTIMAL OPERATION OF COOLING, HEATING AND ELECTRICITY DURING DEVICE FAILURE

3.1 Multi-energy complementary characteristic of IES

When failure happens, the system will be forced to lose load if energy source spare is not enough, and thus reliability is challenged. IES couples several types of energy, and for specific user demands, there are many ways of energy supply. The essence of multi-energy complementarity of IES lies in making full use of the convertibility among different types of energy and co-optimising all parts of the system. In the IES, when the energy supply is insufficient, the other energy suppliers will compensate it through energy conversion devices, which is equivalent to increasing the system’s spare. When a device of the system fails, the corresponding load demands cannot be met. However, if the other energy suppliers with the same kind of energy have a large spare capacity, the load can still be satisfied. If other devices are not enough to provide spare at this time, the load will be at the risk of being removed. Under such circumstance, IES can take the advantage of multi-energy complementarity, so that it can change ‘the form of energy loss’ according to the operational objectives. For example, in the heating season, users have relatively more heat energy demand, and the loss of heating supply will cause greater impacts to users. If the heat energy supply is inadequate, the EB can be put into operation at full power, so that changing ‘the form of energy loss’ can be realised. Even if it will result in tight electrical supply and lead to cut off some electrical loads, it guarantees the supply of more important loads for users in the system, making the user’s loss smaller.

3.2 The complementary and optimal operation during failure and its mathematical mode

The followings are the three different operation objective functions and constraints, and the complementary and optimal operation during failure is achieved under this model.

**Operation objective functions:**

$$ f_1 = \min \left\{ \sum_{t=1}^{T} \alpha_{el,t} P^e_{lost,t} \Delta t + \sum_{t=1}^{T} \alpha_{c,t} P^c_{lost,t} \Delta t + \sum_{t=1}^{T} \alpha_{h,t} P^h_{lost,t} \Delta t \right\} $$  

(7)

$$ f_2 = \min \left\{ \sum_{t=1}^{T} \beta_{el,t} P^e_{lost,t} \Delta t + \sum_{t=1}^{T} \beta_{c,t} P^c_{lost,t} \Delta t + \sum_{t=1}^{T} \beta_{h,t} P^h_{lost,t} \Delta t \right\} $$  

(8)

$$ f_3 = \min \left\{ \sum_{t=1}^{T} \gamma_{el,t} P^e_{lost,t} \Delta t + \sum_{t=1}^{T} \gamma_{c,t} P^c_{lost,t} \Delta t + \sum_{t=1}^{T} \gamma_{h,t} P^h_{lost,t} \Delta t \right\} $$  

(9)

where $f_1$ is based on the user’s perspective with minimising the user’s energy loss; $\alpha_{el,t}, \alpha_{c,t}, \alpha_{h,t}$ are important factors of electricity, cooling and heating load, and they are dynamically changed over time according to the user’s requirement, for example, in the heating season, $\alpha_{h,t}$ is larger, while $\alpha_{el,t}$ and $\alpha_{c,t}$ are smaller. $f_2$ is to minimise the economic losses of energy supply station from the perspective of energy supply station; $\beta_{el,t}, \beta_{c,t}, \beta_{h,t}$ are the energy price for each type of load; and the prices of various types of energy is shown in Table 5 of the Appendix. $f_3$ is to obtain the best reliability indices; $\gamma_{el,t}, \gamma_{c,t}, \gamma_{h,t}$ are ‘energy value coefficients’, which are first proposed in this study. As there are great differences in cooling, heating and electricity energy, the amount of energy utilisation and transformation for different types of energy is also different, so this concept is proposed to unify the available value of different energies. $\gamma_{el,t}, \gamma_{c,t}, \gamma_{h,t}$ respectively represent the available value of electricity, cooling and heating energies. $T$ is the total simulation time, $P^e_{lost,t}, P^c_{lost,t}, P^h_{lost,t}$ respectively represent the energy loss of electricity, cooling and heating load at time $t$.

The three different operation objective functions are put forward standingly, respectively, in the angle of users, energy supply stations and social benefits. They are used to minimise the user’s energy loss, minimise the economic loss of the energy supply station and obtain the best energy supply indices, respectively. One of the three objectives will be chosen to optimise the operating state during failure, and which optimisation objective is chosen depends on actual demands and the decision-makers. Such as if the maker is the owner of the energy supply station, the second objective may be chosen to minimise the energy station loss.

**Equality constraints:**

1. Electricity power balance

$$ P^e_{EN,t} + P^e_{GT,t} + P^e_{ECN,t} + P^e_{DG,t} + P^e_{EB,t} + P^e_{ER,t} = P^e_{D,t} - P^e_{lost,t} $$  

(10)

2. Heating power balance

$$ P^h_{EB,t} + P^h_{GT,t} + P^h_{ECN,t} + P^h_{GB,t} = P^h_{D,t} - P^h_{lost,t} + P^h_{AC,t} $$  

(11)
3. Cooling power balance

\[ P_{\text{ER},t}^c + P_{\text{AC},t}^c + P_{\text{GCN},t}^c = P_{\text{D},t}^c - P_{\text{hst},t}^c\] (12)

4. Natural gas balance

\[ P_{\text{GN},t}^c = P_{\text{GT},t} + P_{\text{GR},t}\] (13)

where \( P_{\text{EN},t}^c, P_{\text{GN},t}^c \) represent the power input from the EN and the GN at time \( t \); \( P_{\text{GCN},t}^c \) represents the electricity power from inter-station connection network and the output of distributed generations; \( P_{\text{GCN},t}^c \) represents the heating and the cooling powers of the TCN; \( P_{\text{D},t}^c, P_{\text{D},t}^c \) respectively, represent electricity, heating and cooling loads at time \( t \); \( P_{\text{GT},t} \) and \( P_{\text{GR},t} \) represent the natural gas consumed by GTs and GBs, respectively.

Inequality constraints:

1. Energy input constraints

\[ 0 \leq P_{\text{EN},t}^c \leq P_{\text{EN},t}^{\text{max}} \] (14)
\[ 0 \leq P_{\text{GN},t}^c \leq P_{\text{GN},t}^{\text{max}} \] (15)

2. Device output constraints

\[ 0 \leq P_{\text{D},t}^c \leq P_{\text{D},t}^{\text{max}} \] (16)

3. Output constraints of distributed generation

\[ 0 \leq P_{\text{WT},t} \leq P_{\text{WT},t}^{\text{max}} \] (17)
\[ 0 \leq P_{\text{PV},t} \leq P_{\text{PV},t}^{\text{max}} \] (18)

4. Transmission power limitation of the connection network

\[ -P_{\text{GCN},t}^{\text{max}} \leq P_{\text{GCN},t}^c \leq P_{\text{GCN},t}^{\text{max}} \] (19)

5. Constraints on load loss

\[ 0 \leq P_{\text{hst},t}^c \leq P_{\text{D},t}^c \] (20)

where \( i \) represents the type of loads, including electricity, cooling, and heating loads; \( P_{\text{EN},t}^{\text{max}}, P_{\text{GN},t}^{\text{max}} \) represent maximum input from EN and GN; \( P_{\text{D},t}^{\text{max}} \) represents the output power of the device \( j \); \( P_{\text{D},t}^{\text{max}} \) is its maximum limit value, which is determined by the construction capacity and conversion efficiency; \( P_{\text{WT},t}^{\text{max}} \) represents the upper output limit of the distributed wind turbine, which is obtained based on the wind turbine construction capacity and real-time wind speed; \( P_{\text{PV},t}^{\text{max}} \) is similarly obtained; \( P_{\text{GCN},t}^{\text{max}} \) is the transmission limit of the connection network, and when it is positive, it indicates that energy flows into the energy supply station, and when it is negative, it indicates that energy flows out of the energy supply station.

4 | ENERGY SUPPLY RELIABILITY INDICES AND ASSESSMENT PROCESS

4.1 | Reliability indices

The traditional reliability assessment gives the reliability index of single energy systems, which cannot evaluate the overall reliability of IES. Therefore, this study proposes the following three new indices from different perspectives to improve the shortcomings of traditional reliability indices.

1. Average annual energy loss (AAEL)

It expresses the AAEL (MWh/a) due to device fault, which is defined as follows:

\[ AAEL = \gamma_x AALE_{x} + \gamma_y AALE_{y} + \gamma_z AALE_{z} \] (21)

where \( AALE_{x}, AALE_{y}, AALE_{z} \) are energy loss of electricity, heating and cooling supply; \( N \) is the number of years for simulation; \( \bar{x} \) is the random state of the system at time \( t \), \( F_AAELe(\bar{x}) \) is the experimental function defined as

\[ F_{\text{AAEL},x}(\bar{x}) = \max \left\{ 0, P_{\text{D},t}^{\text{ER},x} + P_{\text{ER},t}^{\text{ER},x} \right\} \] (25)
\[ F_{\text{AAEL},y}(\bar{x}) = \max \left\{ 0, P_{\text{D},t}^{\text{ER},y} \right\} \] (26)
\[ F_{\text{AAEL},z}(\bar{x}) = \max \left\{ 0, P_{\text{D},t}^{\text{ER},z} \right\} \] (27)

1. Insufficient energy supply probability (IESP)

It represents the probability (%) of an insufficient energy supply event, which is defined as follows:

\[ IESP = \frac{1}{T} \sum_{t=1}^{T} \left( \frac{\left| F_{\text{IESP},x}(\bar{x}) \right|}{\left| F_{\text{IESP},y}(\bar{x}) \right|} \right) \Delta t \] (28)
where $IES_P$, $IES_H$, and $IES_C$ are the probability of insufficient electricity/heating/cooling supply, respectively, $F_{IESP}$ represents the experimental function, and it is defined as

$$F_{IESP,e/c/h}(\overline{X_t}) = \begin{cases} 0 & \text{System has no load loss in state } \overline{X_t} \\ 1 & \text{System has load loss in state } \overline{X_t} \end{cases} \quad (32)$$

1. Insufficient energy supply time (IEST)

It indicates the time of insufficient energy supply throughout the year (h/a) due to device fault, and its calculation formula is

$$IEST = \frac{1}{N} \sum_{t=1}^{T} \left( \frac{F_{IESP,e}(\overline{X_t}) \cdot \Delta t}{F_{IESP,h}(\overline{X_t})} \right) \cdot \Delta t \quad (33)$$

$$IEST_e = \frac{1}{N} \sum_{t=1}^{T} (F_{IESP,e}(\overline{X_t}) \cdot \Delta t) \quad (34)$$

$$IEST_h = \frac{1}{N} \sum_{t=1}^{T} (F_{IESP,h}(\overline{X_t}) \cdot \Delta t) \quad (35)$$

$$IEST_C = \frac{1}{N} \sum_{t=1}^{T} (F_{IESP,c}(\overline{X_t}) \cdot \Delta t) \quad (36)$$

4.2 Sequential Monte Carlo reliability assessment process used in IES

Usually, IES is a large-scale system with a great number of devices. The failure device and failure occurrence in the system are uncertain. Since the traditional analytical methods are not suitable for large-scale systems and are difficult to reflect the timing characteristics, sequential Monte Carlo method is used to simulate the state sequence of the system over a long time span and can more effectively reflect the operation state of IES. We can easily get the operation state data of all devices through the Monte Carlo method, so we can get the optimal operation strategy based on the data. Thus, the Monte Carlo method is used in this study to evaluate the energy supply reliability of IES. The following assumptions are made for IES constructed in Section 2 of this study: The fault among devices is independent of each other and do not affect each other, which means the system will not have chain faults; all devices in the system can be repaired, and they have only two states: Normal operation and the fault states. It is assumed that the normal operation time of the device (the time to fault (TTF)) and the repair time of the device (the time to repair (TTR)) are both subject to an exponential distribution.

The process of reliability assessment is shown in Figure 3, which can be divided into the following steps:

Step 1: Enter initial data, which mainly includes the fault rate and the repair time of each device, the parameters of distributed generators, load data...

Select a operation objective function and start Monte Carlo loop

Generate the TTF of all devices; select the device with the smallest TTF as the faulty device; generate the TTR of the faulty device

During the failure, optimize the output of each device according to the operation objective

The model solver is used to solve the optimization results to obtain the loss of various types of loads.

Calculate the system reliability index and the annual reliability index and get the final result

Average the annual reliability index and get the final result

Simulation time: 8760h?

Yes

No

FIGURE 3 Reliability assessment flowchart of device output optimization during failure

FIGURE 4 The output of wind power generation and photovoltaic power generation
TABLE 1  System reliability assessment indices under objective 1

| Index | Electrical | Cooling | Heating | Integrated energy system (IES) |
|-------|------------|---------|---------|---------------------------------|
| AAEL  | 5.035 MWh/a | 11.439 MWh/a | 11.014 MWh/a | 18.874 MWh/a |
| IESP  | 0.0476%  | 0.1641%  | 0.1721%  | 0.2934%  |
| IEST  | 3.8251 h/a | 14.118 h/a | 15.709 h/a | 28.911 h/a |

Note: AAEL is average annual energy loss; IESP is insufficient energy supply probability; IEST is insufficient energy supply time.

TABLE 2  System reliability assessment indices under objective 2

| Index | Electrical | Cooling | Heating | IES |
|-------|------------|---------|---------|-----|
| AAEL  | 5.915 MWh/a | 6.456 MWh/a | 13.443 MWh/a | 17.239 MWh/a |
| IESP  | 0.0418%  | 0.1620%  | 0.1659%  | 0.2938%  |
| IEST  | 3.8011 h/a | 14.213 h/a | 14.7109 h/a | 27.433 h/a |

Step 2: Select one of the three operation objective functions mentioned above and perform the Monte Carlo simulation.

Step 3: Calculate the TTF of each device, select the device with the smallest TTF as the faulty device, and use this smallest time as the normal operation time of the system, then calculate the fault duration time (TTR) of the faulty device.

Step 4: During the failure, fully mobilise the multi-energy complementary characteristic and optimise the output of each device according to the operation objective, and then use the Grobi solver to obtain the loss of electricity, heating and cooling.

Step 5: Accumulate the simulation time, if the simulation time is less than 8760 h, return to step 3, otherwise go to step 6.

Step 6: Perform N times of simulations and obtain the average annual reliability index of the system by averaging the N sample years.

5  CASE ANALYSIS

5.1  The introduction of the case

The system structure of the study case is as shown in Figure 1. There are three energy supply stations, and the ECN is built between stations 1 and 2 and between stations 2 and 3, while the TCN is only built between station 1 and 2. The capacity of the devices in power stations are shown in Tables 7, 8 and 9 of the Appendix. The maximum transmission power of the ECN is 2000 kW, and the maximum transmission power of the TCN is 1000 kW. Sequential Monte Carlo simulations are performed, which covers 100 years and each year is divided into three typical seasons: The cooling season (16 May to 15 September), the heating season (16 November to 15 March of the following year), and the transition season (16 March to 15 May and 16 September to 15 November). In the cooling season, there are electricity and cooling loads, while the heating season has electricity and heating loads, and the transition season only has electricity load. The load curve of typical seasons is shown in Figures 7, 8 and 9.

The photovoltaic power generation is built in stations 1 and 3, and its installed capacity is 3000 and 5000 kW, respectively, the wind power generation is built in station 2 and the installed capacity is 4000 kW. The output curves of photovoltaic power and wind power generations of each energy supply station are shown in Figure 4.

5.2  System reliability indices analysis under different operation objectives

Based on the proposed reliability assessment method and the complementary and optimal operation during device failure, the simulation results are illustrated in Table 1.

The case verifies that IES can provide differential reliability guarantee for loads of different importance. As shown in Table 1, both cooling and heating energy loss are more than the electrical energy loss because the optimal operation objective 1 established in this study is based on the user's perspective to minimise the user's energy loss. From the perspective of energy use, electrical energy can be converted into cooling and heating energies, and continue to supply cooling and heating loads, while

TABLE 3  System reliability assessment indices under objective 3

| Index | Electrical | Cooling | Heating | IES |
|-------|------------|---------|---------|-----|
| AAEL  | 5.126 MWh/a | 6.908 MWh/a | 12.017 MWh/a | 16.092 MWh/a |
| IESP  | 0.0678%  | 0.1503%  | 0.1709%  | 0.2927%  |
| IEST  | 4.0023 h/a | 13.356 h/a | 15.1024 h/a | 28.253 h/a |

TABLE 4  Energy conversion efficiency of devices

| 𝜂_{EGT} | 𝜂_{HGT} | 𝜂_{GB} | 𝜂_{EB} | 𝜂_{ER} | 𝜂_{AC} |
|---------|---------|--------|--------|--------|--------|
| 0.3     | 0.4     | 0.9    | 4      | 4      | 1.3    |

TABLE 5  Prices of various types of energy

| Energy types | Time         | Energy price (yuan*(kW h)^{-1}) |
|--------------|--------------|---------------------------------|
| Electricity  | Peak period  | 1.345                           |
|              | Flat period  | 0.9                             |
|              | Valley period | 0.478                          |
| Heating      | Per hour     | 0.3                             |
| Cooling      | Per hour     | 0.7                             |
TABLE 6  Failure rate and repair time of devices

| Equipment                      | Gas turbine (GT) | Gas boiler (GB) | Electric boiler (EB) | Electric refrigerator (ER) | Absorption chiller (AC) | Electrical connection network | Thermal connection network |
|--------------------------------|------------------|-----------------|----------------------|-----------------------------|-------------------------|-------------------------------|----------------------------|
| Failure rate (times/a)        | 1.839            | 3.416           | 2.278                | 1.927                       | 2.015                   | 2.365                         | 2.102                      |
| Repair time (h)               | 3.32             | 4               | 5                    | 4.2                         | 2                       | 2.55                          | 3.6                        |

TABLE 7  The capacity of the devices and the load data in power station 1

| Energy station | Device          | Capacity (kW) |
|----------------|-----------------|---------------|
| Energy station 1 | Gas turbine    | 9860          |
|                 | Gas boiler      | 17,997        |
|                 | Electric boiler | 10,000        |
|                 | Electric refrig. | 6898          |
|                 | Absorption chiller | 16,966    |
|                 | Max electrical load | 12,754   |
|                 | Max heating load | 40,315        |
|                 | Max cooling load | 25,055        |

TABLE 8  The capacity of the devices and the load data in power station 2

| Energy station | Device          | Capacity (kW) |
|----------------|-----------------|---------------|
| Energy station 2 | Gas turbine    | 11,860        |
|                 | Gas boiler      | 25,114        |
|                 | Electric boiler | 10,000        |
|                 | Electric refrig. | 9635          |
|                 | Absorption chiller | 20,294   |
|                 | Max electrical load | 11,317   |
|                 | Max heating load | 35,772        |
|                 | Max cooling load | 22,232        |

Also, the above results give the indices of each single energy system and IES and there is no significant difference between the cooling and heating indices since the user demand characteristics of heating and cooling load are relatively similar when measured in one year. It is found that the energy supply reliability of the system cannot be evaluated only by a single system index of the cooling, heating and electricity. The proposed AAEL takes the differences of energy sources into account, and it is more optimistic and reasonable than just adding up the reliability indices of each energy system because when the energy loss with a lower quality accounts for a large proportion, the index has revised the available value of different energy according to the ‘energy value coefficient’, which makes a more sensitive and reasonable response. IESP and IEST no longer only consider a single type of energy supply reliability, it simultaneously considers the reliability of the three types of energy supply for cooling, heating and electricity, and any type of energy loss is counted as a lack of energy in IES. In this way, the reliability indices are more suitable for evaluating IES that can supply multiple types of energy.
In Tables 2 and 3, we can see that the change in AAEL is more obvious in both the single energy system indices and IES indices, while the change in IESP and IEST is relatively small. This is because AAEL is closely related to the amount of load loss, and this is exactly the variable that needs to be optimised by mobilising the multi-energy complementary characteristics of IES during the device failure. Therefore, different objective functions will cause larger numerical differences in AAEL. According to the definition of the other two indices, they mainly depend on the inherent fault rate and the repair time of devices. To a certain extent, these two indices mainly focus on reflecting the reliability to supply loads from the device itself. At the same time, it can be found that when the optimal operation is performed under different objectives, the reliability indices of the system are also different. Therefore, after mobilising the multi-energy complementary characteristics of the system for the optimal operation, the system has the ability to adjust the output of the remaining devices and actively select and change ‘the form of load loss’, making the entire system operation more conducive to the reliability of energy supply under different objectives, which fully reflects multi-energy complementary characteristics of IES and its ability to flexibly schedule the energy flows.

5.3 The difference of different device fault on system reliability

In order to explore the difference of different device faults on the system’s energy supply reliability, six hypothetical scenarios for comparative analysis are studied in this section. Each scenario considers the fault of only one of the following devices: GT, GB, RB, ER, AC and the inter-station connection network. This section uses ‘AAEL’ as an example to compare the system reliability in the above six scenarios.

As shown in Figures 5 and 6, among all devices inside the energy supply station, the fault of different devices has a different impact on system reliability. The GT has the greatest impact on the reliability of the system’s energy supply, while the fault of the inter-station connection network has the smallest impact. The impact of each device on the reliability of energy supply can be arranged in order as GT > GB > EB > ER > AC > inter-station connection network. Although the inter-station connection network can optimise scheduling resources to improve the overall energy supply reliability of the system to a certain extent, considering its limited transmission capacity, it cannot take the main responsibility of energy supply; therefore, the fault of the inter-station connection network is not enough to cause a great
fluctuation in energy supply reliability of the system. When the GT fails, it will affect the supply of three types of energy; the specific operation mode, the output of each device and the load loss of energy are determined by the complementary and optimal operation model described in this study. Further, the GT directly supplies electricity and heating energies, and the supply of cooling energy needs to be converted by the AC; therefore, the impact on the electricity and heating supplies is a direct impact, and the impact on the supply of cooling is an indirect impact, and it is expressed on a quantified level such that \( AAE_{Le} \) and \( AAE_{Lh} \) are larger, though \( AAE_{Lc} \) is smaller. The above results and analysis can be used as an important reference for identifying weak links in the system, and can also provide a theoretical basis for formulating strengthening measures and improve the reliability of IES.

6 | CONCLUSION

In this study, we propose a mathematical model for the optimal operation of cooling, heating and electricity in the IES during failure. Additionally, three new indices are proposed to evaluate the reliability of IES collectively. Through the case analysis, the following conclusions can be drawn: First, IES can flexibly schedule energy flow under different objectives to realise adaptive and targeted operational strategies, which can reflect the multi-energy advantages of IES. Second, the new reliability index proposed in this study is more reasonable and optimistic. It is suitable for IES that combines several types of energy together. Also, the variation of the three reliability indices under different operation objectives is explained in detail in the case studies. Finally, the fault scenarios of different devices are assumed and the influence of different device on the energy supply reliability of the system is ranked, which is of great significance to find the weak parts of the system and provide a reference for the system to develop measures to improve the reliability of the system.

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REFERENCES

1. Wang, K., et al.: A survey on energy internet: Architecture, approach, and emerging technologies. IEEE Syst. J. 12(3), 2403-2416 (2018)
2. Wu, J., et al.: Optimal day-ahead scheduling of integrated urban energy systems. Appl. Energy 180, 1–13 (2016)
3. Cheng, L., et al.: Energy internet access equipment integrating cyber-physical systems: Concepts, key technologies, system development, and application prospects. IEEE Access 7, 23127–23148 (2019)
4. Hu, X., et al.: Multi-objective planning for integrated energy systems considering both energy efficiency and economy. Energy 197, 117155 (2020)
5. Brahim, F., et al.: Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system. Energy Build. 90(39), 65–75 (2015)
6. Lin, Y., Bie, Z.: Study on the resilience of the integrated energy system. Energy Procedia 103, 171–176 (2016)
7. Rocha, L.F., et al.: Reliability evaluation of active distribution networks including islanding dynamics. IEEE Trans. Power Syst. 32(2), 1545–1552 (2017)
8. Ringlee, R.J., et al.: Bulk power system reliability criteria and indices: trends and future needs. IEEE Trans. Power Syst. 9(1), 181–190 (1994)
9. Borges, C.L., Dias, J.A.: A model to represent correlated time series in reliability evaluation by non-sequential Monte Carlo simulation. IEEE Trans. Power Syst. 32(2), 1511–1519 (2017)
10. Zou, K., et al.: An analytical approach for reliability evaluation of distribution systems containing dispatchable and nondispatchable renewable DG units. IEEE Trans. Smart Grid 5(6), 2657–2665 (2014)
11. Li, G., et al.: Reliability evaluation of integrated energy systems based on smart agent communication. Appl. Energy 167, 397–406 (2016)
12. Yu, W., et al.: Gas supply reliability assessment of natural gas transmission pipeline systems. Energy 162, 853–870 (2018)
13. Moenigntaa, M., et al.: Generalized analytical approach to assess reliability of renewable-based energy hubs. IEEE Trans. Power Syst. 32(1), 368–377 (2017)
14. Che, L., et al.: Optimal interconnection planning of community microgrids with renewable energy sources. IEEE Trans. Smart Grid 8(3), 1054–1063 (2017)
15. Xu, X., et al.: An evaluation strategy for microgrid reliability considering the effects of protection system. IEEE Trans. Power Delivery 31(5), 1989–1997 (2016)
16. Chaudry, M., et al.: A sequential Monte Carlo model of the combined GB gas and electricity network. Energy Policy 62, 473–483 (2013)
APPENDIX

Energy value coefficient: $\alpha = 1, \beta = 0.486, \gamma = 0.742$

The important factors of electricity, cooling and heating load:

$$\alpha_e = \begin{cases} 
1/4 & t \in \text{the heating season} \\
1/4 & t \in \text{the cooling season} \\
1/3 & t \in \text{the transition season}
\end{cases}$$

$$\alpha_h = \begin{cases} 
1/2 & t \in \text{the heating season} \\
1/4 & t \in \text{the cooling season} \\
1/3 & t \in \text{the transition season}
\end{cases}$$

$$\alpha_c = \begin{cases} 
1/4 & t \in \text{the heating season} \\
1/2 & t \in \text{the cooling season} \\
1/3 & t \in \text{the transition season}
\end{cases}$$

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