Integrated energy system reliability evaluation based on sequential Monte Carlo simulation and fault recovery optimization

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Abstract. In this paper, an integrated energy system (IES) reliability assessment method based on sequential Monte Carlo simulation and fault recovery optimization is proposed considering the flexibility of dispatch and the complementary of multi-energy in IES. The reliability evaluation indices of IES are established considering the energy supply and thermal load delay characteristics. An IES failure recovery optimization model is established in which the shutdown loss and the minimum operating cost under the failure scenario are considered comprehensively. CPLEX software is applied to solve the proposed problem in order to obtain the electric and thermal load reduction power and component equipment output. Based on the principle of sequential Monte Carlo simulation, an IES reliability assessment method and process are designed. The analysis of calculation examples shows that the use of failure recovery optimization strategies and consideration of thermal load delay characteristics can effectively improve the reliability of IES.

1. Introduction

The integrated energy system (IES) with the core concept of multi-energy complementation and energy cascade utilization is an important way to realize energy transformation, energy saving and emission reduction. In recent years, multi-energy power flow calculation, optimal configuration of energy equipment and operation control have become hotspots in IES researches. However, only few researches were focused on IES reliability evaluation as a guide for planning and operation. On one hand, the structure and operation mode of IES are quite different from traditional energy supply systems, and the reliability assessment indicators suitable for traditional energy supply systems cannot fully describe the reliability of IES energy supply; on the other hand, due to the existence of multiple energy coupling devices, the energy supply loss can be reduced through multiple energy mutual aid and optimal dispatch during the failure recovery phase. Therefore, research on IES reliability evaluation considering fault recovery optimization is of great significance for obtaining accurate IES reliability indicators.

At present, Ref. [1] proposed a reliability evaluation method of electrothermal coupled energy system considering the comprehensive demand response of multiple energy sources, analyzed the basic structure of the electrothermal coupled energy system, and established the different components...
output model. Ref. [2] proposed an integrated energy microgrid reliability evaluation method with multiple energy storage systems, and quantitatively analyzed the impact of multiple energy storage on the reliability of the integrated energy microgrid, but the paper did not consider the normal operation period of the system. Ref. [3] established the power supply reliability model of the gas-electric coupling IES, and proposed an analytical method for evaluating the power supply reliability of the electric coupling IES. In [4] an IES reliability assessment method that taken into account the multiple time scales and the basic operation strategy of the IES was proposed, but the assessment method did not consider the impact of distributed power and energy storage system. Ref. [5] analysed the reliability of the energy hub using Markov method, however, the influence of distributed power is not considered. Ref. [6] proposed an IES adequacy assessment method that considered the dependence of the energy generation side and the demand side, and uses this method to model the adequacy of the production capacity system containing multiple energy sources.

Most studies on the reliability of IES just simply formulated strategies for the conversion sequence between multiple energy sources, only considering energy input capacity limitations and component maximum output limitations. The optimal conversion between various energy sources and the optimal output of the components in the IES are not considered. In addition, the structure of IES used in most IES reliability assessment studies are with fewer internal equipment, distributed power, energy storage and other components, which cannot fully describe the characteristics of multi-energy complementarity, coordination and optimization of the IES.

In view of the existing problems in the reliability assessment of the IES, this paper establishes an IES fault recovery optimal dispatch model that can calculate the optimal reduction level of the IES's electric and thermal loads. The optimization goal of the model is to minimize loss of energy supply and operating costs. The reliability evaluation method and process of the IES based on the sequential Monte Carlo simulation principle are designed, and the reliability evaluation indices of the IES are analyzed and calculated. The positive effects of the fault recovery optimization model and the thermal load delay characteristics on the reliability of the IES are analyzed through simulation examples.

The organization structure of this paper is as follows: Section 2 establishes the basic model and reliability evaluation indices of the IES; Section 3 establishes the reliability evaluation process based on sequential Monte Carlo and taking into account load delay characteristics; Section 4 establishes an IES failure recovery optimization model that used to solve the component output parameters and load reduction levels under fault conditions, the failure recovery model sets a foundation for the calculation of reliability indicators; Section 5 verifies the effectiveness of the models, indicators and methods proposed in this paper through simulation analysis of calculation examples.

2. IES structure and reliability evaluation indices

2.1. Typical structure of IES

The IES consists of Power electricity (Pe), Power gas (Pg), and Load electricity (Le) and heat (Lh), which are input to users by external Power grid and natural gas network, as shown in figure 1.

In figure 1, the IES includes capacity, conversion, energy storage equipment, and energy networks. Capacity equipment includes combined heating and power (CHP), gas boiler (GB), wind turbine (WT), photovoltaic cell (PV); conversion equipment has power distribution transformers (Transformer, T), electric boilers (Electric Boiler, EB); energy storage equipment includes electric energy storage (ES) and heat storage (HS). Energy networks include power grids, gas grids, and heat grids. The IES equipment and network model can be found in ref. [7].
2.2. IES reliability evaluation indices

The IES reliability evaluation indices adopt the average annual Expectation of Energy Not Supply (EENS), the Average Reduction Duration Index (ARDI) and the Average Service Availability Index (ASAI). When calculating the reliability index of heat load, the delay characteristic of heat load needs to be considered.

The delay characteristic of the thermal load describes the lag of the user's feedback to the interruption of the thermal energy supply. The temperature of the heating medium will gradually decrease when the heating is interrupted. As long as the temperature is within the user's acceptable range, the system is still judged to be normal, and the system is judged to be faulty until the medium temperature is lower than the user's lowest acceptable temperature $T_{\text{min}}$.

2.2.1. Expectation of Energy Not Supply (EENS)

The EENS calculated for electric load means the expected value of the lack of power generated by all equipment failures every year. The calculation formula is:

$$EENS_E = \frac{\sum_{i=1}^{N^y} \sum_{t=1}^{T_{MC}} L_{\text{ecut}}^i(t) \cdot T_{\text{ecut}}^i(t)}{T_{\text{MC}}}$$

(1)

where $T_{\text{ecut}}^i(t)$ is the electric load reduction time of IES of the $i^{th}$ failure in the $y^{th}$ year at time $t$, if the electric load reduction occurs at time $t$, $T_{\text{ecut}}^i(t)$ is equal to 1, and if the electric load reduction does not occur, it is equal to 0; $L_{\text{ecut}}^i(t)$ is the power reduction of IES of the $i^{th}$ failure in the $y^{th}$ year at time $t$; $T_{\text{MC}}$ is the total years of Monte Carlo simulation.

The EENS calculated for thermal load means the expected value of the lack of thermal energy generated by the failure of all equipment each year. The calculation formula is:

$$EENS_H = \frac{\sum_{i=1}^{N^y} \sum_{t=1}^{T_{MC}} L_{\text{h cut}}^i(t) \cdot (T_{\text{h cut}}^i(t) \cdot T_{\text{h satified}}^i(t))}{T_{\text{MC}}}$$

(2)

where $T_{\text{h cut}}^i(t)$ is the thermal load reduction time of IES of the $i^{th}$ failure in the $y^{th}$ year at time $t$, if the thermal load reduction occurs at time $t$, $T_{\text{h cut}}^i(t)$ is equal to 1, and if the thermal load reduction does not occur, it is equal to 0; $T_{\text{h satified}}^i(t)$ is the time for the $i^{th}$ failure of IES in the $y^{th}$ year when the heating temperature at time $t$ still meets the heating requirements, if the heating temperature at time $t$ meets the user's requirements, $T_{\text{h satified}}^i(t)$ is equal to 1, and if the user's requirements are not met, $T_{\text{h satified}}^i(t)$ Equal to 0; $L_{\text{h cut}}^i(t)$ is the thermal load power reduction of IES of the $i^{th}$ failure in the $y^{th}$ year at time $t$.

2.2.2. the Average Reduction Duration Index (ARDI)

The power supply availability of the electric load is immediately zero when the electric load is reduced, and the ARDI calculated for electric load is:
When the IES heating power is less than the heat load demand, it will take some time for the heating temperature to drop to the minimum heating temperature. Therefore, the ARDI calculated for thermal load is:

$$ARDI_h = \frac{\sum_{x} \sum_{y} \sum_{t} T_{heat}^h(t)}{T_{MC}}$$

(3)

2.2.3. the Average Service Availability Index (ASAI)

The Average Service Availability Index refers to the ratio of the average annual actual energy supply time to the required energy supply time. The calculation formulas are:

IES power service availability expectation is:

$$ASAI_e = 1 - \frac{ARDI_e}{8760}$$

(5)

IES thermal service availability expectation is:

$$ASAI_h = 1 - \frac{ARDI_h}{8760}$$

(6)

3. Framework of IES reliability assessment method considering operation optimization

3.1. Sequential Monte Carlo Simulation

The state change of IES can be simulated through the cycle process of “operation-shutdown-operation” when the two-state model is used to evaluate the reliability of the IES. $\lambda$ is the component failure rate (times/year), $\mu$ is the component repair rate (times/year), $TTF$ is the trouble-free working time of the component, and $TTR$ is the repair time. Generate random numbers between [0,1] to sample the $TTF$ and $TTR$ of each component. The sampling formula is:

$$1 = -\frac{1}{\lambda} \ln R_1$$

$$1 = -\frac{1}{\mu} \ln R_2$$

(7)

where $R_1$ and $R_2$ are random numbers uniformly distributed between [0,1].

3.2. Reliability assessment process

The IES reliability evaluation process based on sequential Monte Carlo simulation considers the optimal scheduling of normal and failure scenarios. Analyse the consequences of the operation status of the extracted IES. First, perform optimal scheduling of the IES under normal operating conditions, find the equipment operating parameters under normal operating conditions, and then call the optimal scheduling model established in this article for the IES failure recovery scenario, and combine the thermal load delay characteristics to obtain The electric heating load reduction and the duration of the reduction in the state of component failure and shutdown. Finally calculate the reliability index of IES.

The specific steps of the IES reliability assessment are shown in figure 2.
Read component parameters and wind, light and load data, initialization simulation time and the TTF of components.

Find the faulty component and extract the TTR of the faulty component.

Calling the normal operation optimal scheduling model to solve the energy storage state.

Call the fault recovery optimization model in the fault scenario to solve the load reduction time and the insufficient energy supply.

Statistic reliability data, advance the analog clock to the recovery time.

Beyond the simulation period? Yes

Beyond the simulation period? No

Calculate the reliability indicators during simulation.

Extract the new TTF of this faulty component.

Complete one year of simulation? Yes

Complete one year of simulation? No

Figure 2. Reliability assessment process of IES.

4. Optimal Model of IES Failure Recovery

4.1. Optimal scheduling of IES in normal scenarios

Under normal conditions, IES operation optimization scheduling mainly considers the economy of system operation, and minimizes the cost of electricity purchased by IES from the external grid and the cost of gas purchase from the external gas grid, and when IES generates excess electricity to return power to the external grid, power purchase cost is negative. Based on the IES optimization model in [8], the day-ahead optimization scheduling of IES is performed, and the operating parameters of the energy storage equipment under normal operating conditions are obtained.

4.2. Optimized energy supply recovery for IES in failure scenarios

4.2.1. Optimized recovery model for failure scenarios considering shutdown loss and minimum operating cost

When a component of IES fails, the component immediately stops running and the output energy is zero. At this time, the power balance in the IES is destroyed, and it is necessary to adjust the equipment operating parameters and even reduce the load. However, due to the complex energy coupling relationship in the IES, the minimum load reduction level caused by the fault is difficult to intuitively judge. Therefore, optimize the energy supply recovery of the IES after the failure, and make the IES operating cost as low as possible on the premise of ensuring the reliability of the load energy supply.

(1) Objective function

In order to minimize the amount of load reduction and system operating cost at the same time, the objective function of this paper is the lowest sum of load reduction cost and operating cost.

\[
\min F = [C_{\text{cut}}(t) + C_{\text{op}}(t)] \cdot \Delta t \tag{8}
\]

\[
C_{\text{cut}}(t) = K_{\text{elec}} C_{\text{elec}}(t) L_{\text{elec}}(t) + K_{\text{heat}} C_{\text{heat}} L_{\text{heat}}(t) \tag{9}
\]

\[
C_{\text{op}}(t) = C_{\text{ele}}(t) + C_{\text{gas}}(t) \tag{10}
\]

where \( \Delta t \) is the running time of the IES; \( C_{\text{cut}}(t) \) and \( C_{\text{op}}(t) \) are respectively the load reduction cost and operating cost under the failure of the IES during the period; \( C_{\text{ele}}(t) \) and \( C_{\text{gas}}(t) \) are the cost of purchasing and selling electricity from the grid and the cost of purchasing gas from the gas grid per unit time of the IES; \( L_{\text{elec}}(t) \) and \( L_{\text{heat}}(t) \) are respectively the reduction of electric heating load during \( t \) period; \( C_{\text{elec}} \) and \( C_{\text{heat}} \) are the prices of electricity and heat respectively; \( K_{\text{elec}} \) and \( K_{\text{heat}} \) are the cost
reduction coefficients of electric and heating load respectively, and the value is large to ensure that the IES will not reduce the load for economy in the event of a failure, which will reduce its reliability.

(2) Restrictions

In the process of optimizing and dispatching the IES, it is necessary to meet the corresponding constraints, including the power and heat balance constraints in the system, the transmission power constraints of the connecting pipeline, the equipment output constraints, the energy storage equipment constraints, etc. [8-9]. The optimal scheduling of the fault recovery phase also needs to consider the associated impact of the faulty equipment, that is, the fault topology constraint.

The IES topology given in this article shows that when a component $X_k$ fails, the output of itself and its associated components $X_1, X_2, \ldots, X_m$ are all 0. For example, when a natural gas pipeline fails, the output of the gas boiler and the electrical and thermal output of the gas turbine are both 0.

$$P_{X_k}(t) = 0 \quad (t = 1, 2, \ldots, m)$$

where $P_{X_k}(t)$ is the output of element $X_k$ at time $t$; $m$ is the number of affected components.

5. Simulation result

5.1. Parameter setting

The structure of an IES with electric-gas input and electric-heat output is shown in figure 1, and the configuration parameters of its internal components and reliability parameters are shown in table 1. Assuming that the equivalent failure rate of natural gas input is 0.12 times/year, the average repair time is 5 hours, the maximum input power of natural gas is 400kW; the equivalent failure rate of power input is 0.15 times/year, the average repair time is 5 hours, the maximum input or output power of electrical energy is 350kW. The maximum charging and discharging efficiency of ES and HS are both 0.25, the maximum capacity is 0.9, the minimum capacity of ES is 0.2, and the minimum capacity of HS is 0.1. The average output end electrical load demand is 170kW, and the average thermal load demand is 85kW. The annual hourly electricity, thermal load demand, annual wind speed, and sunlight data are detailed in ref. [8]. The parameters of the thermal load delay characteristic model are referred to [4]. Sequential Monte Carlo simulation is used to evaluate the reliability of the integrated energy system, and the maximum simulation period is 10,000 years.

| Element | Capacity | Effectiveness | Failure rate (times/year) | Repair time (h) |
|---------|----------|---------------|---------------------------|----------------|
| CHP     | 100 kW   | 0.29          | 0.03                      | 20             |
| GB      | 100 kW   | 0.9           | 0.03                      | 20             |
| EB      | 100 kW   | 0.9           | 0.02                      | 20             |
| T       | 400 kW   | 1             | 0.013                     | 5              |
| WT      | 100 kW   | -             | 0.02                      | 10             |
| PV      | 150 kW   | -             | 0.02                      | 10             |
| ES      | 100 kWh  | -             | 0.03                      | 20             |
| HS      | 100 kWh  | -             | 0.03                      | 20             |

5.2. The influence of fault optimization model on reliability results

In the case that IES does not use the fault recovery optimization scheduling model, in addition to the faulty component, other components in the IES during the fault period will continue to operate according to the operating parameters at the moment before the fault. The output of the faulty component and the component that cannot continue to run due to the influence of the faulty component is adjusted to 0. In the case of adopting the fault recovery optimized scheduling model, the output of the components not affected by the fault will be flexibly adjusted through the calculation of the fault recovery optimized scheduling model to ensure the reliability of energy supply. Table 2
shows the calculation results of the reliability index of the IES electric heating load whether the fault recovery optimal dispatch model is used.

Table 2. The influence of fault recovery optimal dispatching model on electric heating load index.

| Model comparison       | Electric load reliability index | Heat load reliability index |
|------------------------|---------------------------------|-----------------------------|
|                        | EENS (kWh/year) | ARDI (h/year) | ASAI  | EENS (kWh/year) | ARDI (h/year) | ASAI  |
| Adopt fault dispatch model | 63.2440         | 0.759         | 0.9999134 | 6.9981         | 0.175         | 0.9999800 |
| No failure scheduling model | 7.9116          | 0.162         | 0.9999815 | 0.2683         | 0.006         | 0.9999993 |

From the simulation results in table 2, it can be seen that the reliability of power supply and heating reliability of IES using the fault recovery optimization scheduling model has been greatly improved compared with the failure recovery optimization scheduling model. Compared with the failure recovery optimization scheduling model without the use of the failure recovery optimization scheduling model, the expected short supply of electrical load with the failure recovery optimization scheduling model has been reduced by 55.3324kWh/year, a relative reduction of 87.49%, and the electrical load reduction time has been reduced by 0.597h/year, a relative reduction of 78.66%. At the same time, the expectation of insufficient heat load supply is reduced by 6.7298kWh/year, which is a relative reduction of 96.17% compared with the failure recovery optimization scheduling model. The heat load reduction time is reduced by 0.169h/year, and a relative reduction of 96.57% compared with the stand-alone operation. Thermal reliability has been greatly improved. Through fault recovery optimization scheduling, when the electric load is facing the risk of lack of supply, CHP units and transformers increase the output to reduce the lack of supply of the electric load. The electric boiler reduces the output so that more electricity is used for the supply of the electric load. When there is a risk of lack of supply, CHP units, gas boilers, and electric boilers increase the output to improve the reliability of heat load energy supply.

5.3. The influence of thermal load delay characteristics on the reliability of IES

When the capacity of the heating equipment in IES is not enough to support all the thermal load in a fault state, the delay characteristic of the thermal load will have an impact on the reliability indices. The capacity of the CHP unit in the calculation example is set to 50kW and the simulation is performed. With the other component parameters unchanged, the comparison of the electrical and thermal load reliability index of the integrated energy system with and without considering the thermal load delay characteristic is shown in Table 3.

Table 3. The influence of thermal load delay characteristics on the electric heating load indices.

| Whether to consider delay | Electric load reliability index | Heat load reliability index |
|--------------------------|---------------------------------|-----------------------------|
|                          | EENS (kWh/year) | ARDI (h/year) | ASAI  | EENS (kWh/year) | ARDI (h/year) | ASAI  |
| Consider delay           | 23.992           | 0.384         | 0.99995616 | 1.5378         | 0.042         | 0.9999521 |
| Not consider delay       | 22.672           | 0.383         | 0.99995627 | 0.15343        | 0.0018        | 0.9999980 |

Through the analysis of the calculation results in table 3, it can be seen that the insufficient supply of electrical load is expected to be slightly reduced when considering the thermal load delay characteristics, a relative reduction of 5.50%, the duration of electrical load reduction is slightly reduced, and the reliability of power supply is slightly improved. This is because reducing the thermal energy supply can reduce the output of the electric boiler and thus reduce the power consumption. When the electrical load demand is also relatively large, reducing the thermal load demand can reduce the expectation of insufficient power supply. At the same time, considering the thermal load delay characteristics, the insufficient supply of the thermal load is expected to be greatly reduced, with a relative reduction of 89.87%, the duration of the load reduction of the thermal load is also reduced, and the reliability of heating is greatly improved.

6. Conclusion

Aiming at the problem of IES reliability evaluation, this paper considered the operation optimization of IES normal operation and failure operation, and established a comprehensive energy system failure scenario optimization recovery model that minimizes power losses and operation costs. On the basis of
the fault scenario optimization recovery model, an IES reliability evaluation method based on sequential Monte Carlo simulation and fault recovery optimization was proposed, and conclusions are as follows:

(1) The fault recovery optimization scheduling model enables IES to flexibly adjust the output of components during fault recovery, greatly improving the reliability of IES power supply and heating.

(2) The delay characteristic of the heat load will play a positive role in the reliability of IES's energy supply to a certain extent.

(3) The proposed IES reliability evaluation method based on Monte Carlo simulation integrates the operation timing of the components in the IES and considers the optimal scheduling of IES failure recovery, which realizes an effective evaluation of the reliability of IES energy supply.

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