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Integrated Energy System Planning Method Considering Integrated Demand Response and Reliability Constraints

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Abstract. At present, most comprehensive energy planning methods aim at economy. A distributed integrated energy system planning method considering reliability and integrated demand response is proposed. This method considers that IDR can effectively realize the peak valley cutting of load characteristics, improve the system economy, and increase the reliability constraint penalty cost to make it more realistic. The example results show that the proposed method can consider the economy and reliability of configuration results under different conditions, and realize the selection of equipment.

1 Introduction

Distributed Integrated Energy System (DIES) is an integrated energy system located in and coupled with various distributed energy terminals. It breaks the original mode of separate design and operation of various energy supply systems and achieves the goal of multi-energy complementary and energy cascade utilization through coordinated planning and operation of different energy supply systems [1].

IES can flexibly utilize different types of energy and various coupling devices, so it has a variety of operational strategies and configuration methods[2]. The literature [3-5] established an integrated energy system planning optimization model considering a variety of different equipment and energy types, and it is verified by simulation that the rational allocation of integrated energy system equipment types and capacities can not only achieve "multi-energy complementary".

However, most of the current planning models take economy as the goal. In this paper, considering both economy and reliability, a distributed integrated energy system planning method considering reliability and integrated demand response is established.

2 Distributed Integrated Energy System Model

The distributed integrated energy system proposed in this paper consists of CHP system, gas boiler, electric refrigerator and absorption chiller, including four loads of cold, heat, electricity and gas. In IDR, loads are divided into fixed loads and response loads based on their ability to participate in the demand response and their priority.

The fixed load is:

$$P_{k,t}^{\mathrm{FL}} = P_{k,t}^{\mathrm{FL0}} \tag{1}$$

Where, $k = 1,2,3$ representing three load types of electricity, heat and cold respectively, $P_{k,t}^{\mathrm{FL}}$ represents the demand for fixed energy at the t-time of the k-th fixed energy, and $P_{k,t}^{\mathrm{FL0}}$ represents the demand under the benchmark price as the benchmark value.

The response load is:

1) Can reduce load[6]:

$$P_{k,t}^{\mathrm{CL}} = P_{k,t}^{\mathrm{CL0}}\left[1+\varepsilon_{k,t}^{\mathrm{CL}}\left(\rho_t^{e}-\rho_t^{e0}\right)/\rho_t^{e0}\right] \tag{2}$$

Where, $P_{k,t}^{\mathrm{CL}}$ represents the reduction of the the k-th load that can be cut at the t-time under the dynamic electricity price, ρ_t^{e} is the electricity purchase price of the user at the t-time, ρ_t^{e0} and $P_{k,t}^{\mathrm{CL0}}$ is the benchmark electricity price of the t-time and its corresponding reduction amount of load that can be cut respectively, $\varepsilon_{k,t}^{\mathrm{CL}}$ represents the price elasticity factor, reflecting the impact degree of price change on the user' s participation in the comprehensive demand response at the t-time.

2) the transferable load is[7]:

$$P_{k,t}^{\mathrm{SL}} = P_{k,t}^{\mathrm{SL0}}\left[1+\varepsilon_{k,t}^{\mathrm{SL}}\left(\rho_t^{e}-\rho_t^{e0}\right)/\rho_t^{e0}\right] \tag{3}$$

Where, $\varepsilon_{k,t}^{\mathrm{SL}}$ represents the price elasticity coefficient of the k-th transferrable load in the t-time, $P_{k,t}^{\mathrm{SL0}}$ and ρ_t^{e0} represents the amount of the k-th transferrable load in the t-time under benchmark and variable electricity

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price respectively. In this paper, it is assumed that the load will be transferred to adjacent time periods and linearly decrease in the maximum duration. The mathematical model of this assumption is as follows:

$$\sum_{t'=[t+1,t+T_R]} P_{k,t't}^{SLC} = P_{k,t}^{SL0} - P_{k,t}^{SL} \tag{4}$$

$$P_{k,t't}^{SLC} = P_{k,(t+1)t}^{SLC} - \varpi_k (t'-t), t' = [t+1, t+T_R] \tag{5}$$

Where, $P_{k,t}^{SLC}$ represents the transfer of the k-th transferable load from from the period t to the period t'. T_R represents the maximum duration of the transferable load transfer, ω_k represents the transfer attenuation coefficient indicating the effect of the load transfer amount decreasing with time.

3) The alternative load is:

$$P_{k,t}^{TL} = P_{k,t}^{TL0} \left[1 + \varepsilon_{k,t}^{TL} \left(\rho_t^e - \rho_t^g \right) / \rho_t^g \right] \tag{6}$$

$$P_{k,t}^{TL} - P_{k,t}^{TL0} = \lambda \cdot P_{k,t}^{TLG} \tag{7}$$

Where, $\varepsilon_{k,t}^{TL}$ represents the price elasticity coefficient of the k-th alternative load of the user in the t-time, $P_{k,t}^{TL0}$ and ρ_t^e represents the amount of the k-th alternative load in the t-time under benchmark and variable electricity price respectively. λ represents the conversion efficiency between the natural gas and the natural gas. $P_{k,t}^{TLG}$ represents the magnitude of the power of the alternative load converted to the gas load under the t-time electricity price.

3 Distributed Integrated Energy System Equipment Optimization Configuration Model

In this paper, a distributed integrated energy system equipment optimization configuration model is established. For a variety of electricity price schemes, the optimal electricity price and the optimal allocation results of distributed integrated energy system equipment can be obtained by comparing the allocation results and costs under different electricity price schemes.

3.1 setting of electricity price scheme

According to the time-of-use electricity pricing method proposed in the literature[8], under the condition of fixed peak-valley electricity price ratio and peacetime electricity price, we can get a variety of different participating alternative electricity price schemes by changing peak-valley pull ratio △. Considering the comprehensive interests of operators and customers, △ needs to:

$$L_V / L_P \le \Delta \le 1 \tag{8}$$

Where, △is the ratio between peak-flat electricity price difference and flat-valley electricity price difference, L_P and L_V represents the total load of peak and valley period respectively.

3.2 Integrated Energy System Two-Layer Planning Model

3.2.1Upper-level planning

(1) objective function

The goal of upper-level planning is to achieve optimal game relationship between the economy and reliability of the operator's construction of integrated energy system, which can be expressed as:

$$\min f = C_{inv} + C_{op} + kC_I \tag{9}$$

Where, C_{inv} is the annual investment equivalent cost, C_{op} is DIES annual operating cost, C_I is the reliability constraint penalty cost, and numerically, k is the reliability penalty cost coefficient, reflecting the importance of system reliability in planning.

① Investment cost: mainly including investment cost, operation cost and residual value of equipment, which can be expressed as:

$$C_{inv} = \sum_{i=1}^{N} \sum_{j=\Omega_i} \left[\left(C_{inv}^{i,j} + C_m^{i,j} - C_{res}^{i,j} \right) n_{ij} \cdot R_{ij} \cdot I_{ij} \right] \tag{10}$$

Where, i represents the equipment type, which means $i = 1,2,3,4$ represent CHP system, gas boiler, absorption refrigerator and electric refrigerator respectively, $N = 4$ represents four types of equipment, Ω_i represents the set of alternative models of the i-th equipment, $C_{inv}^{i,j}$ represents the initial investment cost of the j-th alternative type of the i-th equipment, $C_{res}^{i,j}$ represents the residual value of the j-th alternative type of the i-th equipment, and takes 5% of the initial investment, $C_m^{i,j}$ represents the operation and maintenance costs of the j-th alternative type of the i-th equipment, such as labour costs and maintenance costs, and takes 3% of the initial investment, n_{ij} represents the number of installation units of the j-th alternative type of the i-th equipment, I_{ij} represents the equipment installation status of the j-th alternative type of the i-th equipment, which is a 0-1 variable, 1 indicates the selection of this type of equipment, 0 is the opposite. R_{ij} represents the capital recovery coefficient of the equipment, which can be expressed as:

$$R_{ij} = \frac{r(1+r)^{l_{ij}}}{(1+r)^{l_{ij}}-1} \tag{11}$$

Where, r represents the discount rate, which is 6.7% in this paper, l_{ij} represents the life expectancy of the j-th alternative type of the i-th equipment.

②Operating cost: This paper selects three typical days of summer, winter, spring and autumn to optimize operation:

$$C_{\text{op}} = \sum_{ttt=1}^{3} C_{\text{op}}^{ttt} days_{ttt} \tag{12}$$

Where, $ttt = 1,2,3$ represents three typical days of spring, autumn, summer and winter, C_{op}^{ttt} represents the daily running cost of a typical day, which is obtained by the lower layer optimization operation, $days_{ttt}$ is the number of days per typical day.

③Reliability constraint penalty cost:

$$C_I = I \tag{13}$$

Where, I is the comprehensive energy reliability impact assessment index.

(2) Constraint condition

Equipment capacity needs to meet the requirements of the maximum cold load and heat load, which can be expressed as:

$$\sum_{i=3}^{4} \sum_{j=\Omega_i} X_{ij}\eta_{ij}n_{ij}I_{ij} \geq L_{\max}^{\text{C}} \tag{14}$$

$$\sum_{i=1}^{2} \sum_{j=\Omega_i} X_{ij}\eta_{ij}n_{ij}I_{ij} \geq L_{\max}^{\text{H}} \tag{15}$$

Where, X_{ij} indicates the installation capacity of the Category j alternative type of the Category i device, $L_{\max}^{\text{C}}$ and $L_{\max}^{\text{H}}$ respectively represent the maximum cold load and the maximum heat load.

Integrated energy systems also need to meet reliability constraints.

$$R_{\text{LOEE}} \leq R_{\text{LOEE,max}} \tag{16}$$

$$R_{\text{SAIDI}} \leq R_{\text{SAIDI,max}} \tag{17}$$

Where, $R_{\text{LOEE,max}}$ represents the maximum value expected for the out-of-supply energy, and $R_{\text{SAIDI,max}}$ represents the maximum value of the energy deficiency duration of system.

3.2.2Lower-level planning

Lower-level optimization optimizes the output of a variety of devices with the lowest operating cost of the day:

$$\min C_{\text{op}} = C_{\text{g}} + C_{\text{e}} \tag{18}$$

Where, Cg represents the cost of gas purchase, Ce represents the cost of transaction with the superior power grid.

1)Natural gas purchase costs include the cost of natural gas consumed by the gas-fired boiler, the cost of natural gas consumed by the system, and the cost of direct natural gas supply after the replacement load is converted into the gas load:

$$C_{\text{g}} = \lambda_{\text{g}} \cdot \sum_{t=1}^{24} \left(\frac{P_{\text{CHP}}^{t}}{\beta} + \frac{P_{\text{eGB}}^{t}}{\eta_{GB} \cdot \beta} + \sum_{k=1}^{3} P_{k,t}^{\text{TLG}}\right) \tag{19}$$

Where, λ_{g} represents the purchase price.

2)The interaction cost with the power grid is the difference between the electricity purchase cost and electricity sales revenue:

$$C_{\text{e}} = \sum_{t=1}^{24} \left(\lambda_{\text{e,in}}^{t} \cdot P_{\text{PG,in}}^{t} - \lambda_{\text{e,out}}^{t} \cdot P_{\text{PG,out}}^{t}\right) \tag{20}$$

Where, $\lambda_{e,in}^{t}$ and $\lambda_{e,out}^{t}$ respectively represent the unit income of the distributed integrated energy system from the power grid at time t, $P_{PG,in}^{t}$ and $P_{PG,out}^{t}$ respectively represent the amount of electricity purchased from the grid at any time and the spare amount online.

4 Study Analysis

In this paper, an industrial park in north China is selected as an example to optimize the allocation of comprehensive energy system.

4.1Analysis of calculated results

The reliability penalty cost coefficient k is set as 1, and the optimal peak, valley and level electricity prices are respectively 1.26 yuan /kWh, 0.3 yuan /kWh and 0.77 yuan/kWh. Under the electricity price solutions, integrated energy system optimization configuration results as shown in table 1.

Table 1. DIES Optimized Configuration Results.

Type of device	Model and quantity
Thermoelectric Co-production	1*CHP1+1*CHP3
Gas boilers	1*GB1+1*GB3
Absorbent chillers	1*AC2
Electric chillers	1*EC2

4.2 Analysis of the impact of reliability and IDR on optimized configuration results

This paper sets up the following four scenarios for comparative analysis:

Scenario 1) no integrated energy system, no reliability, no IDR;

Scenario 2) an integrated energy system is established without considering reliability or IDR;

Scenario 3) an integrated energy system is established considering the reliability and setting k as 1 but without considering IDR.

Scenario 4) an integrated energy system is established considering reliability and IDR and setting k as 1.

Table 2. Optimized configuration results and cost comparison for each scenario.

	CHP	Gas boilers	Absorption chillers	Electric chillers	Cost of investment (￥10,000)	Operating costs (￥10,000)	Total cost (￥10,000)	Reliability Constraint Penalty Cost (￥10,000)
1	—	1*GB2+ 2*GB3	—	2*EC3	304.38	8763.18	9067.56	155.25
2	1*CHP1+1*CHP3	1*GB3	1*AC2	1*EC2	1639.44	6497.62	8021.89	56.89
3	1*CHP2+1*CHP3	1*GB1+1*GB3	1*AC3	1*EC3	1700.74	6971.44	8707.90	38.73
4	1*CHP1+1*CHP3	1*GB1+1*GB3	1*AC2	1*EC2	1661.14	6512.32	8112.89	47.88

Through comparative analysis, the following conclusions can be drawn:

1) Compared with scenario 1, scenario 2 is provided by the traditional distribution system.

2) Compared with scenario 1, the reliability of scenario 2 is greatly improved. It shows that the integrated energy system is more economical and reliable than the distribution system.

3) Compared with scenario 2, the construction cost and the operating cost increased, indicating that the selection result of the distributed integrated energy system can be optimized both economically and reliably by including reliability in the selection model.

4) Compared with scenario 3, the initial investment cost and the operating cost decreased, indicating that considering IDR can effectively improve the economy of the system.

5 Conclusions

Considering that IDR can effectively realize the peak and valley cutting of load characteristics and improve the system economy, adding the reliability constraint penalty cost into the planning model can realize the selection of equipment considering the economy and reliability of configuration results under the condition of sufficient degree.

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