Research on Optimization of Comprehensive Energy System Operation Scheduling Based on Multiple Energy Storage Coupling Mechanism

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Abstract. A comprehensive energy system based on multi-energy complementation is an important way to improve regional energy utilization efficiency and optimize resource allocation. Taking the minimization of the running cost of the integrated energy system as the objective function, a matrix model of the energy flow of the integrated energy equipment is established, and a method combining dynamic programming and improved particle swarm optimization is proposed. Under the same load and energy price setting, the horizontal comparison method was used to analyze the optimization of the integrated energy system under the conditions of no energy storage, two heat storage only, and three composite heat storage and cooling settings. The results showed that the operating costs of working condition three and working condition two are reduced by 14.65% and 5.92%, respectively compared with working condition one. The existence of energy storage devices has a significant impact on optimizing the overall operation scheduling of the system, while reducing the use of unnecessary energy supply equipment. At the same time of running costs, it can also achieve a more stable operation of the system.

1. Introduction
Energy is the basis of human survival and production activities, and it is also a manifestation of the competitiveness of the national economy, people's livelihood and national strategy. Its type and utilization method reflect the needs of social development and are restricted by the level of science and technology. From the perspective of the regional supply side, different forms of energy in China are generally planned separately and operated independently. The model increases investment costs and the energy efficiency is low, causing environmental pollution. In addition, from the perspective of regional users, under the promise of satisfying the user's base load demand, each single energy supply system is difficult to achieve efficient use of multiple energy sources even under optimization. Under this background, a comprehensive energy system based on multi-energy complementarity was born. It refers to the use of advanced technologies and management models in a certain area to realize electricity in various links such as energy production, transmission, storage and consumption. The energy system forms of complementary utilization and coordinated optimization of various types of energy sources, such as gas, heat, cold, etc., provide an important path for solving regional energy supply and resource optimization.

Through a large amount of literature investigation and analysis, it is found that the existing optimization scheduling problem of integrated energy systems often uses a single optimization...
algorithm in the solution process. For systems containing multiple energy storage devices, it is necessary to search and optimize in the high-dimensional variable space. And the calculation amount increases sharply on the calculation period length. In response to these problems, this study performs an optimized scheduling analysis on a comprehensive energy system that includes compound heat and cold storage, while providing a full-cycle calculation process method from user load forecasting to the optimization of the operation status of each equipment, and provides a coupling. The optimization method of dynamic programming and particle swarm optimization algorithm realizes the utilization of regional comprehensive energy flexibility, efficiency and reliability.

2. Comprehensive Energy System Energy Model and Optimal Scheduling

2.1. Load forecasting model
In this paper, the state space model is used to calculate the user’s cooling and heating loads, and it is expressed in matrix form as follow

\[ CT^{i+1} = AT^i + BU \]  

(1)

In order to predict the cooling and heating load of the building, the relationship equation between cooling and heating load and temperature distribution needs to be established, namely

\[ y = T^{i+1}d \]  

(2)

The simultaneous equation (1) and equation (2) can be solved to obtain the cold and heat loads as follow

\[ y_i = \sum_{i=1}^{p} \theta_i y_{i-1} \Delta t + \sum_{i=1}^{p} \theta_i u_{i-1} \Delta t \]  

(3)

2.2. System energy flow matrix model
Considering the cold and heat load of the user area, when the power is required by the load, the user constructs the cold storage constraint of the balancing function of cold, heat, electricity and heat storage load. On this basis, the integrated energy flow matrix model is established by using the mainline energy modeling idea, which provides a basic tool for the subsequent optimization algorithm. The electrical load balancing constraint is as follow

\[ L_e + P_{cc} + P_{chp} = E_{in} \eta_e + G_{chp} \cdot \eta_{chp} \]  

(4)

The cold load balancing constraint is as follow

\[ L_e + E_{cc} = H_{ab} \cdot \eta_{ab} + P_{cc} \cdot \eta_c \]  

(5)

The heat load balance constraint is as follow

\[ L_h + H_{ab} + E_{hs} = G_{chp} \cdot \eta_{chp} + P_{chp} \cdot \eta_h + G_{gb} \cdot \eta_gb \]  

(6)

Based on the node-branch modeling method, the energy main line matrix model is established. The input power \( P \), load power matrix \( L \), coupling matrix \( G \), and the energy flow matrix equation \( P = L \times G \) is used to simulate the operation of the equipment.

\[ L = \begin{bmatrix} L_e + P_{chp} + P_{cc} \\ L_h + H_{ab} + H_{hs} \\ L_c + H_{cs} \end{bmatrix} \]  

(7)

\[ G = \begin{bmatrix} \eta_e & \eta_{chp} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_{chp} & \eta_{gb} & \eta_{chp} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \eta_{ab} & \eta_{cc} \end{bmatrix} \]  

(8)

\[ P = \begin{bmatrix} E_{in} & G_{chp} & G_{chp} & G_{gb} & G_{chp} & G_{ab} & G_{cc} \end{bmatrix} \]  

(9)
2.3. System optimization model

The objective function for optimizing the operating cost of energy supply equipment is as follows:

\[
\min C_{op} = \min \sum_{t=0}^{T} \left[ f_e(t) \cdot E_{in}(t) + f_g(t) \cdot \left[ G_{chp}(t) + G_{gb}(t) \right] \right]
\]  

(10)

The vector \( P_5 = [G_{chp}, G_{gb}, P_e, H_{ab}] \) needs to meet the constraint conditions under a certain capacity, which can be expressed as a matrix constraint:

\[
P_{\min} \leq \eta \cdot P_5 \leq P_{\max}
\]  

(11)

The heat and cold storage equation constraints are as follows:

\[
E_{s+1}^{x} = (1 - \delta) E_{s}^{x} + \left( e_{s,c} \cdot P_{s,c}^{t} - 1 / e_{s,d} \cdot P_{s,d}^{t} \right) \cdot \Delta t
\]  

(12)

The two kinds of energy storage equipment operating constraints in the system are as follows:

\[
0 \leq P_{s,c}^{t} \leq u_{s,c} \cdot P_{s,c}^{\max}
\]  

(13)

\[
0 \leq P_{s,d}^{t} \leq (1 - u_{s}) \cdot P_{s,d}^{\max}
\]  

(14)

\[
P_{s,c}^{t} \cdot P_{s,d}^{t} = 0 \& \& P_{s,c}^{t} + P_{s,d}^{t} > 0
\]  

(15)

\[
E_{s}^{x} \leq E_{s}^{i} \leq E_{s}^{\max}
\]  

(16)

\[
E_{s}^{T} = E_{s}^{0}
\]  

(17)

2.4. System optimization algorithm

This study uses an optimization method that combines dynamic programming theory with an improved particle swarm optimization algorithm. The specific algorithm steps include three major parts.

1. Calculation initialization and parameter input. \( x_{ij}^{k}, c_1, c_2, w, h, p_{0,b}, p_{0,g} \) and other PSO related parameters are initialized. Input parameters: hourly cooling, heating, and electric loads \( L_{c}(j), L_{h}(j), L_{e}(j) \), hourly electricity prices, gas prices \( p_{e}(j), p_{g}(j) \).

2. Circular computing body with dynamic programming method as the core. Setting cycle \( j \leq T \), \( j + + \) ( \( j \) expressed in time, in units of 1 hour, \( T = 24 \) hours). Optimizing the operation of the system at the time \( j \) and \( j + 1 \) within the time, solving to obtain the optimal solution under the current constraint boundary setting, and then by continuously selecting different state quantities \( E_{ij}^{1,b} \) and \( E_{ij}^{1,c} \) combinations to obtain a set of optimal solution sets, complete the first \( j \) Time optimization work. Before entering the \( j + 1 \) period, you need to modify the objective function:

\[
\min C_{op}^{j} = \min \left\{ f_e(t) \cdot E_{in}(t) + f_g(t) \cdot \left[ G_{chp}(t) + G_{gb}(t) \right] + C_{op}^{j-1} \left( E_{ij}^{j-1}, E_{bh}^{j-1} \right) \right\}
\]  

(18)

3. The improved particle swarm optimization algorithm is used in the dynamic programming method. In this study, the improved particle swarm optimization algorithm is as follows:

\[
v_{ij}^{k+1} = w v_{ij}^{k} + c_1 r_1 \left( p_{ij}^{k} - x_{ij}^{k} \right) + c_2 r_2 \left( p_{ij}^{k} - x_{ij}^{k} \right)
\]  

(19)

\[
x_{ij}^{k+1} = h \left( x_{ij}^{k} + v_{ij}^{k+1} \right) + (1 - h) r_3 x_{ij}^{k}
\]  

(20)
3. Case Study

3.1. Basic data
The case has determined the capacity and performance parameters of each energy supply equipment, as shown in Table 1.

| Element             | Capacity / Kw | Efficiency / Cop | $\eta_e = 0.3$ | $\eta_h = 0.4$ |
|---------------------|---------------|------------------|----------------|----------------|
| Cogeneration        | 120           | $\eta_e$ = 0.3   | $\eta_h$ = 0.4 |
| Gas boiler          | 400           | 0.8              |                |                |
| Electric refrigerator| 300           | 3                |                |                |
| Absorption chiller  | 300           | 0.7              |                |                |
| Electric heat pump  | 100           | 2                |                |                |
| Heat storage device | 1000          | 0.95             |                |                |
| Cold storage device | 1500          | 0.95             |                |                |

The user’s cooling, heating and electric loads are provided by the integrated energy system. In order to deeply explore the impact of composite energy storage equipment on the optimal operation of the integrated energy system, this case analysis and displays three operating conditions, as shown in Table 2.

| Working condition | Heat storage | Cold storage |
|-------------------|--------------|--------------|
| 1                 | X            | X            |
| 2                 | V            | X            |
| 3                 | V            | V            |

3.2. Case result analysis
Finally, in order to more clearly compare and analyze three integrated energy systems with different energy storage schemes, this paper compares the operating costs of three different operating conditions in the same cycle. The results are shown in Figure 1. The full-day operating costs of conditions 1 to 3 are 2818.3, 2651.4, and ¥2405.4 respectively. The operating costs of operating conditions 3 and 2 are reduced by 14.65% and 5.92% relative to operating condition 1, respectively. The operating cost of the system has a critical impact. In addition, as shown in Figure 1, the comparison of the three operating conditions in terms of hourly operating costs. After the use of heat and cold storage devices, it is possible to significantly achieve “the peak cutting and valley filling” of the operating costs within the cycle, greatly improving the smooth operation of the system effectiveness.

Figure 1. The Operating Fee for The Next Cycle Under Three Operating Conditions
4. In Conclusion
In this paper, including a composite heat storage and refrigeration equipment, the energy simulation and optimal scheduling analysis of an integrated energy system are provided. On the basis of providing general solution steps for this type of problem, in order to solve the problem of excessive search space in the problem, we propose a method that combines dynamic programming theory with improved particle swarm optimization algorithm is used to achieve fast, accurate and efficient global optimization. From the aspects of load prediction and analysis of the integrated energy system, design and operation scheduling of energy supply system, this paper proposes relevant algorithms for simulation and comparative analysis of an integrated energy system with different energy storage conditions. The results show that the heat storage device has a critical impact on the operating cost of the integrated energy system. The scheduling of charging and discharging of the energy storage device directly affects the overall operating cost. The operating cost of the simulated operating conditions 3 and 2 is 1 point relative to the operating conditions. Do not reduce 14.65% and 5.92%. In addition, after the use of heat and cold storage devices, the "peak cutting and valley filling" of the operating costs within the cycle can be clearly achieved, which greatly improves the operational smooth efficiency of the system and can reduce unnecessary supply. The use of energy equipment not only reduces the system operating costs, but also improves energy efficiency.

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