Optimization and Analysis of Distributed Energy System with Energy Storage Device

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Abstract

Aiming at distributed energy system (DES) with energy storage device, the mathematical models of major equipments are established in this paper. With the objective functions of the daily minimum operation cost and the minimum equipment quantity, a mixed integer nonlinear multistage objective function is established, which is solved by the means of dynamic programming and penalty function and then the system optimization is completed. According to the case of a hospital in Tianjin, the optimized result is compared with the other two modes, which are DES without energy storage device and sub-production system (the existing system of the hospital). The result shows that the system with energy storage device is better than the system without energy storage device, and the economy of DES is superior to sub-production system significantly.

Keywords: Distributed energy system; energy storage device; penalty function; optimization; economy

1. Introduction

Distributed energy systems (Referred as DES) generally refers to the distributed combined cooling, heat, and power system (CCHP), which provide multiple terminal energies at the same time in order to bring about cascaded utilization of energy [1]. In recent years, scholars both at home and abroad have made a lot of research on distributed energy. The economic research aspects: Sundberg and Henning discussed the effect of energy price on CHP system cost minimization [2], Gamou showed the effect and evaluation of energy load fluctuations on CCHP economic and device capacity optimization, on basis of which a new research program was advanced [3]. There are also a large number of research on storage device and system device configuration and optimization of operation strategy of DES [4]-[10].

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On the basis of the above studies for distributed energy system, aiming at distributed energy system (DES) with energy storage device, the mathematical models of major equipments of CCHP and a mixed integer nonlinear multistage objective function are established in this paper, which are solved by the means of dynamic programming and penalty function, and then the system optimization is completed. According to a case (a hospital in Tianjin), the optimized result is compared with the other two modes in terms of economic, that DES without energy storage device and sub-production system (the existing system of the hospital).

2. Models of Distributed Energy System for Main Equipments

The main equipments of CCHP generally include generation power plant, waste heat boiler, electricity compression chiller, waste heat absorption chiller unit, energy storage equipments, and control systems. Due to the part-load performance of various equipments has greater impact on overall energy consumption, it is necessary for major equipments to be established the mathematical models and to be optimization analyzed, optimization results are as follows:

2.1. Power plant

\[ P_{GT} = \alpha_{GT}E_{GT} + b_{GT} \]
\[ Q_{GT} = p_{GT}E_{GT} + q_{GT} \]
\[ P_{GT\_min} \leq P_{GT} \leq P_{GT\_max} \]

\( a \) and \( b \)—Constant for relation between power generation and fuel-discharge. \( p \) and \( q \)—Constant for relation between flue gas waste heat and fuel flow.

\[ Q_{B}^{h} = p_{B}^{h}Q_{GT} \quad Q_{B\_min}^{h} \leq Q_{B}^{h} \leq Q_{B\_max}^{h} \]
2.2. Waste heat boiler

2.3. Double-effect lithium bromide absorption chiller

\[
Q_A^c = Q_B^h \text{COP}_c, \quad Q_A^h = Q_B^h \text{COP}_h
\]

\[
Q_B^{\text{nom}_{\text{min}}} \leq Q_B^h \leq Q_B^{\text{nom}_{\text{max}}}
\]

2.4. Natural stratified water storage device

The capacity of water storage system storing cold (heat) depends on the amount of cold (hot) water stored by water storage tank and the number of cooling (heat) temperature difference, which refers to the absolute value of the temperature difference between the air conditioning load return water and the supply water of water storage tank. For a certain volume of water storage tank, the actual available storage capacity can be showed by the following expression \([11]\):

\[
R = \rho \cdot V \cdot C_p \cdot \Delta t \cdot \epsilon \cdot \alpha
\]

*\(R\)—available storage capacity in the water storage tank, kJ;*

*\(\Delta t\)—the temperature difference between return water when cold (heat) release and inflow water when storing cold (heat), °C;*

*\(\epsilon\)—improvement of water storage tank;*

*\(\alpha\)—volume availability of water storage tank;*

3. Optimization of Distributed Energy System

3.1. Models of optimization

The mathematical models of main equipments of the system as described earlier, for various energy such as electricity, heat, and cooling, the energy demand-supply balance are as follows:

Electrical balance:

\[
P_{GT,k} + P_{buy,k} = P_{dem,k} + P_{sys,k} + P_{re,k}
\]

\[
P_{sys,k} = 0.09Q_{dem,k} + 0.03Q_{dem,k}^c
\]

Gas thermal balance:

\[
Q_{GT,k} = Q_{A,k}^c + Q_{A,k}^c + Q_{RD,k}
\]

Heat balance:

\[
Q_{A,k}^h + Q_{B,k}^h + Q_{S,k} = Q_{k}^{hd}
\]

Cooling balance:

\[
Q_{R,k}^c + Q_{RE,k}^c + Q_{S,k} = Q_{k}^{cd}
\]
3.2. Objective function

Multi-stage goal programming is used for optimization of system integration. System operating strategy can be determined by pivotal operating parameters. For improving the system of economic, optimal objective function is that the minimum total operating cost (including natural gas costs and purchasing costs), the optimization result can only shows total energy input/output and distribution at time under the conditions of the minimum cost. The pivotal operating parameters which affect the system economic refer to amount of purchasing power, gas, operation and maintenance costs of thermal power units in each time. The operation and maintenance cost for gas turbine cycle thermal power plant is 0.042–0.064 yuan per unit of energy output of a kWh. In order to minimize storage period operating cost under the condition of a given capacity, the objective function is as follows:

\[
J_1 = \min \left\{ \sum_{k=0}^{K-1} \phi_{buy,k} P_{buy,k} + \sum_{k=0}^{K-1} \phi_{gas} F_{GT,k} + \sum_{k=0}^{K-1} \Psi_k P_{GT,k} \right\}
\]

To make the system structure simple and easy control, secondary optimization object refers to the amount of the equipment meet the minimum load requirement. At the same time, the optimization determines the range of capacity and initial operation strategy of the equipment.

\[
J_2 = \min \left\{ N_{GT}, N_A, N_B, N_{RE} \right\}
\]

3.3. Solution

Mixed-integer nonlinear programming algorithm is used in this paper; the main steps are as follows: The first step, building super structure, establishing mixed-integer nonlinear programming model; Second step, to integer variable continuous treatment. The original problem is transformed for more constraints nonlinear planning problem; Third step, introducing penalty factor \( p \) to structure punishment item to be further simplified; Forth step, assigning initial value, as Diego generation number \( k \); variable number \( n \); constraints conditions number \( m \); calculation precision \( e \) and vector of initial value; Fifth step, using simplex method and acceleration method for the programming, searching optimal solutions; Sixth step, judging if it meets optimal function value, then checking if coordinates points meet constraints conditions; Seventh step, if meet the conditions, then get the optimal solution through calculation. Otherwise extending the penalty factor 10 times, \( k = k + 1 \), then go to the fourth step, and so the cycle.

Due to the established objective function in the paper (6), which makes the total operation cost minimum in multiple times and energy storage balance and constraint equations containing energy storage balance for last time and this time, so each time the system output parameters depend not only on the input parameters of the system, but also associated with several input and output parameters for the times before. We use dynamic programming methods for solving this problem in this paper. So-called multi-stage refers to the decision-making process in order of time or space, to break the problem into a number of interrelated stages, starting from the initial state, in order to make decisions at each stage, to the completion state. These decisions form a sequence of decisions, and determine the optimal routes for the process.

4. Case Optimization and Analysis

Taking a hospital building as an example, whose construction area is 110,000 square meters, system input is natural gas and electricity purchased, the system output is heat, cold, electrical load the building
required. Optimizing the objective functions of CCHP with energy storage device, then selecting the devices based on the available equipment optimization parameters. Table 1 shows the quantity and capacity of selected devices through the optimization based on the optimize results.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Capacity</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas turbine</td>
<td>1170kW</td>
<td>2</td>
<td>Rated power generation efficiency 0.24</td>
</tr>
<tr>
<td>Heat absorption chiller</td>
<td>2871kW</td>
<td>2</td>
<td>Refrigeration coefficient 1.27</td>
</tr>
<tr>
<td></td>
<td>2248kW</td>
<td></td>
<td>Heating coefficient 0.925</td>
</tr>
<tr>
<td>Waste heat combustion boiler</td>
<td>2500kW</td>
<td>1</td>
<td>η = 0.9</td>
</tr>
<tr>
<td>Electric refrigerator</td>
<td>4000kW</td>
<td>1</td>
<td>COP = 5</td>
</tr>
<tr>
<td>Energy storage device</td>
<td>512m³</td>
<td>2</td>
<td>Temperature difference(cooling)8℃ (heating)15℃</td>
</tr>
</tbody>
</table>

Table 2. TOU electricity price of Tianjin

<table>
<thead>
<tr>
<th>Time</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~5</td>
<td>0.335</td>
</tr>
<tr>
<td>6</td>
<td>0.829</td>
</tr>
<tr>
<td>7~10</td>
<td>0.286</td>
</tr>
<tr>
<td>11~17</td>
<td>0.829</td>
</tr>
<tr>
<td>18~22</td>
<td>1.286</td>
</tr>
<tr>
<td>23</td>
<td>0.335</td>
</tr>
</tbody>
</table>

Note: for the system with energy storage device, the electricity price in trough falls 15% on the basis of the existing in Tianjin.

Taking the typical day of winter as an example, the following figures show the comparation of the system operating, (a) for the CCHP with energy storage devices and (b) without energy storage devices.

From Fig.2, it is known that the power supply method of the CCHP with energy storage device and without are unanimous basically in the time when electricity price is in the trough, but in peak times during the day, for combined supply system with energy storage device, the proportion of gas turbine power generation on their own power supply is higher than the system without energy storage device, which to a certain extent reduces the operating costs of the system. In night, because it needs for filling heat for system with energy storage device, the heat load is much larger than the one without energy storage device, so one gas turbine is opened and runs in full load; For system without energy storage device, due to little heat in night, using the mode that only one gas turbine runs and the minimum load rate is 60%, the ways rely on the electric purchased from grid to meet user power demand.

![Fig. 2. Diagram of the balance of power supply](image-url)
Fig. 3 shows that for energy storage system, during 7:00 to 20:00, the absorption chiller can be able to run at full capacity and full use of waste heat from flue gas. From 12:00 to 20:00, heat users need is less than the amount of heat supplied by absorption chiller operating at full capacity, the excess heat is stored in storage tanks by energy storage devices, and next day from 7:00 to 11:00, the heat in storage tanks will be released when absorption chiller can not supply enough heating in order to regulation. For system without energy storage devices, during 12:00 to 20:00, the absorption chiller runs at part load conditions and do not full use of waste heat from flue gas so that greater heat loss; From 7:00 to 11:00, when heat is needed most, using gas boiler which uses the gas purchased to supply heat, the operating cost for each hour is greater than one of the energy storage system.

Fig. 4 (b) shows that for system without energy storage, from 23:00 to next day 5:00, gas turbine runs at the minimum load rate 60%. The main reason is that heat load is small at this time which does not reach one-fourth of the peak value, whereas cold load is also small, at this time only part waste heat continues to be used after waste heat for heating, to led waste heat emissions more serious; The gas turbine runs at the load rate of 90% in other peaks, and waste heat emissions volume is relatively small. From Fig.4 (a) it is known that, for energy storage system by which greater heat load needed for store energy, the gas turbine runs at full load in the trough which can make full use of energy and has better economic benefits.

The equipment configuration and operation strategy have been optimal through the optimization for the system, so that the system's total economic has been further improved. The existing system of the hospital for heating, cooling, power supply is sub-production system, and the way of energy supply is that purchasing the electricity from the municipal power grid, using direct-fired lithium bromide absorption chiller for cooling and heating, when heat or cooling is not enough, using the electric refrigerator and gas-
fired boiler respectively for added. Comparing supply system (with energy storage devices) with one without energy storage devices in economic. Program 1 refers to the program with cooling storage and program 2 is the program without cooling storage.

<table>
<thead>
<tr>
<th>Table 3. The investment of CCHP system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project investment</strong></td>
</tr>
<tr>
<td>Gas turbine</td>
</tr>
<tr>
<td>Waste heat combustion boiler</td>
</tr>
<tr>
<td>Waste heat LiBr absorption chiller</td>
</tr>
<tr>
<td>Installation (gas turbine + LiBr unit)</td>
</tr>
<tr>
<td>Electric refrigerator</td>
</tr>
<tr>
<td>Energy storage device</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4. Sheet of investment, cost, profit, and economical index of solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project</strong></td>
</tr>
<tr>
<td>Power generation</td>
</tr>
<tr>
<td>Generation benefits</td>
</tr>
<tr>
<td>Cooling supply</td>
</tr>
<tr>
<td>Cooling price</td>
</tr>
<tr>
<td>Cooling benefits</td>
</tr>
<tr>
<td>Heat supply</td>
</tr>
<tr>
<td>Heat price</td>
</tr>
<tr>
<td>Heating benefits</td>
</tr>
<tr>
<td>Gas consumption</td>
</tr>
<tr>
<td>Gas cost</td>
</tr>
<tr>
<td>Operation and maintenance costs</td>
</tr>
<tr>
<td>Electricity cost for cooling storage</td>
</tr>
<tr>
<td>Electric refrigerator cost</td>
</tr>
<tr>
<td>Total income</td>
</tr>
<tr>
<td>Total expenditure</td>
</tr>
<tr>
<td>Net income</td>
</tr>
<tr>
<td>Static Payout Period</td>
</tr>
<tr>
<td>Dynamic Payout Period</td>
</tr>
<tr>
<td>Net Present Value</td>
</tr>
</tbody>
</table>

Note: 1. Electric refrigerator initial investment = the capacity ×1000 yuan/kWh. 2. Energy storage device initial investment = the volume capacity ×500 yuan/kWh.

Distributed energy system income mainly includes power generation income, heating and cooling benefits, whereas the main expenditure includes fuel cost of natural gas, electric refrigerators electricity charges and maintenance cost. The lifetime of each system is calculated at 20 years, and table 5 shows the investment, costs, profits and economic indicators, where natural gas price is 2.4 (y/m³), the electricity price is 0.355 (y/kWh) in the trough, and the electricity price ratio (peak/trough) ) is 3.6225. CCHP 1 refers to the system with energy storage devices, and CCHP 2 refers to the system without energy storage devices.

From table 4 it is known that the static payout period and dynamic payout period of system with energy storage devices are all less than the system without energy storage devices through the comparison of two programs, so system with energy storage devices has better nature of the initial investment recovery. From the perspective of net present value, net present value of two programs are far greater than zero,
which illustrates that these two programs is economically viable, and the net present value of energy storage system program is greater. So the supply system with energy storage devices is the best.

5. Symbol Table

- $k$ Number of interval time divided in cycle day.
- $E$ Electricity generation or electricity consumption in the $k$-th time.
- $F$ Gas consumption, M$^3$
- $Q$ Cooling, heat, kWh.
- $J$ Operating cost in a storage cycle.
- $p, q, r, s$ The property coefficient of equipment.
- $\delta$ Symbol characterizing gas turbine and absorption chiller to open or stop.
- max, min The upper and lower limits of variable.
- Superscript $c, h, a$ Cooling supply, heat supply, electricity consumption of the auxiliary.
- Superscript $d, hd, cd$ Demand of electricity, heat and cooling.
- Subscript $GT, B, AR(A)$ Gas turbine, boiler, waste heat absorption unit.
- Subscript $RE, S, RD$ Electric refrigerator, energy storage device, heat release.
- Superscript $xc, xh$ Gas heat used by waste heat absorption unit for heating and the gas heat energy cost for refrigeration.
- Subscript $buy, gas1, gas2$ Purchasing electricity, gas consumption of gas turbine, gas consumption of gas boiler.

Acknowledgement

This work was supported in part by Tianjin Natural Science Fund under Grant 06YFGZGX18300.

References