Integrated energy system planning of distribution network considering load timing coupling characteristics

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Abstract. The integrated energy system can effectively improve energy utilization and reduce environmental pollution. Existing research mainly focuses on the equipment type, capacity and optimal configuration of the pipeline network of the integrated energy system in the microgrid. However, there are few studies on the planning of integrated energy systems at the distribution network level. Therefore, under the condition of fully considering the time-series coupling characteristics of the cooling and heating load, a mathematical model of the integrated energy system planning of the distribution network is established in this article. A method of planning and solving the integrated energy system of the distribution network based on the K-means clustering algorithm is proposed to realize the coordinated planning of multiple integrated energy stations in the distribution network. An example of distribution network in Xinjiang region verifies the rationality and effectiveness of the proposed method.

1. Introduction

The integrated energy system uses natural gas as fuel and has the advantages of high efficiency, low emissions and low noise. It is a more efficient, reliable and environmentally friendly energy supply system than the traditional distribution system. According to relevant data, operating costs can be saved by 12%, 11%, 23%, 21% and carbon dioxide emissions can be reduced by 22.7%, 34.4%, 34.3%, and 61.4% respectively by adopting the system for office buildings, shopping malls, and hotels and hospitals and other types of buildings.

The existing integrated energy system planning is mainly for the equipment type and capacity of the integrated energy station in the microgrid[1]. The existing distribution network planning mainly studies the situation with distributed energy[2], and lacks the planning of integrated energy system at the distribution network level. Therefore, it has important theoretical and practical significance to determine the number, location and capacity of multiple integrated energy stations from the distribution network level.

In [3], the distribution network planning problem with integrated energy system is studied. The distribution network, gas pipelines and integrated energy system are optimized, but the number and locations of integrated energy stations are manually designated. In order to comprehensively study the integrated energy system planning from the level of the distribution network, based on graph theory in [4], the concept of "energy distance" was proposed, and an optimization model of energy station "station-network" layout was established. The issues of location selection of heating energy stations in
the distribution network and optimization of pipeline routing are discussed, and a comprehensive energy station and pipeline layout planning model is established using the p-median model. An integrated energy station planning method that minimizes the weighted distance between load centers and energy stations was proposed in [5], but the layout of energy stations and pipelines is not equivalent to the shortest path problem. Multiple lines are allowed to be laid in a single pipeline channel, but only the shortest path is considered and the cost that can be reduced by the shared channel is ignored, and the model adopts heuristic algorithm to solve the local optimum. The comprehensive energy system planning method that considers the complementarity of the load sequence is proposed in [6], and the method for determining the number of energy stations and the initial site location is given, but the method is more complicated and difficult to implement.

Therefore, a planning method for the number, site and capacity of integrated energy stations in the distribution network is proposed in this paper, taking full consideration of the coupled characteristics of the cooling and heating load time series.

2. Mathematical model of integrated energy system planning in distribution network

The planning problem of the integrated energy system in the distribution network is to determine the number, site and capacity of integrated energy stations in the planned distribution network, and then determine the energy supply radius of each energy station and the distribution of the pipe network between the energy station and each load. Therefore, the objective function of the integrated energy system planning of the distribution network can be expressed as:

\[ \min F = C_{\text{station}} + C_{\text{pipenet}} \]  

Where, \( C_{\text{station}} \) — The annual value of the comprehensive cost of all energy stations in the distribution network; \( C_{\text{pipenet}} \) — Comprehensive annual value cost of pipe network in distribution network.

The whole life cycle theory is adopted[7], the expression is as follows:

1. The expression of the annual value of the comprehensive cost is:

\[ C_{\text{station}} = \sum_{i=1}^{N_{\text{station}}} \left[ \frac{r_0 (1 + r_0)^n}{(1 + r_0)^n - 1} f \left( P_i \right) \right] \]  

Where, \( N_{\text{station}} \) — The number of new integrated energy stations; \( r_0 \) — Discount rate; \( P_i \) — The cold and heat load demand of the energy station \( K \); \( f \left( P_i \right) \) — The investment cost of the energy station \( K \) (ten thousand yuan). It can be solved according to the load within the energy supply range of the integrated energy station.

2. The comprehensive annual cost expression of the energy pipeline network is:

\[ C_{\text{pipenet}} = \sum_{i=1}^{N_p} c_{p,i} l_i \]  

Where, \( N_p \) — Plan the number of pipelines in the distribution network; \( c_{p,i} \) — Cost per unit length (ten thousand yuan) of pipe \( i \); \( l_i \) — The length of the pipe \( i \) (m).

3. The expression of pipeline cost per unit length of pipeline is:

\[ c_{p,i} = \frac{r_0 (1 + r_0)^n}{(1 + r_0)^n - 1} c_c + c_{\text{loss}} + c_m \]  

Where, \( c_c \) — Construction cost per unit length of pipeline (ten thousand yuan); \( m_i \) — The life cycle of the pipeline (years); \( c_{\text{loss}} \) — The operating loss of the pipeline (ten thousand yuan); \( c_m \) — Pipeline maintenance cost (ten thousand yuan);

4. The expression of the construction cost per unit length of the pipeline is:

\[ c_c = g \left( d_i \right) \]
Where, \( d_i \) — The diameter of the pipeline.

(5) The expression of the operating loss cost of the pipeline is:

\[
 c_{\text{loss}} = \frac{4\pi d_i T_p C_e}{\ln \left( \frac{d_i + 2\delta_i + \delta_a}{d_i + 2\delta_i} \right) \times \text{COP} \times 10^7}
\]  

(6)

Where, \( \lambda \) — Thermal conductivity of pipe insulation material \( (W/(m \cdot ^\circ C)) \);
\( t_c \) — The average temperature difference inside and outside the pipe \( (^\circ C) \);
\( T_p \) — Maximum annual working time of circulating water pump \( (h) \);
\( C_e \) — Unit price \( (¥/(kW \cdot h)) \);
\( \delta_i \) — Pipe thickness \( (mm) \);
\( \delta_a \) — Insulation thickness of pipe \( i \) \( (mm) \);
\( \text{COP} \) — The energy efficiency ratio of the integrated energy system.

(6) The pipeline maintenance cost expression is:

\[
 c_m = \mu c_a
\]  

(7)

Where, \( c_m \) — Maintenance cost of pipeline \( (ten \; thousand \; yuan) \); \( \mu \) — The proportional coefficient of maintenance costs.

The planning of the integrated energy system is also subject to the constraints of the energy supply radius of the energy station, the non-intersection of the energy supply range, and the constraints of the radiation network of the pipe network.

3. Planning and solving method of integrated energy system in distribution network

The integrated energy system planning in the distribution network includes determining the number, site, capacity and pipeline planning of integrated energy stations. Firstly, the number of integrated energy stations is determined. Secondly, the K-means clustering algorithm is used to calculate the objective function (1). Finally, the solution with the smallest cost among multiple iterations is selected. The specific algorithm process is as follows:

(1) Steps to input parameters: The total area \( S \) of the planned distribution network, the maximum and minimum energy supply radius \( r_{\text{max}}, r_{\text{min}} \) of the integrated energy station, the discount rate, the pipe diameter, the life cycle of the pipe, the thermal conductivity of the pipe insulation material, the average temperature difference between the inside and outside of the pipe, and the annual maximum of the circulating water pump Working hours, unit electricity price, pipeline thickness, pipeline insulation thickness, energy efficiency ratio of the integrated energy system, maintenance cost ratio coefficient, number of iterations \( N_t \) are given. The day and night power values of each cooling and heating load is given, the total number of cooling and heating loads is \( N_{ld} \);

(2) Steps for calculating the interval of the number of integrated energy stations in the planned distribution network: According to the total area \( S \) of the planned distribution network, calculate the interval of the number of integrated energy stations \( (the \; number \; of \; clusters) \) according to the following formula \( [N_{\text{min}}, N_{\text{max}}] \),

\[
 N_{\text{min}} = \frac{S}{\pi r_{\text{max}}^2}, \quad N_{\text{max}} = \frac{S}{\pi r_{\text{min}}^2}
\]  

(8)

(3) Number of clusters is \( K = N_{\text{min}} \);

(4) Number of iterations is \( I_t = 1 \);

(5) The steps of given the initial site of the integrated energy station: randomly select \( K \) cold and heat load positions as the integrated energy station site (the center of the cluster);

(6) Number of heating and cooling load is \( l = 1 \).
4

(7) Steps for calculating the distance between the cooling and heating load positions and the cluster centers: Based on the planned urban roads[8], the minimum path method is used to calculate the distance $d_{l,k}$ from the load $l$ to the $K$ cluster centers, $k = 1, 2, ..., K$.

(8) Determine the cluster to which the load belongs and update the cluster center step: add the load to the cluster $k_{\text{min}}$ corresponding to $\min \{d_{l,k} | k = 1, 2, ..., K\}$, and update the cluster center of the $I_t$-th iteration of the cluster. The calculation formula is as follows:

$$
\left( X_{k_{\text{min}},h}, Y_{k_{\text{min}},h} \right) = \frac{\sum_{i=1}^{N_{\text{clus}}} X_i + \sum_{i=1}^{N_{\text{clus}}} Y_i}{N_{\text{clus}}}
$$

(9)

Where $N_{\text{clus}}$ is the load number of the $k_{\text{min}}$-th cluster;

(9) $l = l + 1$;

(10) If $l \leq N_{\mu}$, go to step 7), otherwise, go to step 11);

(11) Calculate the sum of the distances between the loads of each cluster and the respective cluster centers Steps: In the $I_t$-th iteration, for cluster $k = 1, 2, ..., K$, calculate the sum of the distances $D_{k,h}$ of each load of cluster $k$ to its cluster centers $D_{k,h}$:

$$
D_{k,h} = \sum_{i=1}^{N_{k,h}} \sqrt{(X_i - X_{k_{\text{min}},h})^2 + (Y_i - Y_{k_{\text{min}},h})^2}
$$

(10)

Where $N_{k,h}$ is the number of clustering loads in the $I_t$-th iteration;

(12) Calculate the actual construction length of the pipeline: considering the phenomenon of pipeline sharing, according to the literature [6]:

$$
M_{k,h} = 0.38 D_{k,h}
$$

(13)

(14) Calculate the maximum day and night load of each cluster: at the $I_t$-th iteration, for cluster $k = 1, 2, ..., K$, the maximum day and night load of cooling and heating loads:

$$
E_{k,I_t} = \max \left\{ \sum_{i=1}^{N_{k,h}} P_{\text{day},i}, \sum_{i=1}^{N_{k,h}} P_{\text{night},i} \right\}
$$

(12)

Where $N_{k,h}$ is the total number of heating and cooling loads of cluster $k$, and $P_{\text{day},i}, P_{\text{night},i}$ are the day and night load values of each cooling and heating load of cluster respectively;

(15) Calculate the comprehensive annual cost of the energy station:

$$
C_{\text{station}} = \sum_{k=1}^{K} \left( \frac{\tau_d (1 + \tau_r)^{\nu_d}}{(1 + \tau_r)^{\nu_d} - 1} \right) f \left( E_{k,h} \right)
$$

(13)

Where $f \left( E_{k,h} \right)$ is the investment cost of energy station $K$ (ten thousand yuan), which is obtained according to the load within the energy supply range of the integrated energy station;

(16) Steps to record the location and capacity of the integrated energy station: when the number of clusters is $K$, the $I_t$-th iteration, the site of the integrated energy station $k = 1, 2, ..., K$ is
\[
(X_{k,h}, Y_{k,h}) = \left(\frac{\sum_{i=1}^{N_h} x_i + \sum_{i=1}^{N_i} y_i}{N_k}\right)
\]

(14)

Where, \(N_k\) is the load number of the \(k\)-th cluster; the capacity of the integrated energy station \(k = 1,2,\ldots,K\) is \(G_{k,h}\).

17) Move to the next iteration steps: \(I_t = I_t + 1\);
18) Judging step: if the number of iterations \(I_t = I_t + 1\), go to step 5), otherwise, go to step 17);
19) Turn to the next cluster number step: \(K = K + 1\sqrt{a^2 + b^2}\);
20) Judgment step: if the cluster number \(K \leq N_{\text{max}}\), go to step 4), otherwise, go to step 21);
21) Steps to obtain the location and capacity of integrated energy station: According to the formula 
\[
\min\{C_{\text{station}} + C_{\text{pipe}} | K = 1,2,\ldots,N_{\text{max}}, I_t = 1,2,\ldots,N_{\text{It}}\}
\]
, obtain the optimal number of integrated energy station sites \(K^{\text{opt}}\) and the optimal iteration number \(I_t^{\text{opt}}\), and then obtain the optimal integrated energy station site and capacity according to step 15).

Steps 14) and 15) calculated the maximum value of the cooling and heating load during the day and night according to the actual demand of the cooling and heating load and the peak-valley difference, fully considering the time series coupling characteristics of the cooling and heating load, that is, the difference between the day and night load values of each cooling and heating load Larger features. The obtained clustered cooling and heating load values approach in the same direction during the day and night, ensuring the maximum efficiency utilization of the integrated energy system on the time axis, and finding the integrated annual cost of the optimal energy station.

4. Case Studies
The following figure shows the comprehensive energy system planning of a certain area in Xinjiang as an example to verify the effectiveness of the proposed method.

![Figure 1. Planning area of a planned integrated energy system in a certain area of Xinjiang.](image)

As shown in Fig. 1, the planning area is 1.8 square kilometers, the energy supply radius of the integrated energy station is (0.5, 1) kilometers, and the selected pipeline model is shown in Table 1.

| Pipe model | Economic Pipeline Construction cost (t/h) | Pipe thickness (mm) | Insulation thickness of pipeline (mm) |
|------------|------------------------------------------|---------------------|---------------------------------------|
| DN50       | 2.5                                      | 102                 | 3                                     |
| DN70       | 6.1                                      | 122                 | 3                                     |
| DN80       | 9.3                                      | 138                 | 4                                     |
| DN100      | 18.1                                     | 161                 | 4                                     |

Figure 1. Planning area of a planned integrated energy system in a certain area of Xinjiang.

As shown in Fig. 1, the planning area is 1.8 square kilometers, the energy supply radius of the integrated energy station is (0.5, 1) kilometers, and the selected pipeline model is shown in Table 1.
The pipeline service life is 20 years, and the discount rate is 0.08, the pipeline maintenance cost proportional coefficient is 0.25, the electricity price is $0.6/\text{kw h}$, the average temperature difference between the inside and outside of the pipeline is $10^\circ C$, the thermal conductivity of the pipeline insulation material is $0.06 W/(m \cdot \degree C)$, and the annual operating hours of the pump is 3360h. The energy efficiency ratio of integrated energy is 4.2. The position of each load and the magnitude of the active load are shown in Table 2.

| Load serial number | Abscissa (km) | Ordinate (km) | Daytime load (kw) | Load at night (kw) |
|--------------------|--------------|--------------|-------------------|-------------------|
| 1                  | 0.125        | 0.0625       | 134               | 23                |
| 2                  | 0.5625       | 0.125        | 17                | 135               |
| 3                  | 1.0625       | 0.0625       | 106               | 21                |
| 4                  | 0.125        | 0.4375       | 67                | 5                 |
| 5                  | 0.5          | 0.4375       | 67                | 4                 |
| 6                  | 0.0625       | 0.75         | 134               | 13                |
| 7                  | 0.125        | 1            | 67                | 165               |
| 8                  | 0.4375       | 1.125        | 168               | 23                |
| 9                  | 0.8125       | 1            | 17                | 132               |
| 10                 | 0.9375       | 0.6875       | 335               | 78                |
| 11                 | 1.25         | 0.125        | 268               | 56                |
| 12                 | 1.25         | 0.375        | 10                | 116               |
| 13                 | 1.46875      | 0.3125       | 106               | 32                |
| 14                 | 1.125        | 0.65625      | 27                | 89                |
| 15                 | 1.4375       | 0.75         | 17                | 58                |
| 16                 | 1.5          | 0.5          | 84                | 14                |
| 17                 | 1.09375      | 0.9375       | 17                | 93                |
| 18                 | 1            | 1.125        | 106               | 43                |
| 19                 | 1.375        | 1.25         | 12                | 93                |
| 20                 | 1.5          | 1            | 268               | 62                |

Using the method proposed in this paper, the number of iterations is 200, and two solutions are obtained: the number of integrated energy stations in option 1 is 1, and the number of integrated energy stations in option 2 is 2, as shown in Table 3. According to the this table, when the number of energy stations is 1, the total annual cost is 727,570,000 yuan, and when the number of energy stations is 2, the total annual cost is 40.098+32.462=72.56 (ten thousand yuan). Option 2.

The annual value of the total cost of literature [5]: $36.102 + 39.020 = 751,220,000$ yuan; the annual value of the total cost of literature [6]: $33.266 + 40.434 = 737,000$ yuan.
Table 3. Result table of planning scheme.

| Proposal | Plan 1 | Plan 2 |
|----------|--------|--------|
| Coordinate | 0.8875, 0.6359 | 0.5, 0.4375 | 1.0938, 0.9375 |
| Total load during the day (kw) | 2027 | 1084 | 943 |
| Total load at night (kw) | 2075 | 1127 | 948 |
| Comprehensive energy station capacity (kw) | 2075 | 1127 | 948 |
| Total path length between load and energy station (km) | 11.6979 | 6.5625 | 4.8518 |
| Length of pipeline construction (km) | 4.4452 | 2.4938 | 1.8437 |
| Annual value of comprehensive cost of pipe network (ten thousand yuan) | 21.968 | 12.324 | 9.112 |
| Annual value of comprehensive cost of energy station (ten thousand yuan) | 50.789 | 27.774 | 23.350 |
| Annual value of total cost (ten thousand yuan) | 72.757 | 40.098 | 32.462 |

This paper adopts the methods of literature [5] and literature [6] as a comparison, and the results of the planning scheme are shown in Table 4.

Table 4. Results of planning schemes of documents [5] and [6].

| Literature[5] | Literature[6] |
|---------------|---------------|
| Coordinate | 0.5, 0.4375 | 1.0938, 0.9375 | 0.7, 0.61 |
| Total load during the day (kw) | 796 | 1231 | 884 | 1263 |
| Total load at night (kw) | 1004 | 1071 | 812 | 1263 |
| Capacity of integrated energy station (kw) | 1004 | 1231 | 884 | 1263 |
| Total path length between load and energy station (km) | 6.0112 | 4.6455 | 6.1135 | 4.9652 |
| Construction length of pipeline (km) | 2.2847 | 1.7653 | 2.3231 | 1.8868 |
| Annual value of comprehensive cost of pipe network (ten thousand yuan) | 11.290 | 8.724 | 11.481 | 9.325 |
| Annual value of comprehensive cost of energy station (ten thousand yuan) | 24.812 | 30.296 | 21.785 | 31.109 |
| Total cost (ten thousand yuan) | 36.102 | 39.020 | 33.266 | 40.434 |

According to the results of the calculation example, the comprehensive annual value cost of pipelines based on the K-means clustering algorithm for distribution network integrated energy station planning has increased by 14,220 yuan compared with literature [5], and increased by 6,300 yuan compared with literature [6]. However, considering the time-series coupling characteristics of the cooling and heating loads, that is, the characteristics of the large difference between the cooling and heating load requirements during the day and the night. Based on the K-means clustering algorithm, the annual value of the comprehensive energy station cost of the integrated energy station planning of the distribution network is reduced by 39,84 thousand yuan compared with literature [5], and 17,700 yuan compared with literature [6]. The annual value of the total cost is reduced by 25,62 thousand yuan compared with literature [5], and 11,400 yuan compared with literature [6]. It can be seen that the timing coupling characteristics of cooling and heating loads are considered in the optimization of energy station sites and capacity, so that the values of cooling and heating loads during the day and night are approached in the same direction, which greatly reduces the investment cost of building energy stations and improves the overall economics of energy station planning.
5. Conclusion
The comprehensive energy station planning of distribution network, which considers the coupling characteristics of load timing, fully considers the coupling characteristics of cooling and heating load, and has great theoretical significance. The results of the calculation examples prove that it can effectively reduce the planning cost of the integrated energy station. The proposed K-means clustering algorithm-based distribution network integrated energy station planning solution method is easy to implement and has strong practical significance.

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