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Coordinated planning of micro energy grid based on dynamic radial basis function model

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Abstract

The micro energy grid (MEG) couples a variety of energy sources and conducts multi-dimensional coordinated management and distribution of various types of energy, such as cooling, heating and electrical energy, which is a concrete realization of the energy internet in the region. The research on the coordinated planning of the MEG is the key to the economic and reliable operation of the MEG. This paper proposes an MEG coordinated planning method based on dynamic radial basis function (DRBF) model. An MEG model considering the operational characteristics and economics of energy supply devices is established, and the DRBF model planning strategy is proposed in combination with the Latin hypercube sampling method to solve the optimal planning. The effectiveness of the established model and the solution method is verified by simulation. The proposed method can obtain reasonable devices' configuration and optimal operation scheme simultaneously, and improve the energy efficiency.

Keywords: micro energy grid, radial basis function, coordinated planning, configuration

1. Introduction

With the rapid development of modern society, energy demand will continue to increase, and the energy development pattern based on traditional energy sources has been unsustainable. The concept of the energy internet [1] can meet the global energy needs in a clean and green way in the future, and has a great impact on the development of society. As a specific implementation of the energy internet in the region, the micro energy grid (MEG) coordinates and controls multiple energy sources, which can meet the various energy needs of users [2, 3]. The concept of MEG is given in [4], which specifically refers to the coordination and optimization of energy generation, transmission, distribution, conversion, storage and consumption in the process of planning, construction and operation. MEG can improve the flexibility, safety, economy of social energy supply systems [5].

Reasonable and effective configuration planning for MEG is the key to MEG research. At present, researchers have made certain achievements in the research of MEG modelling and configuration planning. The performance of combined cooling, heat and power (CCHP) system and the performance of distributed generation (DG) units have been modulated in [6], and the multi energy-type coordinated microgrid day-ahead and real time scheduling models are established in [7]. Reference [8] presents a highly integrated and reconfigurable microgrid framework containing various DG units and energy storage systems, which can provide electrical and heating energy. In [9-11], the authors discuss the different types of energy hub structure and the corresponding energy management strategies for the operation of MEG. Reference [12] presents an overall review of the modeling, planning and energy management of the CCHP microgrid. Reference [13] uses the particle swarm optimization algorithm to solve the microgrid optimization configuration model, optimizes the configuration and location of the DG

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units. A two-stage optimal planning and design method for CCHP microgrid system was presented in reference [14]. An active distribution system power-supply planning model considering cooling, heating and power load balance is proposed in reference [15].

Overall, the existing research has made some progress in MEG operation and planning, but there are still some problems. 1) At present, most of the microgrid planning studies consider operating costs, but most of them are the optimization of the output of a single device, and do not involve multi-constrained optimization of multiple energy devices, which makes the planning results have certain limitations. 2) Most planning algorithm lacks an effective search mechanism, which leads to excessive calculation and reduces the solution efficiency.

In this paper, a dynamic radial basis function (DRBF) model is proposed by using the RBF model combined with Latin hypercube sampling (LHS) method to solve the MEG planning problem. The original model is corrected by the optimal values obtained in each round by RBF, and the configuration and operation scheme of the main devices of the MEG are obtained. Through the proposed method, the MEG optimal configuration can be more efficiently planned, so that the system investment and energy consumption cost can be reduced under the premise of meeting the user's energy demand.

2. Micro Energy Grid Optimization Model

The MEG needs to meet user's cooling, heating and electrical energy demand in operation. Through the CCHP system and DG units, the gas resources are converted into electrical energy to supply for the user, and the waste heat is used to provide the demand cooling and heating load to the user through heat exchanger and direct-fired absorption chiller. In this situation, MEG can realize the resource ladder recycling and reducing the resource loss. The proposed MEG system contains different energy conversion, supply and storage devices, including internal combustion engine, direct-fired absorption chillers, heat exchanger, photovoltaic (PV), wind turbines (WT), electric chiller, ice storage air-conditioner, energy storage systems (battery storage, thermal storage and ice tank), and it also can purchase electricity from the grid. The structure of CCHP integrated MEG is shown in Figure 1.

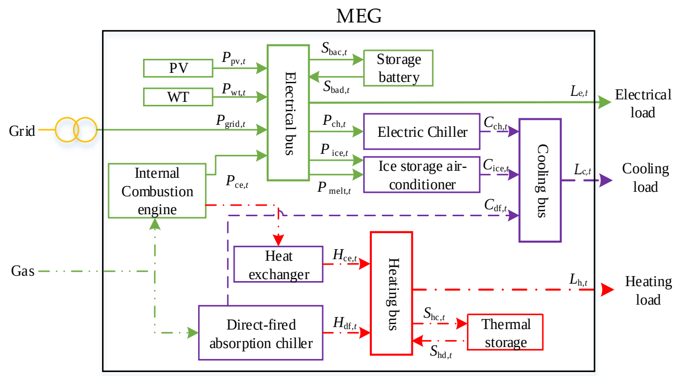

Fig. 1. Structure of MEG.

2.1. Objective function

The objective of the MEG planning is to minimize the total economic cost of MEG. The objective function is as follow:

$$\begin{aligned}\min C_{\text{total}} &= C_{\text{ELE}} + C_{\text{GAS}} + C_{\text{O\&M}} + C_{\text{EM}} + C_{\text{P}} \\ &= \sum_{t=1}^{8760}[c_{\text{e},t}\cdot P_{\text{grid},t}\cdot\Delta t + c_{\text{g},t}\cdot V_{\text{g},t}\cdot\Delta t + \sum_{n=1}^{N} c_n\cdot P_{n,t}\cdot\Delta t + (a\cdot V_{\text{g},t} + b\cdot P_{\text{grid},t})\cdot\Delta t] + C_{\text{P}}\end{aligned} \tag{1}$$

where, C_{total} is the total economic cost of the MEG per year. C_{ELE} represents the total electricity-purchasing cost. C_{GAS} represents the total gas-purchasing cost. $C_{\text{O\&M}}$ represents the operation & maintenance cost of all devices in MEG. C_{EM} represents the gas emission cost of MEG. C_{P} repersents the construction cost of MEG life cycle construction cost to each year. Δt is the time interval, which is set to be 1h in this paper.

In addition, $c_{e,t}$ denotes the electricity price of the grid in period t. $P_{grid,t}$ denotes power output of the grid in period t. $c_{g,t}$ denotes the natural gas price, $V_{g,t}$ denotes the gas volume consumed by MEG in period t. c_n is the maintenance cost coefficient for the n-type device; $P_{n,t}$ is the output of the n-type device, and N is the quantity of devices in the MEG. a is the pollutant cost coefficient per unit volume of gas, b is the pollutant cost coefficient corresponding to per kWh electricity-purchasing from the grid.

2.2. Coordinated planning constraints

In order to ensure the stable operation of the MEG, the system needs to balance the supply and demand of cooling, heating and electrical energy. According to the structure and composition of the MEG in Figure 1, the system has to meet the following energy balance equations, devices operating constraints and energy storage systems constraints, simultaneously.

1) Energy balance equations

$$C_{df,t} + C_{ch,t} + C_{ice,t} = L_{c,t} \tag{2}$$

$$H_{he,t} + H_{df,t} + S_{hd,t} = L_{h,t} + S_{hc,t} \tag{3}$$

$$P_{grid,t} + P_{pv,t} + P_{wt,t} + P_{ce,t} + S_{bad,t} = L_{e,t} + P_{ch,t} + P_{ice,t} + P_{melt,t} + S_{bac,t} \tag{4}$$

Equations (2)-(4) are cooling, heating and electrical energy balance equations, respectively.

In equations (2) and (3), $H_{df,t}$, $C_{df,t}$ are the heating and cooling power of direct-fired absorption chiller. $H_{he,t}$ is the heating power of heat exchanger. $L_{h,t}$, $L_{c,t}$ are user's demand heating and cooling loads. $S_{hc,t}$, $S_{hd,t}$ are charging and discharging power of thermal storage. $C_{ch,t}$, $C_{ice,t}$ are the cooling power of electric chiller and ice storage air-conditioner in period t.

In equation (4), $P_{grid,t}$, $P_{ce,t}$, $P_{pv,t}$, $P_{wt,t}$ and $S_{bad,t}$ are power outputs of grid, internal combustion engine, PV, WT and battery storage in period t. $L_{e,t}$ is the user's demand electrical load. $P_{ch,t}$, $P_{ice,t}$, $P_{melt,t}$ are power consumptions when electric chiller working, ice storage air-conditioner making and melting ice. $S_{bac,t}$ is the charging power of storage battery.

2) Devices operating constraints

$$\begin{cases} P_{j.\min} \le P_{j,t} \le P_{j.\max} \\ 0 \le H_{m,t} \le H_{m.\max} \\ 0 \le C_{k,t} \le C_{k.\max} \end{cases} \tag{5}$$

where, $P_{j,\max}$, $P_{j,\min}$ are the maximum and minimum power outputs of the j-type device. $P_{j,t}$ denotes the power output of the j-type device in period t. The j-type devices include all the power output devices. Similarly, $H_{m,t}$, $C_{k,t}$ are the heating output of the m-type device and the cooling output of the k-type device in period t. $H_{m,\max}$, $C_{k,\max}$ are the maximum heating output of the m-type device and the maximum cooling output of the k-type device. The m-type devices include all heating conversion devices. The k-type devices include all cooling conversion devices.

3) Energy storage systems constraints

$$\begin{cases} SOC_{\min} \le SOC_t \le SOC_{\max} \\ 0 \le S_{c,t} \le S_{c.\max} \\ 0 \le S_{d,t} \le S_{d.\max} \end{cases} \tag{6}$$

where, SOC_t is the state of charging of energy storage systems (battery storage, thermal storage and ice tank) in period t. $SOC_{\min}$, $SOC_{\max}$ denote the minimun and maximun state of charging of energy storage systems. $S_{c,t}$ and $S_{d,t}$ are the charing power and the discharging power in period *t*. $S_{c,max}$ and $S_{d,max}$ represent the maximun charing and discharging power, respectively.

3. MEG Planning Strategy Based on DRBF

In the MEG planning model established in Section 2, there are continuous control variables (device output, energy storage system charging and discharging power, etc.), and discrete control variables (charging and discharging energy state of the energy storage system). Therefore, it is a mixed integer nonlinear programming (MINLP) issue. For this kind of problem, the traditional gradient-based optimization algorithm will cause the solution rate to be too slow due to too many variables, which makes the solution effect unsatisfactory. The key of this research is how to quickly and reasonably find the optimal system device configuration and optimal operation scheme under the condition of satisfying various constraints, minimize the total economic cost of MEG, and complete the planning of MEG.

Regarding the issues above, this paper proposes a MEG planning method based on dynamic radial basis model combined with LHS. Through the better global optimization characteristics and robustness of RBF model, the optimal solution would be obtained more efficiently.

3.1. RBF model

The agent model is a mathematical model used to approximate and replace complex and time-consuming “black box” systems in the optimization process. Through the introduction of the agent model, the difficulty of the optimization problem can be reduced and the efficiency of the solution can be effectively improved. Among many agent models, the RBF model has attracted the attention of researchers because of its high approximation accuracy and unique error estimation function for complex nonlinear systems. Therefore, in order to improve the efficiency of the optimization algorithm, this paper uses the RBF model to calculate the MEG planning. The basic principle of the RBF model is described in detail in [16], which will not be repeated here.

Agent model-based optimization methods can be divided into two categories: static surrogate-based optimization (SSBO) and dynamic surrogate-based optimization (DSBO). The SSBO is, in the optimization solution process, the metamodel is no longer updated, and the optimization result largely depends on the approximation accuracy of the initial metamodel. The DSBO is, in the optimization solution process, the metamodel is selectively added to the sample. The points are updated to improve the approximation accuracy of the metamodel and ensure the correctness of the optimization solution. Therefore, in order to ensure the correctness of the solution results, a dynamic RBF model combined with Latin hyper sampling method is proposed.

3.2. LHS method

The utilization of sampling methods to obtain sample points in the planning space is the basis for constructing an agent model. A good sampling method must satisfy both spatial uniformity and projection uniformity. The LHS method can satisfy both spatial uniformity and projection uniformity simultaneously.

In MEG, internal combustion engine and direct-fired absorption chiller account for a large proportion of total device investment and provide the cooling, heating and electrical load for users. Therefore, the capacity of these two devices is selected as the planned capacity of the MEG, and the capacity of other devices is a fixed value. When the planned capacity of the MEG is determined, the MEG planning can be completed.

The two-dimensional graphic composed of the two planned capacity is evenly divided into $n \times n$ sub-intervals. A sample point is randomly selected in each subinterval by LHS method, and a total of n sample points are collected, and the coordinate values of each sample point are recorded. The vertical and horizontal coordinates of each point correspond to the composition of the rated capacity of internal combustion engine and direct-fired absorption chiller, which is shown in Figure 2.

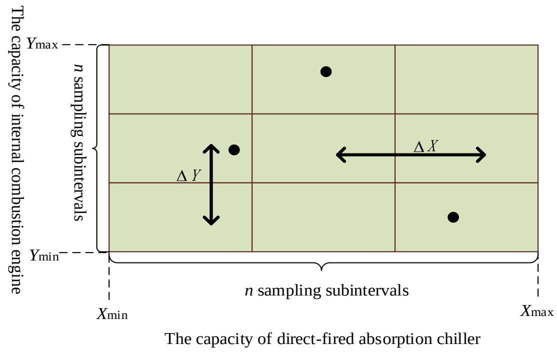

Fig. 2. Initial sample points through LHS.

According to the capacity value corresponding to the initial sample point, the MEG device configuration are determined, and the optimal total economic cost C_{total} of the MEG can be calculated by using the model constructed above.

3.3. Solving procedure of DRBF

In summary, the solving procedure of DRBF model combined with LHS method is shown in Figure 3.

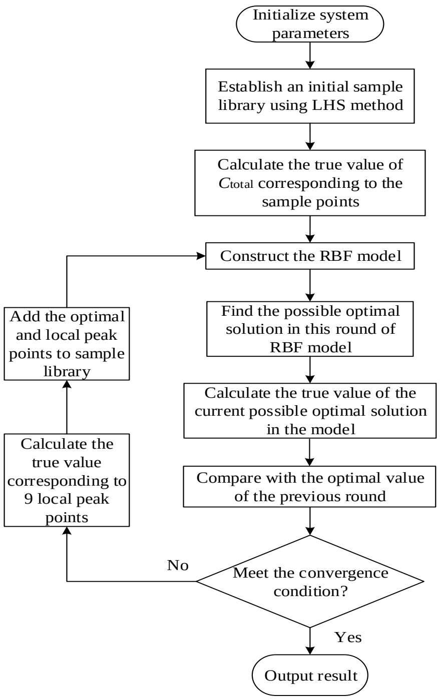

Fig. 3. Solving procedure of DRBF.

4. Case Studies

4.1. Simulation settings

Based on the data of a certain region, this paper establishes the MEG system, and uses the above proposed method to plan the MEG under the premise of meeting the user's cooling, heating and electrical loads. For the convenience of calculation, each day is divided into 24 hours for annual operation optimization to obtain C_{ELE}, C_{GAS}, $C_{O\&M}$ and C_{EM}.

The user's energy demand in the region is provided by the MEG shown in Figure 1. The default system in this paper can purchase electricity from the grid, but does not sell electricity to the grid. The configuration of non-planning devices in the MEG is shown in Table 1 and Table 2. Independent modelling of each device refers to [6, 9-11].

Table 1. The rated capacity of non-planning devices in MEG

PV	WT	Electric chiller
400kW	150kw	1000kW

Table 2. Parameters of energy storage systems

Energy storage type	Capacity/kWh	Maximum input/kW	Maximum output/kW
Battery storage	1000	300	300
Thermal storage	1000	300	300
Ice tank	1000	500	500

The unit construction cost of all devices is calculated by converting the initial construction cost of the device to the full life cycle period cost, which is the average unit cost. The total construction cost includes the sum of the device-purchasing cost and the device construction cost.

4.2. Optimal results and analysis

The model is solved by programming based on Matlab platform. According to the set device parameters and annual load data, this paper takes the rated capacity of the direct-fired absorption chiller as the *x* variable, the rated capacity of internal combustion engine as the *y* variable, and the total economic cost of MEG as the *z* variable to form the three-dimensional sampling space. Figure 4 shows the initial sample library obtained by the LHS method and actual optimization calculation.

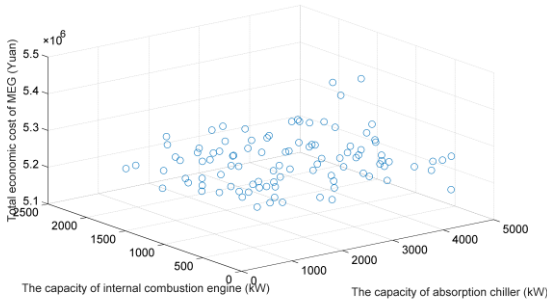

Fig. 4. Initial sample library.

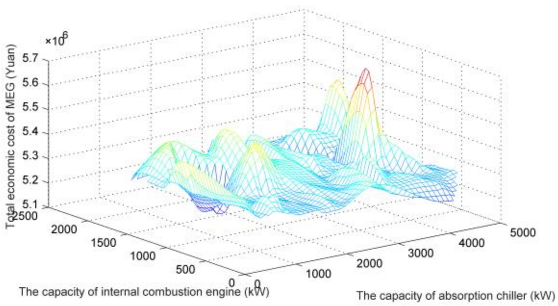

Fig. 5. The first generation RBF model.

According to the initial point coordinate data, the first generation RBF model is constructed, which is shown in Figure 5. By collecting new sample points and adding them to the sample library, the next generation sample library and RBF model are obtained as shown in Figure 6 and Figure 7, respectively.

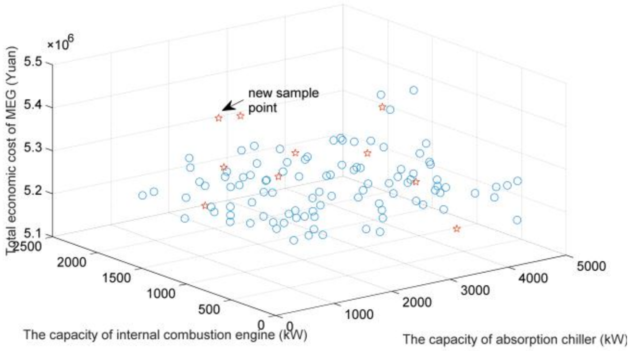

Fig. 6. Second generation sample library.

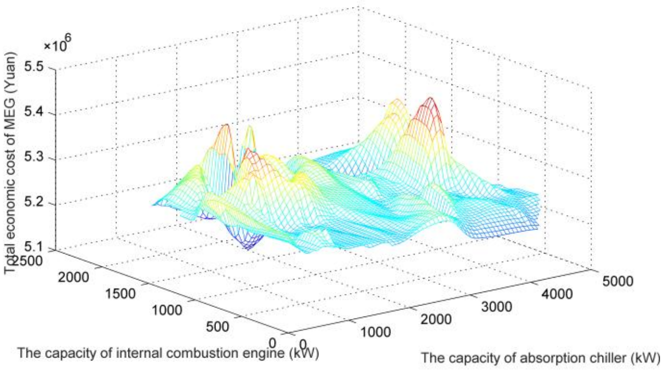

Fig. 7. Second generation RBF model.

According to the proposed DRBF method, the iterative convergence graph can be obtained by multiple sampling point update and correction of the RBF model. Figure 8 shows the total economic cost of MEG with DRBF model updating times.

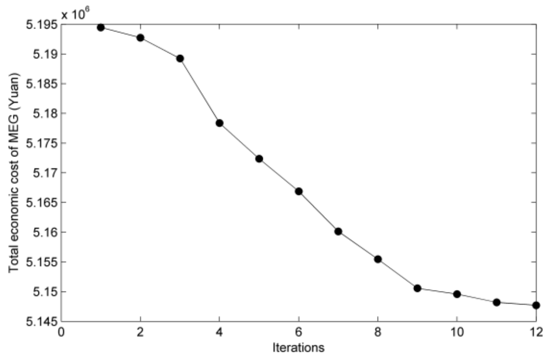

Fig. 8. Iterative convergence graph.

It can be seen from Figure 8 that the DRBF model satisfies the convergence condition after the 12th update, and the final total economic cost of MEG is 5.1477×10^6 Yuan. Through planning, the rated capacity of internal combustion engine is 1022 kW, and the rated capacity of direct-fired absorption chiller is 2380 kW.

By analysing the optimized results, the following conclusions can be drawn:

1) Since the operation optimization of the MEG is considered, the user's load data and energy usage behaviour have a greater impact on the planning. In the whole year, the user has a large demand for cooling and heating load, which makes the capacity demand for the direct-fired absorption chiller higher in the planning, so the capacity of direct-fired absorption chiller rises.

2) In addition, the user's thermoelectric power is relatively high, and in the case of an increase in the rated capacity of direct-fired absorption chiller, insufficient cooling and heating energy can be supplied through electric chiller, ice storage air-conditioner and heat exchanger.

3) The other power generation devices in the MEG has a moderate output ratio. When the electricity price is appropriate, the MEG can purchase the electricity from the grid to meet the user's electrical demand. Therefore, the rated capacity of internal combustion engine is reduced.

5. Conclusion

In this paper, the MEG coordinated planning model based on DRBF is constructed. The sample library is enriched by the possible optimal and local peak points obtained by RBF model, and the optimal capacity of MEG planning devices is obtained by dynamically correcting the RBF model, which finally complete the MEG planning. The system investment and energy consumption cost can be reduced under the premise of meeting the user's energy demand through coordinated planning. The planning model is constructed by taking the cooling, heating and electrical load data of a certain region as an example, and the simulation is carried out. The optimal solution of the planning problem can be found efficiently, and the effectiveness of the established model and the solution method is verified by case studies.

This paper only considers two configuration variables that have great influence on the optimization results to test the proposed method. In the future research, we will continue to study on the planning problem of DRBF model with multiple variables.

Acknowledgements

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