Optimization of Multi-energy Transfer Considering Internal Interaction and External Collaboration in Micro-Energy Network Group

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Abstract. Micro-energy network realizes the complementary of distributed energy production according to the characteristics of users' energy demand and local resource conditions. In order to realize the efficient operation of micro-energy network group, this paper proposed an optimal power transfer model based on Mutual Energy Supporting Pattern in micro-energy network group. The concept of micro-energy network is given and the basic structure of micro-energy network group based on the interconnection of external energy hubs is first established. Then, the micro-energy network model of internal energy hub and optimal power transfer model is established. The optimal power transfer model of micro-energy network group is subdivided into two kinds of operation modes, the internal cooperation mode and the synergy cooperation mode. The internal cooperation mode is to address the problem of energy shortage at the micro-energy network, while the synergy cooperation mode is to solve the problem through the coordination of multiple energy hubs in the micro-energy network group. Finally, the model is validated by a system including electricity, gas, heat/cooling load and external energy hub.

1. Introduction

With the continuous development of integrated energy system (IES), different forms of energy are coupled to each other, and coping with energy shortages, promoting energy conservation and emission reduction, and reducing primary energy consumption have become urgent problems to be solved at present [1-2]. Micro Energy Network is a small integrated energy supply system that integrates energy interconnection, transformation, coupling, storage and other functions. It can achieve multi-energy mutual benefit and local consumption of energy with external energy hubs. It is the basic unit of IES. And important components [3-4]. According to the energy demand characteristics of users and local resource conditions, the micro-energy network can realize the complementarity of distributed energy production, energy cascade utilization and efficient operation [5]. At present, the research on micro-energy network has attracted the attention of related workers at home and abroad. Reference [6] integrated various electrical equipment such as residents' daily life to model the micro-energy network, and considered the user's energy usage preferences, and established a mixed integer linearity planning model that minimizes energy consumption costs, carbon emissions, and load extremes. Reference [7]
established a coordinated operation optimization model of a multi-energy system based on a linear coupling relationship to maximize the use of renewable energy and reduce operating costs. Literature [8] proposed an optimal reliability planning model for the interconnection of electric energy and natural gas in the energy hub, which proved the necessity of comprehensive research on cold, heat, electricity and gas. The above research mainly focuses on the modeling and optimization of a single micro-energy network, and the interconnection between micro-energy networks through energy hubs can further improve the flexibility and reliability of the energy network. Therefore, it is necessary to study the optimized operation model for multiple interconnected micro-energy networks, that is, the micro-energy network group.

The controllable equipment of the micro-energy network group includes the adjustable distributed energy unit inside the micro-energy network and the external energy hub that realizes the interconnection of the micro-energy network [9]. Achieve optimization of multiple energy transfer from different levels of the internal and the synergy cooperation mode of the micro-energy network, and establish a mixed integer linear programming model for the multi-energy transfer of micro-energy network groups. Finally, a case study is verified through the transfer analysis of two mutual aid modes.

2. Micro-energy network model based on energy hub

Micro-energy network consists of 4 links: supply link, transmission link, energy storage link and consumption link, as shown in Fig. 1. Each link is modeled with an energy hub, and the four parts of the model are highly abstracted and integrated to obtain the final micro-energy network model.

2.1. Supply link

The supply part includes external electricity, heat, and natural gas energy networks. The matrix expression of the energy hub is

$$
\begin{bmatrix}
P^s \\
H^s \\
Q^s
\end{bmatrix} =
\begin{bmatrix}
P^{\text{buy}} + P^{\text{re}} + P^{\text{hub}} \\
H^{\text{hn}} + H^{\text{hub}} \\
Q^{\text{gn}} + Q^{\text{hub}}
\end{bmatrix}
$$

(1)

where $P^s$, $H^s$ and $Q^s$ are the supply sources of electricity, heat, and gas, respectively; $P^{\text{buy}}$ is the power purchased from the external micro-grid to the micro-energy network, $P^{\text{re}}$ is the injected power for the new energy generation connected to the micro-energy network, and $P^{\text{hub}}$ is the external energy source. The electric power provided by the hub to the micro-energy network; $H^{\text{hn}}$ is the one-way transmission of heat from the external thermal network to the micro-energy network; $H^{\text{hub}}$ is the heat provided by the external energy hub to the micro-network; $Q^{\text{gn}}$ unidirectionally delivers gas to the micro-energy network from the external gas network; $Q^{\text{hub}}$ is the amount of gas provided by the external energy hub to the microgrid.
2.2. Transmission link
In the multi-energy transmission link, due to the distribution and conversion relations between
different energy sources, this article further divides them into energy distribution stages and
conversion stages.

2.2.1. Energy distribution phase
This paper considers four types of energy conversion devices: power to gas (P2G) system, electric
heating boiler, gas boiler and combined cooling heating and power (CCHP). Assume that the electric
load demand is $P_{\text{load}}$, the electric power demand of the electric boiler is $P_{\text{EB}}$, the heat load demand is
$H_{\text{load}}$, the natural gas demand of the gas boiler is $Q_{\text{GB}}$, and the natural gas demand of the combined heat
and power system is $Q_{\text{CHP}}$. Then in combination with (1), the above-mentioned "electricity-heat-gas" demand $D$
can be obtained by the following formula.

$$D = \begin{bmatrix} P_{\text{load}} \\ H_{\text{load}} \\ Q_{\text{load}} \\ P_{\text{P2G}} \\ Q_{\text{GB}} \\ Q_{\text{CHP}} \end{bmatrix}^T \begin{bmatrix} \lambda_{\text{load}} & 0 & 0 & \lambda_{\text{EB}} & \lambda_{\text{P2G}} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \beta_{\text{load}} & 0 & 0 & \beta_{\text{GB}} & \beta_{\text{P2G}} & 0 \end{bmatrix} \begin{bmatrix} P^s \\ H^s \\ Q^s \end{bmatrix}$$

(2)

where $\lambda_{\text{load}}$, $\lambda_{\text{EB}}$, and $\lambda_{\text{P2G}}$ represent the distribution coefficients of $P^s$ assigned to electric load, electric
heating boiler, and P2G system; $\beta_{\text{load}}$, $\beta_{\text{GB}}$, and $\beta_{\text{P2G}}$ represent $Q^s$ assigned to gas load, gas boiler, and
cogeneration. The distribution factor of the system. The above distribution factors should meet

$$\begin{align*}
\lambda_{\text{load}} + \lambda_{\text{EB}} + \lambda_{\text{P2G}} &= 1 \\
\beta_{\text{load}} + \beta_{\text{GB}} + \beta_{\text{P2G}} &= 1
\end{align*}$$

(3)

2.2.2. Energy conversion phase
After the "electric-heat-gas" of the supply source is distributed to the P2G system, electric heating
boiler, gas boiler and CCHP according to the distribution coefficients $\lambda_{\text{load}}$, $\lambda_{\text{EB}}$, $\lambda_{\text{P2G}}$, $\beta_{\text{load}}$, $\beta_{\text{GB}}$, $\beta_{\text{P2G}}$, and $\beta_{\text{CHP}}$, the "electric-heat-gas" Energy conversion output, the corresponding output is expressed by $P^\text{out}$, $H^\text{out}$, $Q^\text{out}$. In addition, CCHP's lithium bromide device can also output the amount of cold air $L^\text{out}$. Therefore, energy conversion can be expressed as:

$$\begin{bmatrix} P^\text{out} \\ H^\text{out} \\ Q^\text{out} \\ L^\text{out} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & \eta_{\text{P2G}}^{\text{CHP}} \\ 0 & 1 & 0 & \eta_{\text{EB}}^{\text{CHP}} & 0 & \eta_{\text{GB}}^{\text{CHP}} & \eta_{\text{P2G}}^{\text{CHP}} \\ 0 & 0 & 1 & 0 & \eta_{\text{P2G}}^{\text{CHP}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \eta_{\text{L}}^{\text{CHP}} \end{bmatrix} \begin{bmatrix} P^s \\ H^s \\ Q^s \\ \lambda_{\text{load}} & 0 & \beta_{\text{load}} & \eta_{\text{P2G}}^{\text{CHP}} \\ \lambda_{\text{EB}} & \lambda_{\text{EB}} & \beta_{\text{EB}} & \beta_{\text{GB}} & \beta_{\text{P2G}} & \beta_{\text{P2G}} & 0 & \eta_{\text{GB}}^{\text{CHP}} \\ \lambda_{\text{P2G}} & \lambda_{\text{P2G}} & \beta_{\text{P2G}} & 0 & \beta_{\text{P2G}} & \beta_{\text{P2G}} & 0 & \eta_{\text{P2G}}^{\text{CHP}} \\ 0 & 0 & \beta_{\text{load}} & \eta_{\text{P2G}}^{\text{CHP}} & \eta_{\text{GB}}^{\text{CHP}} & \eta_{\text{P2G}}^{\text{CHP}} & 0 & \eta_{\text{L}}^{\text{CHP}} \end{bmatrix} \begin{bmatrix} P^s \\ H^s \\ Q^s \end{bmatrix}$$

(5)

where $\eta_{\text{P2G}}^{\text{CHP}}$, $\eta_{\text{GB}}^{\text{CHP}}$, $\eta_{\text{L}}^{\text{CHP}}$, $\eta_{\text{EB}}^{\text{CHP}}$, $\eta_{\text{P2G}}^{\text{CHP}}$, and $\eta_{\text{L}}^{\text{CHP}}$ respectively denote the efficiency of CCHP's gas-to-electricity, gas-to-heat,
and gas-to-cooling; $\eta_{\text{EB}}^{\text{CHP}}$ represents the electrical conversion efficiency of a thermal boiler; $\eta_{\text{GB}}^{\text{CHP}}$
indicates the gas conversion efficiency of a gas boiler; $\eta_{\text{P2G}}^{\text{CHP}}$ represents the efficiency of P2G.

A matrix expression of the transmission link can be formed by combining (3) and (5), that is,
2.3. Energy storage link.

The energy storage elements in the micro-energy network mainly include energy storage batteries, heat storage tanks, and natural gas storage tanks. Assuming the total amount of electricity, heat, and gas is $P^{BS}$, $H^{HS}$ and $Q^{GS}$, the total output of "electricity-heat-gas" is $P^{out}$, $H^{out}$, $Q^{out}$ and $L^{out}$, that is

$$
\begin{bmatrix}
P^{out} \\
H^{out} \\
Q^{out} \\
L^{out}
\end{bmatrix} =
\begin{bmatrix}
P^{out} + P^{BS} \\
H^{out} + H^{HS} \\
Q^{out} + Q^{GS} \\
L^{out}
\end{bmatrix}
$$

(7)

2.4. Consumption link.

The consumption link mainly refers to the process of demand-side management by the civilian or industrial user side. Suppose the total output of "electricity-heat-gas" is $P^{out''}$, $H^{out''}$, $Q^{out''}$ and $L^{out''}$, which is similar to (7), and its expression is

$$
\begin{bmatrix}
P^{out''} \\
H^{out''} \\
Q^{out''} \\
L^{out''}
\end{bmatrix} =
\begin{bmatrix}
P^{out''} - P^{Cut} \\
H^{out''} - H^{Cut} \\
Q^{out''} - Q^{Cut} \\
L^{out''} - L^{Cut}
\end{bmatrix}
$$

(8)

where the total amount of electric load, heat load, air load and cold load involved in demand-side regulation is $P^{Cut}$, $H^{Cut}$, $Q^{Cut}$ and $L^{Cut}$, respectively.

In summary, according to the modeling of the supply link, transmission link, energy storage link, and consumption link, the energy hub model of the micro-energy network can be obtained as:

$$
\begin{bmatrix}
P^{out''} \\
H^{out''} \\
Q^{out''} \\
L^{out''}
\end{bmatrix} =
\begin{bmatrix}
P^{out''} + P^{hub} + P^{hub} \\
H^{out''} + H^{hub} + H^{hub} \\
Q^{out''} + Q^{hub} + Q^{hub} \\
L^{out''} + L^{hub} + L^{hub}
\end{bmatrix}
\begin{bmatrix}
P^{BS} \\
H^{HS} \\
Q^{GS} \\
L^{Cut}
\end{bmatrix}
$$

(9)

where $C^*$ represents the coupling matrix formed in (6).

3. Micro-energy network model based on energy hub

This paper divides the transfer process into two parts: 1) the internal cooperation of micro-energy network; 2) the synergy cooperation between micro-energy network and external energy hub. For the internal cooperation, a certain "specific" energy shortage is solved from the micro-energy network, and other forms of energy within the micro-energy network are excavated and transformed to achieve multi-energy load balance. For the synergy cooperation, the goal is to optimize the internal multi-energy consumption ratio, and rationally regulate other micro-energy networks, so that the "specific" energy that can be "distributed" by external energy hubs is more in line with actual needs in order to solve this Energy network "specific" energy shortages.

The two transfer optimization models are listed as control variables according to the four links of supply, transmission, energy storage and consumption. The specific content is shown in Table 1. Among them, $\Omega$, $\Phi$, and $\Pi$ represent the set of control variables of the transmission link, energy storage link, and consumption link of multiple controlled microgrids participating in the synergy cooperation.
Table 1. Decision Variables Participating in the Optimization of Micro-Energy Network Transfer

| Link                  | "Internal" Mutual Control Variables | "Synergistic" Mutual Control Variables |
|-----------------------|-------------------------------------|----------------------------------------|
| Supply link           | $P_{buy}$, $P_{re}$, $Q_{gn}$, $H_{hn}$ | $P_{hub}$, $H_{hub}$, $Q_{hub}$        |
| Transmission link     | $\lambda_{load}$, $\lambda_{EB}$, $\lambda_{P2G}$, $\beta_{load}$, $\beta_{EB}$, $\beta_{CHP}$ | $\Omega \{\lambda_{load}$, $\lambda_{EB}$, $\lambda_{P2G}$, $\beta_{load}$, $\beta_{EB}$, $\beta_{CHP}\}$ |
| Energy storage link   | $P_{BS}$, $H_{HS}$, $Q_{GS}$         | $\Phi \{P_{BS}$, $H_{HS}$, $Q_{GS}\}$ |
| Consumption link      | $P_{cut}$, $H_{cut}$, $Q_{cut}$, $L_{cut}$ | $\Pi \{P_{cut}$, $H_{cut}$, $Q_{cut}$, $L_{cut}\}$ |

3.1. Multi-energy transfer optimization model under the internal cooperation mode.

The total cost of micro-energy network's transfer optimization is the increase in production cost of multi-energy transfer in the supply link, the increase in loss cost in the transmission link, the increase in energy storage cost in the energy storage link, and the increase in multi-energy load response cost in the consumption link together.

The production cost increase after the transfer is

$$\Delta F_1 = C_e \cdot \Delta P_{buy} + C_r \cdot \Delta P_{re} + C_q \cdot \Delta Q_{gn} + C_h \cdot \Delta H_{hn}$$

(10)

where $\Delta P_{buy}$, $\Delta P_{re}$, $\Delta Q_{gn}$ and $\Delta H_{hn}$ respectively represent the external power purchase increment, renewable energy generation increase, external gas purchase increment, and external heat purchase increment after the transfer; $C_e$, $C_r$, $C_q$ and $C_h$ are the unit costs of external power purchase, renewable energy generation, external gas purchase, and external heat purchase.

Accordingly, the energy storage cost increment is

$$\Delta F_2 = C_{Pc} \cdot \Delta P_{BS} + C_{Hh} \cdot \Delta H_{HS} + C_{Qh} \cdot \Delta Q_{GS}$$

(11)

where $C_{Pc}$, $C_{Hh}$ and $C_{Qh}$ represent the adjustment costs of electricity, heat, and gas for external energy hubs.

3.2. Multi-energy transfer optimization model under the synergy cooperation mode

In the synergy cooperation mode, the total cost of micro-energy network optimization is mainly the production adjustment costs of other micro-energy networks. The increments $\Delta P_{hub}$, $\Delta H_{hub}$ and $\Delta Q_{hub}$ are described. The total cost of the “cooperative” transfer optimization should be the lowest, and its objective function $G$ is

$$\min G = C_{Ph} \cdot \Delta P_{hub} + C_{Hh} \cdot \Delta H_{hub} + C_{Qh} \cdot \Delta Q_{hub}$$

(14)

where $C_{Ph}$, $C_{Hh}$ and $C_{Qh}$ represent the adjustment costs of electricity, heat, and gas for external energy hubs.
When the micro-energy network transfer optimization model solves the energy shortage problem, the internal cooperation model should be given priority, followed by the synergy cooperation model. Since the model is a mixed integer linear programming problem, this paper uses CPLEX to solve it.

4. Case Study

4.1. Basic data
A regional IES system composed of external energy hubs and micro-energy networks is employed for simulation through the proposed model using MATLAB R2012a. A schematic diagram of the regional IES system is shown in Fig. 2. The parameters of the energy hubs are shown in Table 2, where $P_{hub}$, $H_{hub}$, $Q_{hub}$ are the electricity, heat and gas output value of each energy hub respectively. All the following units of electricity, heat, and cold are kW and the unit of natural gas is m³.

![Figure 2. Diagram of micro-energy network group structure.](image)

**Table 2. Parameters of Energy Storage Devices**

| EH | $P_{hub}$ | $\Delta P_{min} / \Delta P_{max}$ | $H_{hub}$ | $\Delta H_{min} / \Delta H_{max}$ | $Q_{hub}$ | $\Delta Q_{min} / \Delta Q_{max}$ |
|----|-----------|----------------------------------|-----------|----------------------------------|-----------|----------------------------------|
| 1  | 400       | 0/400                            | 200       | 0/200                            | 200       | 0/200                            |
| 2  | 300       | 0/300                            | 200       | 0/200                            | 100       | 0/100                            |
| 3  | 300       | 0/0                              | 100       | 0/0                              | 50        | 0/0                              |
| 4  | 1000      | 0/1000                           | 500       | 0/500                            | 350       | 0/350                            |

A micro-energy network is connected to the energy hub of Fig. 2, whose structure is shown in Fig. 3. Parameters of energy conversion devices and controllable load are shown in Table 3 and Table 4. Besides, the maximum value of the energy increments supplied by the external energy network $\Delta P_{max}$, $\Delta H_{max}$ and $\Delta Q_{max}$ are 150 kW, 100 kW and 100 KW, and the minimum values of them are 0. The maximum charge and discharge power of battery, heat storage tank and gas storage tank are 60 kW, 60 kW and 20 m³/h. The low heating value (LHV) of the natural gas is 9.7.

![Figure 3. Diagram of micro-energy network structure](image)
Table 3. Parameters of Energy Conversion Devices

| Type                        | Combined heat and power | Electric boiler | Gas-fired boiler | Electric to gas |
|-----------------------------|-------------------------|----------------|------------------|-----------------|
| Maximum output              | 200                     | 120            | 30               | 100             |
| Minimum output              | 20                      | 0              | 0                | 0               |
| Other parameters            |                         |                |                  |                 |
| $\eta_{CHP}^{e}=0.3$, $\eta_{CHP}^{h}=0.4$ | $\eta_{EB}=0.95$         | $H^{GB}=0.9$   | $H^{P2G}=0.5$    |

Table 4. Parameters of controllable load

| Type                        | $\Delta P_{cut}^{\text{max}}$ | $\Delta H_{cut}^{\text{max}}$ | $\Delta Q_{cut}^{\text{max}}$ | $\Delta L_{cut}^{\text{max}}$ |
|-----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Maximum/Minimum controllable value | 0/10                          | 0/20                          | 0/30                          | 0/10                          |

Assuming that the electric load in the micro-energy network is heavy, cases could be set as two different operation modes: “internal” and “cooperative” mutual supporting. The specific data is shown in Table 5.

Table 5. Setting conditions of cases 1 and 2

| Case | Current total electric load | Current total heat load | Current total gas load | Current total cold load | Maximum increment of power supply | Users’ maximum demand |
|------|-----------------------------|-------------------------|------------------------|------------------------|-----------------------------------|-----------------------|
| 1    | 400                         | 200                     | 200                    | 20                     | 200                               | 600                   |
| 2    | 400                         | 200                     | 200                    | 20                     | 200                               | 630                   |

4.2. Analysis

4.2.1. Case 1: transfer in “internal” mutual supporting mode.

As can be seen from Fig. 4, under the condition that users’ gas load and heat load have not changed, when the user’s power demand is between 400kW and 600kW, the first step is to supply more power continuously. When users’ demand still cannot be met, $\Delta Q_{gn}$ and $\Delta H_{hn}$ are increased to produce more electrical power. Then, the energy storage of $\Delta P_{BS}$ in the energy storage devices is reduced, and the additional heat and gas storage $\Delta H_{HS}$ and $\Delta Q_{GS}$ are increased. Finally, the electric load $\Delta P_{cut}=3$ kW needs to be interrupted instead of the controllable load interruption of heat, gas and cold loads, and the balance of electric, heat, gas and cold load in the entire micro-energy network can be achieved.

Figure 4. Diagram of unit energy transfer solution of purchasing multi-energy

From the perspective of the transferring cost economically, all coefficients of $F_1$ are lower than $F_2$ and all coefficients of $F_2$ are lower than $F_3$, which indicates that ”internal mutual supporting” is based on the transfer strategy that firstly purchasing the external energy, then absorbing and storing the remaining energy, and finally interrupting load. The entire increment energy transfer path is shown in Figure 5.
In summary, when there is a “shortage” of electrical power, it will lead to changes of electricity, heat and gas increments, which promotes micro-energy network to achieve the power transfer from “heat, gas” to “electricity” in the “internal mutual supporting” mode and further multi-energy transfer optimization.

4.2.2. Case 2: transfer in “cooperative” mutual supporting mode.
As shown in the setting conditions of case 2 in Table 5, the current total electric load is 630 kW, and through the study of case 1, it can be known that the maximum power supply increase is 200 kW. Therefore, the users’ demand of 630 kW cannot be solved by ”internal mutual supporting”.

According to the multi-energy transfer optimization model under the “cooperative” mutual supporting mode proposed in Chapter III, the optimal transfer result of the external energy hubs is given, as shown in Figure 6.

According to Fig. 6 and Table 2, it can be known that the energy of energy hub 1 is supplied by external energy hub 4. Through the “external mutual supporting”, the power injection into energy hub 2 can be reduced by 30 kW, which is used to supplement the energy shortage of energy hub 1. Finally, “internal mutual supporting” is employed on energy hub 1 according to the method of case 1, and the multi-energy transfer optimization of the cooperative mutual supporting by “external” and “internal” can be realized.

5. Conclusion
This paper proposed an optimal power transfer model based on the internal interaction and external collaboration in the micro-energy network group. The model is tested and analyzed through the case study, and the results indicate that the optimal power transfer model proposed in this paper can reasonably “transform”, “transfer” and “interchange” multiple energy in the micro-energy network group. This model gives priority to solving the energy shortage problem at the level of micro-energy network, and secondly, it can “actively” improve the distribution of “energy flow” at the level of external energy hubs. Improving the ability to solve energy shortage problems, the optimal power transfer model has great theoretical and practical significance for the safe, efficient operation and reliable supply of micro-energy network groups.

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