Electricity-heat integrated agent modelling for participation in spot electricity market

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Abstract. Due to the limitation of market rules, many small capacity power plants cannot directly participate in the spot electricity market, reducing the ability of the market to optimize the allocation of power generation resources. Among these power plants, the electric power output of some combined heat and power (CHP) plants is constrained by their heat output, which should be considered in the dispatch. Therefore, the electricity-heat integrated agents are defined and introduced to aggregate small capacity power plants and participate in the spot electricity market. Firstly, the model of electricity-heat integrated agents is formulated based on the aggregation of the internal generators and CHP units. Then, the framework of the spot electricity market with the participation of electricity-heat integrated agents is constructed. Moreover, the market clearing model is further developed by combining the electricity-heat integrated agent model and the security constrained unit commitment model. Simulation results in the case verify the effectiveness of the proposed model and technique.

1. Introduction

With the worsening of global environmental problems and the depletion of traditional fossil energy, a new round of energy revolution characterized by the adjustment of energy structure and the change of energy technology is being carried out in the world [1]. In this context, the coupling relationships between different energy forms, especially electricity and heat energy, have become tighter. For example, in northern China, there are many combined heat and power (CHP) plants undertaking the tasks of both electric power generation and district heating for customers [2].

In order to optimize the allocation of power resources, spot electricity markets have been built and developed to varying degrees in many countries [3]. However, due to the limitation of market rules, there are a large number of power plants with small capacity which cannot directly participate in the spot electricity market [4]. For example, distributed generation such as distributed small hydropower units are not included in the spot market in Zhejiang Province [5]. To address this problem, the distributed power plants with small capacity can be aggregated as an agent which participates in the spot electricity market representing these power plants. Besides, for the electricity-heat integrated agents with CHP plants, their heat generation will affect electricity generation because of the coupling characteristics of CHP technology [6], thus affecting their behaviors in the spot electricity market. To
guide these electricity-heat integrated agents to participate in the spot electricity market, the electricity-heat integrated agent model and corresponding market framework are worth studying.

Many research works have been conducted on the aggregation model of multiple power plants. The advantages of the aggregation of district multiple energy generation resources considering their operational behaviors is analyzed in [7]. A stochastic model is developed taking into account both the internal and external dependencies among multiple energy carriers [8]. In [9], the comprehensive model is formulated to facilitate the participation of distributed multiple generation resources in the demand response programs. The above research works only concentrate on the model of multiple types of generation resources, lacking the effective market framework and mechanism to manage these aggregated generation subjects. In [10], an agent-based method is utilized for the simulation of deregulated electricity market with multiple companies and different services. In [11], the multi-energy virtual power plant aggregating multiple resource forms is introduced in the electricity market. However, these studies ignore the impact of coupling relationship between electricity and other energy forms on the electricity market. As an important integrated energy agent form, the heat energy demand for the electricity-heat integrated agents can have significant effects on their behaviors in electricity market.

This paper aims to develop the electricity-heat integrated agent model for participation in spot electricity market. The CHP units and other generators inside the electricity-heat integrated agent are firstly modeled. Then the aggregation model of the electricity-heat integrated agent considering coupling characteristics is formulated. Moreover, the framework and clearing model of spot electricity market are introduced considering the participation of electricity-heat integrated agents. Finally, simulation results verify the effectiveness of the proposed model and market framework.

2. Model of electricity-heat integrated agents
The electricity-heat integrated agents can participate in the power market as a whole and be dispatched by a single operator. Within the electricity-heat integrated agents, multiple types of power generation resources, e.g., conventional generators and the CHP units, are managed and aggregated. These power generation resources have their own features, which should be considered by the agent operator for effective coordination and dispatch. Consequently, in order to model the electricity-heat integrated agents, the models of the internal power generation resources should be firstly established.

2.1. Conventional generators
Conventional generators mainly refer to thermal power units, including coal-fired units and gas-fired units. They generally undertake the main power generation task in the power system. Because of the similar characteristics, these conventional generators can be described by a unified model, which includes the power boundary constraints, the ramping constraints and the minimum up/down time constraint.

\[
\forall i \in \Omega_{\text{con}}, t \in \Omega_{T}, \quad P_{\text{MIN}} \leq P_{i,t}^{\text{con}} \leq P_{i,t}^{\text{MAX}}
\]

\[
\forall i \in \Omega_{\text{con}}, t \in \Omega_{T}, t > 1, \quad -R D_{i} \leq P_{i,t}^{\text{con}} - P_{i,t-1}^{\text{con}} \leq R U_{i}
\]

\[
\forall i \in \Omega_{\text{con}}, t \in \Omega_{T}, t > 1, \quad [T_{i,t}^{\text{on}}(t-1) - T_{i,t-1}^{\text{on}}] U_{i}(t-1) - U_{i}(t) \geq 0
\]

\[
\forall i \in \Omega_{\text{con}}, t \in \Omega_{T}, t > 1, \quad [T_{i,t}^{\text{off}}(t-1) - T_{i,t-1}^{\text{off}}] U_{i}(t-1) - U_{i}(t) \geq 0
\]

where \(\Omega_{\text{con}}\) and \(\Omega_{T}\) represent the conventional generator set and time set respectively. \(P_{i,t}^{\text{con}}\) is the generating power of the conventional generator \(i\) at time \(t\). \(P_{\text{MIN}}\) and \(P_{\text{MAX}}\) denote the minimum and maximum generation bound of the conventional generator \(i\) respectively. \(R U_{i}\) and \(R D_{i}\) are up and down ramp rates of the conventional generator \(i\) respectively. \(T_{i,t}^{\text{on}}(t)\) and \(T_{i,t}^{\text{off}}(t)\) are the start up duration and shut down duration of the conventional generator \(i\) before time \(t\). \(T_{i,t}^{\text{on}}_{\text{min}}\) and \(T_{i,t}^{\text{off}}_{\text{min}}\) are the minimum limits of them. \(U_{i}(t)\) represents the start up or shut down status of the conventional generator \(i\) at time \(t\), which is a binary variable.
2.2. Combined heat and power units

In the context of the construction of integrated energy system (IES), CHP units have been rapidly developed and widely used all over the world. Besides, many conventional generators have been transformed to obtain heating capacity, thus improving energy efficiency. Therefore, CHP units account for a large proportion in many existing power systems.

CHP units can be divided into back pressure units and extraction condensing units. For the back pressure CHP units, the exhaust steam of the back pressure turbine is used for heating. As their electric generation power is directly proportional to the heat generation power, the electricity-heat coupling characteristics of the back pressure CHP units are relatively simple, which is shown in Figure 1. For the extraction condensing CHP units, part of the steam is extracted from the turbine for heating. The coupling characteristics of this type of CHP units are relatively complex, which can be represented by the feasible region of an irregular quadrilateral, as shown in Figure 2. A, B, C and D represent the four boundary points of the feasible region. Taking the case of heat generation power equal to \( H^{CHP}_s \) as an example, the dispatching range of electric generation power is \( [P^{CHP}_{\ell 2}, P^{CHP}_{\ell 3}] \), as shown in the EF section in Figure 2. In this paper, the extraction condensing CHP units are mainly considered for modelling and analysis.

![Figure 1. Coupling characteristics of back pressure CHP units.](image1)

![Figure 2. Coupling characteristics of extraction condensing CHP units.](image2)

Based on the feasible region, the extraction condensing CHP units can be modelled using the following constraints.

\[
\forall j \in \Omega_{CHP}, t \in \Omega_t, \quad 0 \leq P^{MIN}_j - c_h H^{CHP}_j \leq P^{CHP}_j \leq P^{MAX}_j - c_v H^{CHP}_j
\]

\[
\forall j \in \Omega_{CHP}, t \in \Omega_t, \quad 0 \leq H^{CHP}_j \leq \left[ P^{CHP}_j - P^{MIN}_j + (c_v + c_h) H^{MAX}_j \right] / c_m
\]

where \( \Omega_{CHP} \) is the CHP unit set. \( P^{CHP}_j \) and \( H^{CHP}_j \) represent the electric generation power and heat generation power of the CHP unit \( j \) at time \( t \) respectively. \( P^{MAX}_j \) and \( P^{MIN}_j \) are the maximum and minimum electric generation power of the CHP unit \( j \) when there is no steam is extracted for heating under the pure condensing condition. \( H^{MAX}_j \) is the maximum heat generation power of the CHP unit \( j \) under the extraction condition. \( c_m \) and \( c_v \) are the slopes of boundary lines AB and BC for the feasible region respectively, which are all the ratio of variation of electric power to variation of heat power.

2.3. Aggregated model

Considering that the spot electricity market has capacity requirements for the market subjects, many distributed generators and CHP units with small capacities cannot participate in the spot electricity market individually. These generators and CHP units can be aggregated by the electricity-heat integrated agents and obtain large aggregation capacities. With the development of communication
technology and measurement equipment, the single operator in the agent can coordinate and dispatch the internal generators. To formulate the aggregated model considering the heating effects, the electric power regulation range, \([P_n^{\text{MIN}}, P_n^{\text{MAX}}]\), of the integrated electricity-heat agent under a certain heating demand level \(H_n\) can be calculated as follows

\[
\forall n \in \Omega_{\text{agent}}, \quad H_n = \sum_{j=1}^{J} H_j
\]

\[
\forall n \in \Omega_{\text{agent}}, \quad \forall j \in \Omega_{\text{CHP}}, \quad H_n H_j, \quad P_n^{\text{MIN}} = \sum_{i=1}^{I} P_i^{\text{MIN}} + \sum_{j=1}^{J} P_j^{\text{MIN}}
\]

\[
\forall n \in \Omega_{\text{agent}}, \quad \forall j \in \Omega_{\text{CHP}}, \quad H_n H_j, \quad P_n^{\text{MAX}} = \sum_{i=1}^{I} P_i^{\text{MAX}} + \sum_{j=1}^{J} P_j^{\text{MAX}}
\]

where \(\Omega_{\text{agent}}\) is the integrated electricity-heat agent set. \(I_n\) and \(J_n\) are numbers of conventional generators and CHP units inside the agent \(n\). \(H_n\) and \(H_j\) are heat generation power of the agent \(n\) and CHP unit \(j\) respectively, which can be acquired through historical data. \(P_n^{\text{MAX}}\) and \(P_n^{\text{MIN}}\) are the maximum and minimum electric generation power of the agent \(n\) when the heat generation power is \(H_n\).

By this means, the electric power regulation ranges of the integrated electricity-heat generation agent can be obtained, which formulate a function of the heat generation power for the agent. This function can be utilized for market clearing when the agent participates in the spot electricity market. Therefore, the heating demand for the agent can serve as a boundary condition of market clearing, and the effects of the heating demand on the spot electricity market clearing results can be quantified.

3. Framework and clearing model of spot electricity market considering the participation of electricity-heat integrated agents

3.1. Market framework with the participation of electricity-heat integrated agents

With the participation of electricity-heat integrated agents, the framework of the spot electricity market and the simulation flow chart are shown in Figure 3 and Figure 4. Under this framework, the electricity-heat integrated agents can compete with the large capacity generators on the generation side. According to the market theory, with the strengthening of generation side competition, the clearing result of power market will be more optimized. Meanwhile, the effects of the heating demand on the market considering the electricity-heat coupling relationship can be reflected in the quotations of the agents.

**Figure 3.** Comparison between equivalent and original load.  **Figure 4.** Simulation flow chart.
3.2. Market clearing model with the participation of electricity-heat integrated agents

The clearing model of the spot electricity market usually includes the day-ahead security-constrained unit commitment (SCUC) model and the real-time security-constrained economic dispatch (SCED) model. Both the SCUC model and the SCED model aim at maximizing social welfare, and the SCED model ignores the unit commitment compared with the SCUC model. This paper mainly concentrates on the SCUC model [4]. The social welfare in the objective function of the model is equal to the electricity consumption benefit minus the generation cost. And the electricity consumption benefit and generation cost are measured by the quotation of the market entities. The objective function is as follows:

\[
\max F = R - C_G - C_A
\]

\[
R = \sum_{t=1}^{T} \sum_{c=1}^{N_C} R_{c,t}(d_{c,t})
\]

\[
C_G = \sum_{t=1}^{T} \sum_{k=1}^{N_G} \left( S_k u_k(t)(1 - u_k(t - 1)) + C_{G_k,t}(P_{G_k,t}) \right)
\]

\[
C_A = \sum_{t=1}^{T} \sum_{n=1}^{N_A} \left( C_{A_n,t}(P_{A_n,t}) \right)
\]

where \( F \) is the total social welfare of the spot electricity market. \( R \) is the electricity consumption benefit of the market consumers. \( C_G \) is the generation cost of the generators which can directly participate in the market, including the start-up and shutdown cost and the operation cost. \( C_A \) is the generation cost of the electricity-heat integrated agents, which is calculated according to the cost of internal generators and CHP units [6]. \( T \) is the number of time steps for the market clearing. \( N_C \), \( N_G \) and \( N_A \) are numbers of the market consumers, the generators and the agents respectively. \( d_{c,t} \) is the load power of the customer \( c \) at time \( t \). \( P_{G_k,t} \) and \( P_{A_n,t} \) are the generation power of the generator \( k \) and agent \( n \) at time \( t \) respectively. \( R_{c,t}(d_{c,t}) \) is the quotation of the market consumer \( c \) corresponding to \( d_{c,t} \). \( C_{G_k,t}(P_{G_k,t}) \) is the quotation of the generator \( k \) corresponding to \( P_{G_k,t} \). \( C_{A_n,t}(P_{A_n,t}) \) is the quotation of the agent \( n \) corresponding to \( P_{A_n,t} \). \( R_{c,t}(d_{c,t}) \), \( C_{G_k,t}(P_{G_k,t}) \) and \( C_{A_n,t}(P_{A_n,t}) \) are piecewise linear functions. \( S_k \) is the start-up cost of the generator \( k \) at time \( t \). \( u_k(t) \) is a binary variable representing the status of the generator \( k \) at time \( t \). Compared with the generators directly participating in the market, it is worth noting that the start-up and shutdown costs of the generators or CHP units inside the electricity-heat integrated agents have been included in the quotation, which are not represented in the objective function.

The constraints of the spot electricity market clearing model include the system constraints and the constraints for generators or agents.

1) The system constraints:

\[
\sum_{k=1}^{N_G} P_{G_k,t} + \sum_{n=1}^{N_A} P_{A_n,t} = \sum_{c=1}^{N_C} d_{c,t}
\]

\[
-P_{\max}^l \leq \sum_{k=1}^{N_G} T_{1,k} P_{G_k,t} + \sum_{n=1}^{N_A} T_{1,n} P_{A_n,t} - \sum_{c=1}^{N_C} T_{1,c} d_{c,t} \leq P_{\max}^l
\]

Equations (8) and (9) are the system power balance constraint and network capacity constraint respectively. \( P_{\max}^l \) represents the transmission capacity of line \( l \). \( T_{1,k} \), \( T_{1,n} \) and \( T_{1,c} \) are coefficients for power flow calculation.

2) The generator constraints:

Since the generators are quoted according to the power segment, the constraints for generators directly participating in the market are as follows.

\[
C_{G_k,t}(P_{G_k,t}) = \sum_{m=1}^{M} C_{G_k,t,m} P_{G_k,t,m}
\]

\[
P_{\min}^{G_k,m} \leq P_{G_k,t,m} \leq P_{\max}^{G_k,m}
\]
where \( M \) is number of the power segments in the quotation. \( C_{Gk,m} \) is the quotation of the generator \( k \) at time \( t \) corresponding to the power segment \( m \). \( P_{Gk,m} \) is the power winning the bidding of the generator \( k \) at time \( t \) corresponding to the power segment \( m \). \( P_{Gk,m}^{\text{min}} \) and \( P_{Gk,m}^{\text{max}} \) are the minimum and maximum power of the power segment \( m \).

In addition, the generator constraints also contain the power boundary constraints, ramping constraints and the minimum start-up and shutdown time constraints, which are introduced in [7].

3) The electricity-heat integrated agent constraints:

The model of the electricity-heat integrated agents has been established in Section 2. Based on the aggregated model, the electric power generation boundaries of the electricity-heat integrated agent under different heat power demands can be acquired. Therefore, the electric power output should be limited within the acquired boundaries.

\[
P_{\text{ex}}^{\text{MIN}} \leq P_{\text{ex},t} \leq P_{\text{ex}}^{\text{MAX}}
\]

(12)

Other constraints for the electricity-heat integrated agents are similar to that of the generators. The parameters and constraints of the generators and CHP units inside the agent will be considered in the quotation and information submitted to the market operator.

The locational marginal price (LMP) model [9] is applied to calculate the electricity prices at different nodes in power systems, which is a typical pricing mechanism in existing electricity markets.

\[
\rho = -\lambda - T^{\top}\mu
\]

(13)

where \( \rho \) denotes the price vector. \( \lambda \) and \( \mu \) denote Lagrange multiplier vectors derived from and . \( T \) denotes the coefficient vector for power flow calculation.

4. Case study

The spot electricity market based on the modified IEEE 30-bus power system is utilized to illustrate the proposed models. It is assumed that there are 6 big capacity generators, 8 small capacity generators and 20 small capacity CHP units in the power system. The heat demand of customers in the system for the CHP units is shown in Figure 5. Two scenarios are considered in the case: scenario A is the base case without considering the participation of the electricity-heat integrated agents. The electric generation power of the small capacity generators and CHP units is regarded as the boundary condition of market clearing. Compared to scenario A, 4 electricity-heat integrated agents can participate in the market in scenario B. Each agent aggregates 2 small capacity generators and 5 small capacity CHP units and cannot be partial to any producer.

![Figure 5. Heat demands of the customers in the power system.](image1)

![Figure 6. Market clearing prices in two scenarios.](image2)

As shown in Figure 5, the heat demand of the customers is high at night and low during the day. This is because the heat power is mainly used for space heating of buildings, which is negatively correlated with ambient temperature. Especially from 10:00 to 18:00 when the ambient temperature is high, the heat demand reaches the minimum values.
According to the framework and market clearing model proposed in this paper, the time-varying electricity market price in two scenarios can be calculated, which is shown in Figure 6. It can be observed that the difference of electricity price between the two scenarios mainly exists in the period from 10:00 to 18:00, which is the same as the period with the minimum heat demand. During this period, compared with scenario A, the price of scenario B is significantly reduced. This is because the electricity-heat integrated agents have relatively large electric power regulation ranges which can alleviate the contradiction between electric supply and demand of the power system, thus reducing the market clearing price.

**Table 1. Social welfare in two scenarios.**

| Scenario | A       | B       |
|----------|---------|---------|
| Social welfare ($) | 309.41  | 375.42  |

The total social welfare in two scenarios are shown in Table 1. With the participation of electricity-heat integrated agents, the total social welfare in scenario B has increased by 66.01 $ compared with scenario A. Consequently, the economy of spot electricity market can be improved when more market entities including electricity-heat integrated agents participate in the market competition.

5. **Conclusions**

This paper proposes the definition and model for the electricity-heat integrated agents. The market framework and market clearing model are formulated considering the participation of the electricity-heat integrated agents. Simulation results demonstrate that the electricity-heat integrated agents can contribute to alleviating the contradiction between electric supply and demand and reducing the peak electricity clearing prices. Moreover, the economy of spot electricity market can be improved with the participation of electricity-heat integrated agents. The proposed model can be further applied in many aspects such as the combination of CHP and heat pumps in pure electric driven heating. In the future, by using the proposed aggregated agent model, more power generation resources can be integrated to the spot electricity market to enhance the competitiveness. The coordination method and strategy of multiple generation resources energy should be further studied in the future work.

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