Operational Flexibility Constrained Intraday Rolling Dispatch Strategy for CHP Microgrid

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ABSTRACT
The increasing penetration of variable renewable energy sources (RES) such as wind power and photovoltaic cell in the microgrid poses a great threat to the power balance. The microgrid operator has to consider the system operational flexibility in the dispatch to overcome the uncertainties. For a multi-energy microgrid, the coupling relationship and complementarity of different energy provides potential capacity for operational flexibility. In this paper, we propose an operational flexibility metric to quantify the ability of the combined heat and power (CHP) microgrid to overcome RES uncertainties in operation. An intraday rolling dispatch strategy for the off-grid CHP microgrid is proposed, which consists of a dispatch decision (DD) stage and a real-time adjustment (RTA) stage. The operational flexibility constraints are incorporated in the DD model to ensure that the uncertainties in the real-time operation can be suppressed. The RTA model is based on a linear programming model. Case studies demonstrate that the proposed dispatch strategy can overcome the uncertainties efficiently and ensure the secure and economic operation of the system.

INDEX TERMS
CHP microgrid, dispatch decision, operational flexibility metric, real-time adjustment, rolling dispatch strategy, uncertainties.

Nomenclature

A. Parameters

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>M</td>
<td>Length of dispatch period</td>
</tr>
<tr>
<td>Δt</td>
<td>Length of time interval of dispatch decision stage</td>
</tr>
<tr>
<td>Δt</td>
<td>Length of time interval of real-time adjust stage</td>
</tr>
<tr>
<td>ηgt</td>
<td>Efficiency of gas turbine</td>
</tr>
<tr>
<td>ηloss</td>
<td>Energy loss rate of gas turbine</td>
</tr>
<tr>
<td>ηhr</td>
<td>Efficiency of heat recovery unit</td>
</tr>
<tr>
<td>ηeh</td>
<td>Efficiency of electrical boiler</td>
</tr>
<tr>
<td>ηgb</td>
<td>Efficiency of gas boiler</td>
</tr>
<tr>
<td>ηhe</td>
<td>Efficiency of heating exchange device</td>
</tr>
<tr>
<td>σbt</td>
<td>Self-charging rate of battery</td>
</tr>
<tr>
<td>ηb,chr,ηbt,dis</td>
<td>Charging/discharging efficiency of battery</td>
</tr>
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<td>ξgb</td>
<td>Adjustable ratio of power of electrical boiler</td>
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<tr>
<td>Pgb, Pgt</td>
<td>Upper/lower limit of power of gas turbine (kW)</td>
</tr>
<tr>
<td>Rg</td>
<td>Ramping rate of gas turbine (kW/h)</td>
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<tr>
<td>Ph</td>
<td>Upper limit of power of electrical boiler (kW)</td>
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<tr>
<td>θgb</td>
<td>Upper limit of power of gas boiler (kW)</td>
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<tr>
<td>Qhr</td>
<td>Upper limit of heat recovery unit (kW)</td>
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<tr>
<td>Qhe</td>
<td>Upper limit of power of heat exchange device(kW)</td>
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<td>Pbt,chr,Pbt,dis</td>
<td>Upper limit of charging/discharging power of battery (kW)</td>
</tr>
<tr>
<td>Wbt, Wgt</td>
<td>Energy capacity of battery (kWh)</td>
</tr>
<tr>
<td>U₁, D₁</td>
<td>Upper limit of charging/discharging power of thermal storage tank (kW)</td>
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<td>W₁, W₁, U₁, D₁</td>
<td>Energy capacity of thermal storage tank (kW)</td>
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<tr>
<td>U₁, D₁</td>
<td>Ramping up/down capacity of gas turbine at period t (kW)</td>
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<td>U₁, D₁</td>
<td>Ramping up/down capacity of electrical boiler at period t (kW)</td>
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<td>Ramping up/down capacity of gas boiler at period t (kW)</td>
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<tr>
<td>U₁, D₁</td>
<td>Ramping up/down capacity of thermal storage tank at period t (kW)</td>
</tr>
<tr>
<td>cng, Hng</td>
<td>Price (¥/m³) and heat value of natural gas (kW/m³)</td>
</tr>
<tr>
<td>R, C_air</td>
<td>Thermal resistance (°C/kW) and heat capacity (kWh/°C) of buildings</td>
</tr>
<tr>
<td>T_air, T_int</td>
<td>Ambient temperature of building at period t (°C)</td>
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<td>T_air, T_int</td>
<td>Indoor temperature at period t (°C)</td>
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<td>T_air, T_int</td>
<td>Upper/lower limit value of indoor temperature (°C)</td>
</tr>
<tr>
<td>T_air, T_int</td>
<td>Optimal value of indoor temperature (°C)</td>
</tr>
</tbody>
</table>
\[ y_{ht}^{t}, y_{ht}^{t+} \]  Relative value of upward/downward fluctuation of supplied thermal power at period \( t \)

\[ \tilde{Q}_{bl}^{t} \]  Forecast value of thermal load at period \( t \) (kW)

\[ \tilde{P}_{res}^{t} \]  Forecast value of power of RES at period \( t \) (kW)

\[ \tilde{P}_{el}^{t} \]  Forecast value of electrical load at period \( t \) (kW)

\[ \delta_{res} \]  Expected forecast error of RES power

\[ \delta_{el} \]  Expected forecast error of electrical load

\[ \Delta P^{t}_{res} \]  Fluctuation value of RES power at period \( t \) (kW)

\[ \Delta P^{t}_{el} \]  Fluctuation value of electrical load at period \( t \) (kW)

\[ \Delta P^{t}_{net} \]  Fluctuation value of net electrical load at period \( t \) (kW)

B. Decision variables

1) DISPATCH DECISION STAGE

\[ e_{gt}^{t} \]  Binary variables to denote on/off state of gas turbine

\[ p_{gt}^{t} \]  Electrical power of gas turbine at period \( t \) (kW)

\[ p_{eh}^{t} \]  Electrical power of electrical boiler at period \( t \) (kW)

\[ Q_{gb}^{t} \]  Thermal power of gas boiler at period \( t \) (kW)

\[ Q_{hr}^{t} \]  Thermal power of heat recovery device at period \( t \) (kW)

\[ Q_{he}^{t} \]  Thermal power of heat exchange device at period \( t \) (kW)

\[ e_{bt,chr}, e_{bt,dis}^{t} \]  Binary variables to denote the charging/discharging state of battery at period \( t \)

\[ p_{bt,chr}, p_{bt,dis}^{t} \]  Charging/discharging power of battery at period \( t \) (kW)

\[ W_{bt}^{t} \]  Energy level of battery at period \( t \) (kWh)

\[ e_{tst,chr}, e_{tst,dis}^{t} \]  Binary variables to denote the charging/discharging state of thermal storage tank at period \( t \)

\[ Q_{tst,chr}, Q_{tst,dis}^{t} \]  Charging/discharging power of thermal storage tank at period \( t \) (kW)

\[ Q_{hl}^{t} \]  Supplied thermal power at period \( t \) (kW)

\[ \Delta Q_{tst}^{t} \]  Adjusted thermal power of thermal storage tank at period \( t \) (kW)

\[ \Delta P_{res}^{t} \]  Demand of ramping up capacity of RES at period \( t \) (kW)

\[ U_{gt}^{t}, D_{gt}^{t} \]  Available ramping up/down capacity of electrical power of gas turbine at period \( t \) (kW)

\[ U_{eh}^{t}, D_{eh}^{t} \]  Available ramping up/down capacity of electrical power of electrical boiler at period \( t \) (kW)

\[ U_{bt}^{t}, D_{bt}^{t} \]  Available ramping up/down capacity of battery at period \( t \) (kW)

2) REAL-TIME ADJUSTMENT STAGE

\[ \chi \]  Curtailment power of Res (kW)

\[ \Delta P_{gt}^{t} \]  Adjusted electrical power of gas turbine at period \( t \) (kW)

\[ \Delta P_{eb}^{t} \]  Adjusted electrical power of electrical boiler at period \( t \) (kW)

\[ \Delta P_{bt}^{t} \]  Adjusted electrical power of battery at period \( t \) (kW)

\[ \Delta Q_{gb}^{t} \]  Adjusted thermal power of gas boiler at period \( t \) (kW)

I. INTRODUCTION

The depletion of traditional fossil fuels and serious environmental pollution make the renewable energy source (RES) play an essential role in the future energy system [1, 2]. The local consumption of variable RES such as wind and solar in the microgrid is considered as a promising way to build a more green energy system for that it can reduce the transmission losses and improve the energy efficiency [3]. As a multi-energy system that integrates distributed units and loads of different energy forms, the combined heat and power (CHP) microgrid can produce electricity and thermal energy and has high energy efficiency owing to the cascade utilization of energy [4-6]. In the CHP microgrid, the RES can be utilized to meet both electrical demand as well as thermal demand and thus the consumption of RES can be improved efficiently by coordinating the production and consumption of the thermal and electrical energy [7, 8].

However, the variable RES brings more uncertainties to the microgrid operation and makes the energy management a complex problem. In a grid-connected microgrid, the fluctuations of RES and loads can be accommodated by the main grid while the off-grid microgrid is exposed to a greater danger due to that it has to overcome the uncertainties by itself, especially when the penetration of variable RES gets higher and higher. In the existing studies, the ways to manage the uncertainties in the power system can be divided into two basic types: 1) the deterministic model based on the operating and contingency reserve requirement [9, 10]; and 2) the non-deterministic model based on the stochastic or robust programming approach. Overall, enhancing operational flexibility is a foundation to deal with the uncertainties [11, 12]. The operational flexibility was defined as “the ability to respond to a range of uncertain future states by taking an alternative course of action within acceptable cost threshold and time window” in [13], and subsequently a flexibility metric was proposed for evaluation in which the time, action, uncertainty, and cost are considered as four determinants. In [14], the operational flexibility in responding to energy market signals and the investment flexibility in responding to the long-term evolution of energy price were unified in a planning optimization framework for a distributed multi-energy generation system. In [15], the wind power was modeled as ramping capacity provider to improve the power system flexibility in short-term operations and a two-stage stochastic real-time unit commitment model including ramp capacity constraints was proposed.

For a multi-energy system such as CHP microgrid, the operational flexibility is more complicated owing to the complicated coupling relationship of different energy forms [14]. The coupling energy relationship, the characteristics of the heating system, and the multi-energy demand all make contributions to the operational flexibility of the system, which have been applied to improve economic performances in many researches [8, 16-18]. In [19], the effect of the flexible thermal load on the micro-CHP unit operation was investigated, and the economic sensitivity on the uncertainties such as temperature, electrical load, and the thermal load was analyzed. In [7], the transmission delay of the district heating network and the thermal...
storage capacity of buildings were modeled comprehensively, which were then utilized to decouple the original relationship of the thermal load and electrical demand, improve the operational flexibility of the CHP unit, and promote the wind power consumption. An inclusive demand response programming including load shifting, load curtailment, and flexible thermal load modeling was proposed in [20] to improve the operational flexibility of an energy hub. A simplified integrated demand response programming that combines electrical-load shifting and flexible heating supply was proposed in [21] to improve the operational flexibility of the CCHP microgrid. In summary, the above researches focus on the flexibility of the microgrid from a perspective of economic performance. The operational flexibility in the real-time scale of the multi-energy microgrid to accommodate the uncertainties of variable RES and loads has not been researched sufficiently.

Besides, although the nature of variable RES such as wind and solar makes the accuracy forecast impossible, the forecast error can be reduced as the interval decreases [22, 23]. Hence, the multi-time-scale dispatch strategy is often utilized to overcome the uncertainties of RES and loads [22, 24-26]. In [23], a model predictive control based on online optimal dispatch schedule consisting of rolling part and feedback correction was proposed for combined cooling, heating, and power (CCHP) microgrid, where the Kalman filter is used to forecast the power of RES and load in feedback correction stage. In [27], an adaptive robust day-ahead energy-reserve co-optimization approach was proposed for urban electrical and gas energy systems, where the second-stage (intraday) decisions are adjusted after the realization of the uncertainties in RES power. In [28, 29], the day-ahead scheduling and real-time dispatch models were proposed for a CCHP microgrid and in the real-time stage, the cooling and electricity are dispatched with different time-scale to follow the variations of RES and demands.

Above all, although there are many researches focused on the dispatch of the multi-energy microgrid, the research on the inherent operational flexibility of the multi-energy microgrid is insufficient. The potential of the real-time operational flexibility to deal with the RES uncertainty has also not been investigated. Therefore, we propose an operational flexibility metric based on the ramping capacity for the CHP microgrid. Considering the coupling relationship between the electrical power and thermal power in the CHP microgrid, an intraday rolling dispatch model (IRDM) that integrates the operational flexibility constraints is proposed to deal with the uncertainties of both RES and electrical load in the off-grid CHP microgrid. The IRDM consists of a dispatch decision (DD) stage and a real-time adjustment (RTA) stage. The contributions of this paper are as follows:

(1) Both the electrical ramping capacity and thermal ramping capacity are integrated into the operational flexibility metric so that the proposed metric can take into account of the complicated energy coupling relationship.

(2) Based on the coupled relationship between the electrical and thermal power as well as the characteristics of the thermal load, an dispatch strategy is proposed for the CHP microgrid intraday dispatch to enhance the operational flexibility, i.e. using the battery and energy coupling devices to follow the fluctuations of the net electrical load firstly, and then using the thermal devices to ensure the thermal comfort of end users.

(3) The operational flexibility constraints are included in the DD model to ensure that the off-grid CHP microgrid has enough ramping capacity to follow the fluctuations of electrical power, based on which a mixed integer linear programming (MILP) model is established to obtain a pre-dispatch plan. The RTA stage is based on an LP model aiming at minimum RES curtailment and minimum regulating quantity.

The remainder of this paper is as follows: In Section II, the system structure and dispatch mechanism are introduced. In Section III, the operational flexibility metric for the CHP microgrid is presented. The intraday rolling dispatch strategy is formulated in Section IV. The case studies and conclusions are given in Section V and VI, respectively.

II. Structure and Mechanism

A typical CHP microgrid consists of external energy network (including the main grid and the natural gas network), variable RES such as wind and solar, CHP system, and loads, as shown in FIGURE 1. The electrical heating device such as the electrical boiler and the electrical heat pump can be equipped to consume the redundant RES and save the primary energy.

The uncertainties in the operation of the CHP microgrid mainly come from the forecast errors of variable RES and loads and contingencies, and we focus on the forecast errors in this paper. The high penetration of RES brings significant uncertainties and risk to the operation of the microgrid, which means an efficient dispatch strategy has to consider the possible adverse situation and leave enough operational flexibility to deal with it. In the CHP microgrid, the battery, gas turbine, and electrical heating devices can be used to accommodate the fluctuations of the net electrical load while the gas boiler, thermal storage tank, gas turbine, and electrical heating device can be used to adjust the heating power and ensure the thermal comfort, as shown in FIGURE 2. Therefore, we analyze the ramping capacity of the electrical power and thermal power in the CHP microgrid separately, based on the minimum and maximum output, ramp rate, and current output of devices. On the other hand, owing to the different physical characteristics, the supply and demand of the electricity must be balanced in real-time while the supply and demand of the thermal energy can have a reasonable deviation [7, 30], as FIGURE 2 shows. Hence, considering the coupling
relationship between the electrical power and thermal power in the CHP system, the characteristic of the thermal load can also make contributions to the operational flexibility. Moreover, different from the electrical load and RES, the thermal load can be considered accurate because the time horizon in the intraday rolling dispatch is very short for the thermal load forecast [31]. Based on this, to enhance the operational flexibility, we can use the energy coupling devices i.e., the gas turbine and electrical heating device to accommodate the uncertainties of the variable RES and the electrical load, and then the thermal power deviation caused by the adjustment is compensated by the thermal devices, i.e., the gas boiler and thermal storage tank.

Besides, the intraday rolling dispatch strategy we proposed consists of two stages. In the first stage, a robust optimization is performed during each period based on the forecast value of the RES and load power, where the operational flexibility constraints including ramping up and ramping down capacity are taken into consideration. Then, the adjustment bounds of each device are calculated according to the dispatch results. In the RTA stage, the real-time power of RES and the electrical load are forecasted. The devices in the CHP system are adjusted to compensate for the fluctuations. The electrical power is balanced based on the linear relationship between the electrical power and thermal power in the intraday interval of RTA.

III. Operational Flexibility Metric

A. Ramping capacity

1) RAMPING CAPACITY OF ELECTRICAL POWER

The ramping capacity of the gas turbine, including the ramping up capacity $U_{gt}$ and ramping down capacity $D_{gt}$, depends on the state of gas turbine $e_{gt}^t$, the output power $P_{gt}$, the upper and lower limits of power of gas turbine ($P_{gt}$ and $P_{gt}$, respectively), and the ramping rate $R_{gt}$, as given in (1), where $\Delta t$ is the length of time interval of RTA.

$$
\begin{align*}
    U_{gt} &= \min \left( e_{gt}^t, P_{gt}^u - P_{gt}^l, R_{gt}\Delta t \right) \\
    D_{gt} &= \min \left( P_{gt}^u - e_{gt}^t P_{gt}^l, R_{gt}\Delta t \right)
\end{align*}
$$

The ramping capacity of the electrical boiler depends on the input power $P_{eb}$, the adjustable power during $\Delta t$, and the maximum power $P_{eb}$, as given in (2), where $\xi_{eb}$ (2) is the adjustable ratio of electrical boiler during $\Delta t$.

$$
\begin{align*}
    U_{eb} &= \min \left( P_{eb}, \frac{\xi_{eb} P_{eb}}{\Delta t} \right) \\
    D_{eb} &= \min \left( P_{eb} - \frac{\xi_{eb} P_{eb}}{\Delta t}, \frac{\xi_{eb} P_{eb}}{\Delta t} \right)
\end{align*}
$$

The ramping capacity of the battery depends on the adjustable range of power and its state of charge (SOC) [11], as given in (3). To avoid frequent changing between charging and discharging states, the charging/discharging state in the RTA stage has to be in accordance with the DD stage.

$$
\begin{align*}
    U_{bb} &= \min \left( e_{bt,dis} P_{bt,dis} - P_{bt,ch}, P_{bt,ch}, \frac{W_{bt}}{\Delta t} - W_{bt} \right) \\
    D_{bb} &= \min \left( e_{bt,ch} P_{bt,ch} - P_{bt,dis}, P_{bt,dis}, \frac{W_{bt}}{\Delta t} - W_{bt} \right)
\end{align*}
$$

In (3), $e_{bt,dis}$ and $e_{bt,ch}$ are state variables of discharging and charging, respectively, $P_{bt,dis}$ and $P_{bt,ch}$ are power of discharging and charging, respectively, $W_{bt}$ is the SOC of battery, and $W_{bt}$ and $W_{bt}$ are upper and lower limits of SOC.

2) RAMPING CAPACITY OF THERMAL POWER

The ramping capacity of the gas boiler depends on the thermal power of gas boiler $Q_{gb}$ and the maximum power $Q_{gb}$ as given in (4), where $\xi_{gb}$ is the adjustable ratio of gas boiler during $\Delta t$.

$$
\begin{align*}
    U_{gb} &= \min \left( Q_{gb} - Q_{gb}, \frac{\xi_{gb} Q_{gb}}{\Delta t} \right) \\
    D_{gb} &= \min \left( Q_{gb} - Q_{gb}, \frac{\xi_{gb} Q_{gb}}{\Delta t} \right)
\end{align*}
$$

The ramping capacity of the thermal storage tank depends on the adjustable range of power and its energy level, as given in (5), where $e_{bt,dis}$ and $e_{bt,ch}$ are state variables of releasing and storing, respectively, $Q_{bt,dis}$ and $Q_{bt,ch}$ are power of releasing and storing, respectively, $W_{bt}$ is the energy level of battery, and $W_{bt}$ and $W_{bt}$ are upper and lower limits of energy level.

$$
\begin{align*}
    U_{st} &= \min \left( e_{st,dis} Q_{st,dis} - Q_{st,ch}, Q_{st,ch}, \frac{W_{st}}{\Delta t} - W_{st} \right) \\
    D_{st} &= \min \left( e_{st,ch} Q_{st,ch} - Q_{st,dis}, Q_{st,dis}, \frac{W_{st}}{\Delta t} - W_{st} \right)
\end{align*}
$$

B. Operational flexibility metric

Based on the ramping capacity of each device, the system-wide ramping capacity of the CHP microgrid can be calculated. Owing to that the output of each device is optimizable in operation, the system-wide ramping capacity may differ in different operation conditions. Therefore, we propose the operational flexibility metric of the CHP microgrid to quantify the system-wide ramping capacity, as given in (6), (6) is a linear programming (LP) model, the objective of which is the sum of the ramping up and ramping down capacity of electrical power. The first and the second constraints are limits of the available ramping capacity of device $U_{gt}$ and $D_{gt}$. The third and the fourth constraints aim to ensure that the gas boiler and the thermal storage tank can...
compensate for the deviation of the supplied thermal power of the gas turbine and electrical heating boiler, i.e., ensure the thermal comfort.

\[
\begin{align*}
\text{max} & \sum U_i^t + \sum D_i^t, \quad x \in \{gt, eh, bt\} \\
0 & \leq U_i^t \leq \bar{U}_i^t, \quad x \in \{gt, eh, bt\} \\
0 & \leq D_i^t \leq \bar{D}_i^t, \quad x \in \{gt, eh, bt\}
\end{align*}
\]

\[s.t.
\begin{align*}
\bar{U}_i^t + \bar{D}_i^t & = \eta_{gt} U_i^t + \eta_{eh} (1 - \eta_{eh}) D_i^t / \eta_{gt} \\
\bar{U}_i^t + \bar{D}_i^t & = \eta_{eh} D_i^t + \eta_{eh} (1 - \eta_{eh}) U_i^t / \eta_{eh}
\end{align*}
\]

(6)

IV. Intraday Rolling Dispatch Model

The intraday rolling dispatch model consists of a DD stage and an RTA stage. The DD stage is used to obtain the optimal dispatch plan while the RTA stage is used to balance the fluctuations of RES and load. In the DD stage, the operational flexibility constraints are incorporated to ensure that the uncertainties in the RTA can be accommodated.

A. Dispatch Decision (DD) model

1) OBJECTIVE FUNCTION

The objective function includes the natural cost of gas of the gas turbine and the gas boiler, as given in (7), where \( M_{DD} \) is the length of the DD period, \( c_{ng} \) and \( H_{ng} \) are the price and heat value of natural gas, respectively, and \( \eta_{gt} \) and \( \eta_{gb} \) are the efficiencies of the gas turbine and the gas boiler, respectively.

\[
\min \frac{c_{ng}}{H_{ng}} \sum_{t \in M_{DD}} \left( \frac{P_i^t}{\eta_{gt}} + \frac{Q_i^t}{\eta_{gb}} \right)
\]

(7)

2) CONSTRAINTS

The constraints of the DD model include the power balance constraints, limits of devices, ESS constraints, thermal supply constraints, RES dispatch constraints, and operational flexibility constraints.

a) Power balance constraints

The constraints of power balance are as follows

\[
\begin{align*}
Q_{gt}^t & = (1 - \eta_{gt} - \eta_{loss}) P_i^t / \eta_{gt} \\
Q_{gb}^t & = \eta_{gb} Q_{gt}^t, \quad Q_{ld}^t = \eta_{ld} Q_{gt}^t \\
Q_{eh}^t & = Q_{et}^t + Q_{eh}^t + Q_{ct,eh}^t = Q_{et}^t \\
P_i^t - P_i' + P_{hi,eh}^t - P_{hi,eh}^t + \bar{P}_{lg}^t - \bar{P}_l^t
\end{align*}
\]

(8)

where \( \eta_{loss} \) is heat loss rate of gas turbine, \( \eta_{hr}, \eta_{eh}, \) and \( \eta_{he} \) are the efficiency of heat recovery unit, electrical boiler, and heat exchanger, respectively, \( Q_{gt}, Q_{hr}, Q_{eh} \) and \( Q_{he} \) output thermal power of gas turbine, heat recovery unit, electrical boiler, and heat exchanger, respectively, \( Q_{ld}^t \) is the thermal power supplied to load, and \( \bar{P}_{lg}^t \) and \( \bar{P}_l^t \) are forecast value of electrical load and RES power, respectively.

b) Limits of devices

The limits of each device are as given in (9), where \( Q_{hr}^t, Q_{he}^t \) are thermal power of heat recovery unit and heat exchanger, respectively, and \( Q_{hr}^t \) and \( Q_{he}^t \) are maximum thermal power of heat recovery unit and heat exchanger, respectively.

\[
\begin{align*}
0 & \leq Q_{ph}^t \leq \bar{Q}_{ph}^t \\
0 & \leq Q_{eh}^t \leq \bar{Q}_{eh}^t \\
0 & \leq Q_{hr}^t \leq \bar{Q}_{hr}^t \\
0 & \leq Q_{he}^t \leq \bar{Q}_{he}^t \\
0 & \leq P_i^t \leq \bar{P}_i^t
\end{align*}
\]

(9)

c) ESS constraints

The constraints of battery are as given in (10), where \( \sigma_{bt} \) is the energy loss rate of battery, and \( \eta_{bt,eh} \) and \( \eta_{bt,dil} \) are charging and discharging efficiencies, respectively. The constraints of thermal storage tank have the similar forms, and the details can be found in [21, 23].

\[
\begin{align*}
0 & \leq P_i'_{b,eh} \leq \bar{P}_{b,eh} \quad (1 - \sigma_{bt}) W_i^t + \\
0 & \leq P_i'_{b,eh} \leq \bar{P}_{b,eh} \quad \left( \eta_{bt,eh} P_i'_{b,eh} - P_i'_{b,eh} / \eta_{bt,eh} \right) \Delta t \\
W_i^t & \leq W_i^t \leq \bar{W}_i^t \\
0 & \leq t_i^{b,eh} + t_i^{b,eh} = 1, \quad t_i^{b,eh}, t_i^{b,eh} \in \{0, 1\}
\end{align*}
\]

(10)

d) Constraints of thermal supply

Based on the thermodynamic model of buildings, the thermal load can be modeled as (11) ~ (13). (11) is the equation of indoor temperature, (12) calculates the relative value the scope of the supplied thermal power, and (13) keeps the balance between demand and supply as well as the variation range of the supplied thermal energy. More detailed description can be found in [21]. In (11) ~ (13), \( T_i^{in\_amb} \) and \( T_i^{in\_room} \) are indoor temperature and ambient temperature, respectively, \( T_i^{in\_opt} \), \( T_i^{in} \), and \( T_i^{in\_amb} \) are the optimal value, allowable maximum value, and allowable minimum value of the indoor temperature, respectively, \( R \) is the thermal resistance of house shell, \( c_{air} \) is heat capacity of air, \( Q_{bl}^t \) is the forecast thermal load, and \( y_{hi,\text{ld}} \) and \( y_{hi,\text{ld}}^t \) are relative value of the downward and upward fluctuation of supplied thermal power, respectively. The thermal supply constraints include (12) and (13).

\[
\begin{align*}
T_i^{in\_amb} - T_i^{in\_room} = R \cdot Q_i^t + T_i^{in\_room} / (1 - e^{-\Delta t / \alpha_{sc}}) - T_i^{in\_opt} - T_i^{in\_room} \\
\gamma_i^{hi,\text{ld}} = \frac{T_i^{hi,\text{ld}} - T_i^{hi,\text{ld}}}{T_i^{hi,\text{ld}} - T_i^{hi,\text{ld}}} \\
\sum_{i \in T} Q_i^t = \sum_{i \in T} \bar{Q}_i^t \\
(1 + \gamma_i^{hi,\text{ld}}) \bar{Q}_i^t \leq Q_i^t \leq (1 + \gamma_i^{hi,\text{ld}}) \bar{Q}_i^t
\end{align*}
\]

(11)

(12)

(13)

e) Constraints of RES

The RES is modeled as dispatchable power injection \( P_{res}^t \) whose upper bound is the forecast power \( \bar{P}_{res}^t \), as shown in (14). Theoretically, in the RTA stage, if the practical RES power is more than the dispatched power \( P_{res}^t \), the exceeding part can be curtailed when the ramping capacity is insufficient to absorb it, and thus the demand of the ramping down capacity of the RES is 0. If the practical RES power is less than \( P_{res}^t \), the microgrid has to compensate for the insufficient power, and the demand of the
ramping up capacity of the RES $\Delta P_{res}^{r}$ can be calculated as (15), where $\delta_{res}$ is the RES expected forecast error and its value depends on the forecast accuracy and the confidence interval [11].

\[
0 \leq P_{res}^{r} \leq \bar{P}_{res}^{r}, \quad \Delta P_{res}^{r} = \max \left( P_{res}^{r} - (1 - \delta_{res}) \bar{P}_{res}^{r}, 0 \right)
\]  

(15)

f) Constraints of operational flexibility

The operational flexibility constraints include (1)~(5), the constraints in (6), and (16). In (16), $\delta_{el}$ is the expected forecast error of the electrical load. The first constraint in (16) ensures that the ramping up capacity can meet the ramping up demand of the RES and electrical load. The second constraint ensures that the ramping down capacity can meet the ramping down demand of the electrical load (the RES power exceeding the dispatched value can be curtailed and hence the ramping down demand of RES is 0).

\[
\begin{align*}
U_{g}^{r} + U_{eb}^{r} + U_{bt}^{r} & \geq \delta_{el} \cdot \bar{P}_{el}^{r} + \delta_{el} \cdot \bar{P}_{el}^{r} \\
D_{g}^{r} + D_{eb}^{r} + D_{bt}^{r} & \geq \delta_{el} \cdot \bar{P}_{el}^{r}
\end{align*}
\]  

(16)

Then, we obtain a mixed integer linear programming (MILP) model where the decision variables include the state and power of each device in the microgrid, the energy level of ESS, the planned ramping up and down capacity, and the thermal power supplied to end users.

B. Real-time adjustment strategy (RTA)

In the RTA stage, the power of the RES and electrical load is forecasted at each time interval $t$. The electrical load fluctuation $\Delta P_{el}^{r}$, RES power fluctuation $\Delta P_{res}^{r}$, and the net electrical load fluctuation $\Delta P_{net}^{r}$ can be calculated as follows

\[
\begin{align*}
\Delta P_{el}^{r} &= P_{el}^{r} - \bar{P}_{el}^{r} \\
\Delta P_{res}^{r} &= P_{res}^{r} - P_{res}^{r} \\
\Delta P_{net}^{r} &= \Delta P_{res}^{r} + \Delta P_{el}^{r}
\end{align*}
\]  

(17)

1) ELECTRICAL POWER ADJUSTMENT

Although the RES may be curtailed in the DD stage to decrease the operational flexibility demand, the actual amount of curtailed RES power depends on the actual RES power and electrical load. Here we define an auxiliary constant as (18) to indicate the direction of RES power fluctuation. If $\Delta P_{res}^{r} > 0$, it means that the actual RES power is larger than the dispatched RES of the DD results so that the curtailment may occur.

\[
\gamma^{r} = \begin{cases} 
1, & \Delta P_{res}^{r} > 0 \\
0, & \Delta P_{res}^{r} \leq 0
\end{cases}
\]  

(18)

Then, if the fluctuation of the net electrical load is above or equal to 0, the model of electrical power adjustment is as given in (19). The model is as (20) if the fluctuation of the net electrical load is less than 0.

\[
\min \chi + \lambda_{bt} \Delta P_{bt}^{r} - \lambda_{bt} \Delta P_{bt}^{r} + \lambda_{gb} \Delta P_{gb}^{r}
\]  

(19)

s.t.

\[
\begin{align*}
\Delta P_{bt}^{r} - \Delta P_{gb}^{r} + \Delta P_{gb}^{r} - \chi &= \Delta P_{net}^{r} \\
0 &\leq \chi \leq \nu^{r} \cdot \Delta P_{net}^{r} \\
0 &\leq \Delta P_{bt}^{r} \leq \bar{U}_{bt}^{r}, x \in \{bt, gt\} \\
0 &\leq -\Delta P_{gb}^{r} \leq \bar{U}_{gb}^{r}, x \in \{bt, gt\}
\end{align*}
\]  

(20)

In (19) and (20), $\chi$ is the amount of curtailed RES power, $\Delta P_{bt}^{r}$, $\Delta P_{gb}^{r}$, $\Delta P_{net}^{r}$ are the adjusted electrical power amount of battery, electrical boiler, and gas turbine, respectively, $\Delta Q_{el}^{r}$, and $\Delta Q_{gb}^{r}$ are adjusted thermal power amount of thermal storage tank and gas boiler, respectively, and $\lambda_{bt}$, $\lambda_{gb}$ and $\lambda_{bt}$ are weight coefficients and their values determine the adjustment order of battery, electrical boiler, and gas turbine. In (19) and (20), the first constraint keeps the electrical power balance, the fifth constraint limits the scope of the supplied thermal power, and the others are the limits of adjustable value.

The electrical adjustment model is an LP, whose object includes the minimum RES curtailment and the minimum adjustment amount. Considering the characteristic of each device, the adjustment orders are given in Table I, and correspondingly the values of weight coefficients should meet the relationship in the following

\[
0 < \lambda_{bt} < \lambda_{gb} < \lambda_{gb} < 1
\]  

(21)

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>ADJUSTMENT ORDER OF DEVICES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adjustment order</td>
</tr>
<tr>
<td></td>
<td>Electrical power</td>
</tr>
<tr>
<td></td>
<td>Thermal power</td>
</tr>
<tr>
<td></td>
<td>Thermal storage tank → gas boiler</td>
</tr>
</tbody>
</table>

2) THERMAL POWER ADJUSTMENT

The adjustment of the gas turbine and electrical heating boiler causes the deviation of the supplied thermal power. The output of thermal storage tank and gas boiler need to be adjusted to ensure the supplied thermal power within the allowable range. The adjustment orders we define is shown in Table I. The adjustment limit of thermal storage tank is as (22), and the gas boiler compensates for the insufficient part only when the thermal storage tank cannot provide enough ramping up/down capacity.
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2929623, IEEE Access

\[-B_u^r \leq \Delta Q_{res}^r \leq U_u^r \quad (22)\]

V. Case Studies

A hypothetical CHP microgrid in North China is used to verify the proposed dispatch strategy. The microgrid consists of a wind turbine (5 MW), a gas turbine (2 MW), a heat recovery device (5 MW), a gas boiler (3 MW), an electrical boiler (3 MW), a heat exchanger (5 MW), a battery (1 MWh), and a thermal storage tank (1 MWh). The system structure is similar to that in FIGURE 1. Compared with the system structure in FIGURE 1, the hypothetical CHP microgrid has no photovoltaic cells and is operated in an off-grid state. Two cases of different wind power proportions are studied for comparison. The forecast value and actual value of the electrical load, thermal load, and wind power are shown in FIGURE 3. The average wind power during a day is 3.72MW and 2.15MW in case I and case II, respectively. The dispatch interval and period of the RTA stage is 1min. Other parameters are given in Table II. The simulations were performed in Matlab 2017a on a personal computer with a 3.4 GHz CPU and 16 GB memory. The optimization problem is solved by GUROBI.

The power of the thermal storage tank, gas boiler, and thermal load are shown in FIGURE 5. During 8:15~8:17 and 8:49~8:51, the discharging power of battery is adjusted upward to follow the increasing net electrical load and the adjustment value of electrical boiler and gas turbine is 0. During 8:05~8:11, 8:30~8:32, and 8:40~8:44, the charging power of battery is adjusted downward, the electrical boiler consumed more power than the DD stage, and the gas turbine produces less power than the DD stage to follow the decreasing net electrical load and increase the wind power consumption. During 8:18~8:30 and 8:46~9:00, the DD results determine that the battery is on discharging state and the discharging power is 0. Therefore, the ramping down capacity of battery is 0 during these periods. Overall, the results show that the power of the gas turbine was adjusted downward at most of the time in the RTA stage to decrease the wind power curtailment.
not exhaust the ramping down capacity of the CHP microgrid so that the left part can be used to promote the wind power consumption.

If we do not consider the operational flexibility constraints in the DD stage, although the DD stage model can be solved, the RTA stage cannot be fulfilled owing to the lack of ramping capacity. The insufficient electrical power in the RTA stage is shown in FIGURE 7. Obviously, the CHP microgrid has no enough ramping up capacity to compensate for the power fluctuation. Besides, the ramping down capacity of the microgrid is always enough because the RES can be curtailed.

2) OPERATION COST

The operating cost of two scenarios (considering/not considering the operational flexibility constraints in the DD model) and their percentage of difference are shown in FIGURE 8. Obviously, the consideration of operational flexibility constraints results in a distinct cost increase in the DD stage. The practical operating cost depends on the schedule in the RTA stage. The natural gas consumption of the gas turbine and gas boiler during 6:00–12:00 is shown in FIGURE 9. During most of the period, the gas turbine consumes more natural gas when the flexibility constraints are considered than when the flexibility constraints are not considered. The total consumed natural gas of the gas turbine in two scenarios is 2655.74m³ and 2313.65m³, respectively, meaning that the gas consumption is increased by 14.8% when considering the flexibility constraints. When the flexibility constraints are not considered, the gas boiler only works during 15:15–15:30. The total consumed natural gas of the gas boiler in two scenarios is 234.85m³ and 34.12m³, respectively, meaning that the role of the gas boiler is more important when considering the flexibility constraints. The total operating cost of two scenarios in the DD stage and RTA stage is shown in Table III. The consideration of operational flexibility constraints makes the cost of the DD stage increasing about 23.64%. However, in the RTA stage, the actual operating cost is less than the DD stage (about 12.14%) owing to that more wind power is consumed in the RTA stage.
### TABLE III
**OPERATING COSTS OF TWO SCENARIOS IN DD AND RTA STAGE**

<table>
<thead>
<tr>
<th>Flexibility Constraints</th>
<th>Cost (¥)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD</td>
<td>7680.67</td>
</tr>
<tr>
<td></td>
<td>9496.57</td>
</tr>
<tr>
<td>RTA</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>8343.07</td>
</tr>
</tbody>
</table>

#### B. Case II

The forecast and the dispatched wind power in case II is shown in [FIGURE 10](#). Owing to that the wind power proportion is lower than the case I, the curtailed amount in DD stage and RTA stage is both less than the case I. The results show just a little wind power is curtailed in the RTA stage. The insufficient electrical power in the RTA stage when the flexibility constraints are not included in the DD model is shown in [FIGURE 11](#). Although the insufficient amount is not as much as the case I, the results indicate that in an off-grid microgrid the operational flexibility constraints have to be considered in the dispatch model.

#### TABLE IV
**OPERATING COSTS OF TWO SCENARIOS IN DD AND RTA STAGE**

<table>
<thead>
<tr>
<th>Flexibility Constraints</th>
<th>Cost (¥)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD</td>
<td>17776.65</td>
</tr>
<tr>
<td></td>
<td>18260.45</td>
</tr>
<tr>
<td>RTA</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>17860.50</td>
</tr>
</tbody>
</table>

In summary, in the intraday rolling dispatch strategy we proposed, although the RES curtailment may emerge in the DD stage to decrease the operational flexibility demand, in RTA stage the operational flexibility can be made full use of to promote the RES consumption. Also, for a specific CHP microgrid, the results show that considering the operational flexibility constraints in the dispatch model produces an extra cost, the amount of which depends on the RES proportion.

#### C. Analysis of operational flexibility

After the dispatch plan is obtained from the DD stage, the operational flexibility metric can be solved based on the model (6) and the ramping capacity of the CHP microgrid in Case I is shown in [FIGURE 13](#). The results show that the battery provides most of the ramping up capacity while the electrical boiler provides most of the ramping down capacity. In fact, the operational flexibility constraints in the DD model integrates the ramping capacity demand to accommodate uncertainties. Considering the RES can be curtailed to decrease the demand for ramping down capacity, the microgrid demand for ramping up capacity is larger than the ramping down capacity which is just as [FIGURE 11](#) shows.

The operating cost of two scenarios (considering/not considering flexibility in DD model) in the DD stage and their percentage of difference are shown in [FIGURE 12](#). Because the wind power proportion is not as high as the case I, the cost of two scenarios is approximately equal, which shows that the consideration of operational flexibility constraints will hardly produce extra cost when the RES proportion is not very high. The total operating cost of two scenarios in the DD stage and RTA stage is shown in Table IV. The consideration of operational flexibility constraints makes the cost of the DD stage increasing about 2.7%. The actual operating cost is less than the DD stage (about 2.1%), and obviously, the reduction rate is less than the case I (12.14%) owing to that the operational flexibility of the CHP microgrid is enough to accommodate the uncertainties and little wind power is curtailed in the DD stage.
VI. Conclusions

In this paper, an operational flexibility metric for the dispatch of the CHP microgrid is proposed. The characteristic of the thermal load is applied to enhance the microgrid operational flexibility. An intraday rolling dispatch strategy combining a dispatch decision stage and a real-time adjustment stage is proposed for the off-grid CHP microgrid. The case studies demonstrate that our strategy can accommodate the uncertainties of electrical power and ensure the secure and economic operation of the CHP microgrid. The results also show that the operational flexibility metric we proposed is useful in accessing the ramping capacity of the CHP microgrid.

References
