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Abstract—This article proposes a new two-stage hybrid stochastic-information gap-decision theory (IGDT) based on the network-constrained unit commitment framework. The model is applied for the market clearing of joint energy and flexible ramping reserve in integrated heat- and power-based energy systems. The uncertainties of load demands and wind power generation are studied using the Monte Carlo simulation method and IGDT, respectively. The proposed model considers both risk-averse and risk-seeker strategies, which enables the independent system operator to provide flexible decisions in meeting system uncertainties in real-time dispatch. Moreover, the effect of feasible operating regions of the combined heat and power (CHP) plants on energy and flexible ramping reserve market and operation cost of the system is investigated. The proposed model is implemented on a test system to verify the effectiveness of the introduced two-stage hybrid framework. The analysis of the obtained results demonstrates that the variation of heat demand is effective on power and flexible ramping reserve supplied by CHP units.

Index Terms—Combined heat and power (CHP), flexible ramping reserve, hybrid IGDT–stochastic, information gap-decision theory (IGDT), market clearing, stochastic programming.

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<thead>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>t</td>
<td>Time interval.</td>
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<tr>
<td>i</td>
<td>Generation unit.</td>
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<tr>
<td>r</td>
<td>Wind turbine.</td>
</tr>
<tr>
<td>b, b'</td>
<td>Electric network buses.</td>
</tr>
<tr>
<td>j</td>
<td>Electric network loads.</td>
</tr>
<tr>
<td>L</td>
<td>Transmission line of electric network.</td>
</tr>
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<td>s</td>
<td>Scenario.</td>
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Constants

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>NT</td>
<td>Sum of time intervals.</td>
</tr>
<tr>
<td>NC</td>
<td>Number of CHP plants.</td>
</tr>
<tr>
<td>NG</td>
<td>Number of non-CHP plants.</td>
</tr>
<tr>
<td>NW</td>
<td>Number of wind power turbines.</td>
</tr>
<tr>
<td>NB</td>
<td>Number of buses.</td>
</tr>
<tr>
<td>NQ</td>
<td>Number of heat loads.</td>
</tr>
<tr>
<td>NJ</td>
<td>Number of electric loads.</td>
</tr>
<tr>
<td>a, b, c, d, e, f</td>
<td>Cost coefficients of the CHP unit.</td>
</tr>
<tr>
<td>Pimax/Pimin</td>
<td>Upper/lower capacity of unit i (MW).</td>
</tr>
<tr>
<td>RU/RD</td>
<td>Ramp-up/down of unit i (MW).</td>
</tr>
<tr>
<td>Tio/Tid</td>
<td>Minimum up/down time of unit i (MW).</td>
</tr>
<tr>
<td>Xl</td>
<td>Reactance of electric line L.</td>
</tr>
<tr>
<td>PFe</td>
<td>Reactance of electric line L (MW).</td>
</tr>
<tr>
<td>Dj,t</td>
<td>Power transmission capacity of electric line L (MW).</td>
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<tr>
<td>Djt,s</td>
<td>Forecasted electricity demand at time t (MW).</td>
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<td>HDqt</td>
<td>Forecasted electricity demand at time t in scenario s (MW).</td>
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<td>HDqt,s</td>
<td>Forecasted heat demand at time t in scenario s (MW).</td>
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<tr>
<td>RFRUi/RFRDi</td>
<td>Requirement of upward/downward flexible ramping reserve at time t (MW).</td>
</tr>
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</table>

NOMENCLATURE


\[ \frac{C_{\text{FRU}}}{C_{\text{FRD}}} \]

\[ P_{r,t} \]

\[ F^C \]

\[ \text{First-Stage Variables} \]

\[ SU_{i,t}, SD_{i,t} \]

\[ P_{i,t} \]

\[ H_{i,t} \]

\[ P_{r,t} \]

\[ P_{FL,t} \]

\[ \delta_{b,t} \]

\[ \text{Upward/downward flexible ramping reserve of unit } i \text{ at time } t (\$/MWh). \]

\[ \text{Forecasted wind power (MW).} \]

\[ \text{Cost function of unit } i (\$). \]

\[ \text{Start-up/shut-down cost of unit } i (\$). \]

\[ \text{Power dispatch of unit } i (\text{MW}). \]

\[ \text{Heat generation of CHP unit (MWth).} \]

\[ \text{Wind power dispatch (MW).} \]

\[ \text{Line flow at line } L (\text{MW}). \]

\[ \text{Voltage angle of network buses.} \]

\[ \text{Upward/downward flexible ramping reserve provided by unit } i (\text{MW}). \]

\[ \text{Binary ON/OFF status indicator of unit } i. \]

\[ \text{ON/OFF time of unit } i. \]

\[ \text{Second-Stage Variables} \]

\[ \Delta P_{i,t,s}^U / \Delta P_{i,t,s}^D \]

\[ \Delta H_{i,t,s}^U / \Delta H_{i,t,s}^D \]

\[ P_{FL,t,s} \]

\[ \delta_{b,t,s} \]

\[ \text{Adjusted upward/downward power dispatch of unit } i (\text{MW}). \]

\[ \text{Adjusted upward/downward heat generation of CHP unit (MWth).} \]

\[ \text{Line flow at line } L \text{ and scenario } s (\text{MW}). \]

\[ \text{Voltage angle of buses at scenario } s. \]

\[ X_{i,t} / X_{i,t-1} \]

\[ I_{i,t} \]

\[ X_{i,t}^\text{on} / X_{i,t}^\text{off} \]

\[ I_{i,t} \]

\[ X_{i,t-1} \]

I. INTRODUCTION

RECENTLY, significant interests have been observed in harvesting renewable energy due to global concerns on climate changes and the decrement of fossil fuels [1]. The annual wind production will achieve 2182 TWh by 2030 according to the statistics reported by International Energy Agency [2]. Considering the uncertainties associated with power generation of wind turbines and photovoltaic systems as the most popular renewable energy sources, different solutions are proposed for handling such issues. Flexible ramping products (FRPs) are defined as practical solution approaches to deal with uncertainties of power load demand and predicted renewable power production, which are products providing additional upward and downward flexible ramping [3]. Such products are introduced as FRPs in California Independent System Operator market and ramp capability in the Midwest Independent System Operator market [4], [5].

The difference between the application of FRPs with respect to other power market services, such as frequency regulation, spinning reserve, and nonspinning reserve, should be highlighted. In fact, certain predetermined contingencies of the power network at each time are managed by the above-mentioned services. In addition, spinning and nonspinning reserves play a role in performing upramping flexibility; however, FRPs cover both upramping and downramping services. Moreover, 5-min intervals and several seconds are checking time intervals for FRPs and frequency regulation, respectively [4]. Several studies have focused on such products in unit commitment (UC) problem. FRPs of independent system operator (ISO) market was incorporated in real-time stochastic UC in [4] without consideration of transmission limits. In [6], a market clearing of joint energy and flexible ramping reserve for coordinated electricity and natural gas networks was studied in the presence of demand response programs. In that work, Zhang et al. concentrated on the impact of natural gas network constraints in flexible ramping reserve scheduling of gas-fired units. The effect of emerging flexible resources, such as electric vehicles, demand response programs, and balance storage systems, on generation scheduling, spinning reserve, and flexible ramping reserve of generation units and system operation cost was investigated in [7].

Combined heat and power (CHP) plants are practical solutions in supplying the heat and power demands of industrial, commercial, and residential sectors. CHP plants are able to recover wasted heat in the conversion process of fossil fuels to power and heat. They take advantages of increasing the efficiency of power and heat supply to 90% and decreasing the gases emissions nearly 13%–18% [8]. The other advantages of the CHP units are improving the reliability of delivered energy and security of supply [9]. It should be noted that the generated heat and power by the CHP plants have mutual dependence, which is defined as feasible operating region (FOR). Considering the significant advantages of CHP units in terms of cost savings and reduction of gas emissions, penetration of such technologies in providing heat and power demand of networks has been increased. Accordingly, several remarkable works have been done in the area of optimal operation of CHP plants in power networks. In [10], the optimal operation of CHP units in renewable-energy-based microgrid was studied, where autoregressive integrated moving average concept was implemented to produce the wind power output scenario. The UC problem for CHP-based microgrids was studied in [11] considering fuel cell and battery storage systems. The uncertainties of load demand and power market price are modeled in this article by using scenario-based modeling method. In [12], a CHP-based market clearing model was proposed, and the effect of constraints of power and heat network was investigated on the daily operation cost.

Information gap-decision theory (IGDT) is a robust decision modeling method for severe uncertain parameters and does not need probability distribution function of the uncertain parameters unlike the other uncertainty modeling approaches, such as Monte Carlo simulation (MCS) concept and scenario-based modeling approaches. In addition, this method does not need to determine the maximum radius of uncertain parameter, which takes advantages of flexibility rate of the model in defining different strategies for the operator. Actually, the IGDT aims to obtain maximum uncertainty radius for uncertainty parameters in a way that the objective function is satisfied in the predefined interval. In power systems, IGDT is applied for bidding strategies challenges in electricity networks [13], UC problem [14], and restoration of distribution networks [15]. In [16], a self-scheduling model was studied based on the IGDT method, which aimed to obtain the maximum profit of generation company considering the uncertainty associated with power market price. In [17], IGDT concept was developed for modeling uncertainty of wind power generation in the UC problem considering demand response programs. The profit of heat and power generation plants was maximized using an IGDT model in [18] considering the uncertainty of the power market price. A robust framework based on the IGDT procedure was proposed in [19] for studying the security-constrained unit commitment (SCUC) problem in
TABLE I
COMPARISON OF THE LITERATURE WITH THE CURRENT WORK

<table>
<thead>
<tr>
<th>References</th>
<th>CHP</th>
<th>Uncertainties</th>
<th>Uncertainty modeling method</th>
<th>FRPs</th>
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<tr>
<td>[20]</td>
<td>✔</td>
<td>Electric load ✔</td>
<td>Robust</td>
<td></td>
</tr>
<tr>
<td>[12]</td>
<td></td>
<td>Wind ✔</td>
<td>Deterministic</td>
<td></td>
</tr>
<tr>
<td>[19]</td>
<td>✔</td>
<td></td>
<td>IGDT</td>
<td></td>
</tr>
<tr>
<td>[17]</td>
<td>✔</td>
<td></td>
<td>IGDT</td>
<td></td>
</tr>
<tr>
<td>Proposed model</td>
<td>✔</td>
<td>✔</td>
<td>Hybrid IGDT-Stochastic</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Overall perspective of the proposed model.

the presence of latium-ion energy storage technologies, where
the uncertainty of load demand was taken into account. A robust
network-constrained UC (NCUC) scheme was introduced in
[14] based on the IGDT method considering energy storage
system, demand response programs, and transmission switching.

Table I classifies the literature in modeling and investigating
the NCUC problem by providing a summary of uncertainty
parameters and models. To the best knowledge of the authors,
the network-constrained market clearing of joint energy and flexible
ramping reserve for integrated heat and power systems under
a hybrid optimization approach has not been discussed. Thus,
this article proposes a novel two-stage hybrid IGDT–stochastic
NCUC procedure for market clearing problem of joint energy and
flexible ramping reserve in energy systems with penetration
of CHP plants and wind turbines. An overall view of the pro-
posed scheme is demonstrated in Fig. 1. The main contributions
of this article can be highlighted as follows.

1) The proposed two-stage hybrid IGDT–stochastic NCUC
framework contains a here-and-now decision-making pro-
cess in the first stage and wait-and-see procedure in
the second one. The proposed model considers both
risk-averse (RA) and risk-seeker (RS) strategies, which
enables ISO to provide flexible decisions in meeting sys-
tem uncertainties in real-time dispatch.

2) This article introduces a novel network-constrained
market-clearing model of joint energy and flexible ramp-
ing reserve in integrated heat- and power-based energy
environment. The impact analysis of FOR of the cogener-
ation units on the participation of such units in energy and
flexible ramping reserve market and operation cost of the
system is performed.

3) The uncertainties associated with system heat and power
load demands and power production of the wind turbines
are studied in the proposed model employing stochastic
programming and the IGDT approach to achieve an almost
realistic market environment. Accordingly, the proposed
model takes the advantages of increasing the flexibility and
reliability of the market clearing operation in real-time dis-
patch when system encounters with different uncertainty
scenarios.

The remainder of this article is organized as follows. The
problem formulation of the proposed network-constrained joint
energy and flexible ramping reserve market clearing model is
provided in Section II. The application of hybrid approach in
the NCUC problem is provided in Section III. Section IV introduces
the case study, the obtained results, and the associated analysis.
Finally, Section V concludes this article.

II. PROBLEM FORMULATION

The proposed two-stage hybrid IGDT–stochastic NCUC
model clears energy and flexible ramping reserve market simulta-
neously in energy systems containing combined heat and
power, thermal units, and wind turbines. The objective of the
proposed model is hourly scheduling of generation units and
flexible ramping reserve to minimize the operation cost of
system. Uncertainties of wind power generation and heat and
electricity demands are taken into account in the proposed
model. First, the two-stage stochastic problem is considered
studying the heat and electricity demands uncertainty. Then,
the IGDT will be adapted for dealing with uncertainty of wind
power generation in Section III. Finally, the two-stage hybrid
IGDT–stochastic model is presented. This section provides the
objective function and constraints of the proposed model.

A. Proposed Stochastic NCUC Problem

The proposed stochastic NCUC framework contains two
stages, which is formulated as (1), where the first stage includes
the cost of power generation, start-up-/down, and flexible ramp-
ing reserve. On the other hand, the second stage contains the
adjustment of power due to fluctuations of power and heat loads
in real-time dispatch, which is defined as different scenarios.
First, the stochastic programming is developed for the proposed
model, which will be updated in the following subsections
to implement the hybrid stochastic–IGDT concept. A mixed
integer nonlinear programming is considered for the proposed
model, which includes the power generation cost of thermal and
Fig. 2. FOR of the CHP plant.

CHP units and flexible ramping reserve cost for such plants

\[ \begin{aligned}
OF_f &= \min \sum_{t=1}^{NT} \sum_{i \in NG} \left[ F_i^c(P_{i,t}) + SU_{i,t} + SD_{i,t} \right] \\
&+ \sum_{t=1}^{NT} \sum_{i \in NC} \left[ F_i^c(P_{i,t}, H_{i,t}) + SU_{i,t} + SD_{i,t} \right] \\
&+ \sum_{i=1}^{NT} \sum_{s=1}^{NS} \left[ \sum_{i \in NG} \left( F_i^c(\Delta P_{i,t,s}) - F_i^c(\Delta P_{i,t,s}^D) \right) \right] \\
&+ \sum_{i \in NC} \left( F_i^c(\Delta P_{i,t,s}^D) \right).
\end{aligned} \]  

(1)

B. Equality and Inequality Constraints of Generation Units

The thermal and CHP plants offer upward and downward flexible ramping reserves based on their rampup and rampdown capability, which are scheduled by ISO considering the fluctuations in real-time dispatch. Accordingly, the following equations are stated including the power adjustment in the second stage:

\[ \begin{aligned}
0 &\leq FRU_{i,t} \leq R_{i,up}^{FRU} & (2a) \\
0 &\leq FRU_{i,t} + \Delta P_{i,t,s}^U \leq R_{i,up}^{FRU} & (2b) \\
0 &\leq FRD_{i,t} \leq R_{i,down}^{FRD} & (3a) \\
0 &\leq FRD_{i,t} + \Delta P_{i,t,s}^D \leq R_{i,down}^{FRD} & (3b).
\end{aligned} \]

The energy and flexible ramping reserve offered by the thermal and CHP plants should be limited to the lower and upper bounds in first and second stages as follows:

\[ \begin{aligned}
P_{i,t} + FRU_{i,t} &\leq \max P_{i,t} & (4a) \\
P_{i,t} + \Delta P_{i,t,s}^U + FRU_{i,t} &\leq \max P_{i,t} & (4b) \\
P_{i,t} - FRD_{i,t} &\geq \min P_{i,t} & (5a) \\
P_{i,t} - \Delta P_{i,t,s}^D - FRD_{i,t} &\geq \min P_{i,t}. & (5b)
\end{aligned} \]

The power and heat generated by CHP plants have mutual dependence, which is called FOR. The FOR of the CHP type considered in this article is shown in Fig. 2, which can be formulated in the first stage and the second stage as follows:

\[ \begin{aligned}
P_{CHP,t} + FRU_{CHP,t} - PA_{CHP} &
- \frac{P_{CHP}^A - P_{CHP}^B}{H_{CHP}^A - H_{CHP}^B} (H_{CHP,t} - H_{CHP}^A) \leq 0 & (6a) \\
P_{CHP,t} + \Delta P_{CHP,t,s}^U + FRU_{CHP,t} - PA_{CHP} &
- \frac{P_{CHP}^A - P_{CHP}^B}{H_{CHP}^A - H_{CHP}^B} (H_{CHP,t} + \Delta H_{CHP,t,s}^U - H_{CHP}^A) \leq 0.
\end{aligned} \]

(6b)

\[ \begin{aligned}
P_{CHP,t} - FRD_{CHP,t} - PD_{CHP} &
- \frac{PD_{CHP}^C}{H_{CHP}^C - H_{CHP}^D} (H_{CHP,t} - H_{CHP}^D) \geq -(1 - V_{CHP,t}) M & (7a) \\
P_{CHP,t} - \Delta P_{CHP,t,s}^D - FRD_{CHP,t} - PD_{CHP} &
- \frac{PD_{CHP}^C}{H_{CHP}^C - H_{CHP}^D} (H_{CHP,t} - \Delta H_{CHP,t,s}^D - H_{CHP}^D) \geq -(1 - V_{CHP,t}) M & (7b)
\end{aligned} \]

(8a)

\[ \begin{aligned}
P_{CHP,t} - FRD_{CHP,t} - PD_{CHP} &
- \frac{PD_{CHP}^C}{H_{CHP}^C - H_{CHP}^D} (H_{CHP,t} - H_{CHP}^D) \geq -(1 - V_{CHP,t}) M & (8b)
\end{aligned} \]

C. Network Constraints

Power balance of the electrical energy network should be considered to provide the load demand by the generated power of thermal units, CHP plants, and wind power production considering the power flow between the system buses. The power load balance and power flow between system nodes as well as limitation of limitations of power flow in the first and second stages can be provided as follows:

\[ \begin{aligned}
\sum_{i=1}^{N_U} P_{i,t} + \sum_{r=1}^{N_W} P_{r,t} - \sum_{j=1}^{N_J} D_{j,t} = \sum_{L=1}^{N_L} PF_{L,t}^0 & (10a) \\
\sum_{i=1}^{N_U} \left( P_{i,t} + \Delta P_{i,t,s}^U - \Delta P_{i,t,s}^D \right) & (10b)
\end{aligned} \]

\[ \begin{aligned}
P_{F_{L,t}}^0 = \frac{\delta_{0,t} - \delta_{0,t}^L}{x_L} & (11a)
\end{aligned} \]
\[
PF_{l,t,s} = \frac{\delta_{b,t,s} - \delta_{b',t,s}}{x_L}
\]
\[
P_F^{\text{max} L} \leq P_F^0 L \leq P_F^{\text{max} L}
\]

The needed upward/downward flexible ramping of the system at each time interval should be satisfied by
\[
\sum_{i=1}^{NU} \text{FRU}_{i,t} \geq \text{RFRU}_t
\]
\[
\sum_{i=1}^{NU} \text{FRD}_{i,t} \geq \text{RFRD}_t.
\]

It is assumed that the ISO has introduced a ramp prediction tool for determining the value of needed upward/downward flexible ramping of the system for following the variation of net load in the real-time dispatch stage.

The heat balance of the network verifies the balance between heat generation of the CHP plants and heat load of the network considering the uncertainty associated with heat load in the second stage of the proposed model.

\[
\sum_{i=1}^{NC} H_{i,t} = \sum_{q=1}^{NQ} H_{D,q,t}
\]
\[
\sum_{i=1}^{NC} (H_{i,t} + \Delta H_{i,t,s} - \Delta H_{i,t,s}) = \sum_{q=1}^{NQ} H_{D,q,t,s}.
\]

It should be noted that the minimum up-time and down-time limitations and rampup and rampdown rate equations are also considered in this article, which are presented in [21] and [22] by details.

III. A PPLICATION OF HYBRID IGDT–STOCHASTIC ON THE NCUC PROBLEM

In this article, the stochastic and IGDT models are developed for handling uncertainties associated with wind power productions and heat and power load demands.

A. IGDT Principles

The IGDT model does not require extra information, such as a probability distribution function or fuzzy membership set of uncertain parameters. Such model obtains an optimal solution with high accuracy and practicality level unlike the stochastic modeling concept [23], [24], which determines the output variables dependent on the stochastic scenarios. The mathematical definition of uncertain parameters set can be stated by
\[
U = U(\Psi, \alpha) = \left\{ \Psi : \frac{\Psi - \bar{\Psi}}{\Psi} \leq \alpha \right\}
\]

where \(\bar{\Psi}\) is the forecasted value of the uncertain parameter \(\Psi\). Moreover, \(\alpha\) is the maximum deviation of the uncertain parameter from the forecasted value, which is defined as uncertain unknown radius for the decision maker. An optimization problem under the IGDT technique can be formulated as a bilevel optimization problem by (17) and (18), which describe two strategies of RA and RS, respectively.

\[
\alpha_r = \max \left\{ \alpha : \left( \frac{\max_{\Psi \in U(\Psi, \alpha)} OF_C \leq \Delta_C = (1 + \beta_r)OF_b} \right) \right\}
\]
\[
\alpha_o = \min \left\{ \alpha : \left( \frac{\min_{\Psi \in U(\Psi, \alpha)} OF_o \leq \Delta_o = (1 - \beta_o)OF_b} \right) \right\}
\]

where \(\Delta_C\) and \(\Delta_o\) are the satisfactory values of the objective function depending on \(\beta_r\) and \(\beta_o\), respectively, which are obtained by the decision maker. \(\beta_r\) is the robustness level against the increment of the objective function concerning the basic condition value. \(\beta_o\) is the opportuneness level against the decrease in the objective function with respect to the basic condition value.

B. Hybrid IGDT–Stochastic Model

The proposed hybrid IGDT–stochastic NCUC model clears the joint energy and flexible ramping reserve market of CHP-based energy systems dealing with the uncertainties associated with electric and heat load demands and wind power generation using stochastic programming and IGDT, respectively. A simplified structure for the proposed hybrid IGDT-stochastic NCUC scheme is demonstrated in Fig. 3.
The NCUC problem for energy and flexible ramping reserve market clearing model based on the two-stage hybrid IGDT- stochastic concept can be formulated using RA and RS strategies. In the RS strategy, the uncertain parameter has an unfavorable effect on the objective function. As a result, the system operator estimates a higher cost due to the undesirable variations of wind power. Since only a reduction in wind power generation has a desired effect on the objective function, the proposed model can be stated as a single-level problem, which is shown as follows:

\[ \alpha_c = \max \alpha \]

\[
\sum_{i=1}^{NU_i} \left( P_{i,t} + \Delta P^U_{i,t,s} - \Delta P^D_{i,t,s} \right) + \sum_{r=1}^{N_M} P^f_{r,t}(1 - \alpha) 
- \sum_{j=1}^{NJ} D_{j,t,s} = \sum_{j=1}^{NJ} PF_{r,t,s} 
\]

\[ OF_c = \sum_{i=1}^{NT} \sum_{i \in iNG} \left[ F^c_i(P_{i,t}) + SU_{i,t} + SD_{i,t} \right] C^{DRU}_{i,t} + C^{FRD}_{i,t} 
+ \sum_{i=1}^{NT} \sum_{i \in iNC} \left[ F^c_i(P_{i,t}, H_{i,t}) + SU_{i,t} + SD_{i,t} \right] C^{DRU}_{i,t} + C^{FRD}_{i,t} 
+ \sum_{i=1}^{NT} \sum_{i \in iNS} \sum_{s=1}^{\pi_s} \left[ F^c_i(\Delta P^U_{i,t,s}, \Delta P^D_{i,t,s}) \right] \right]
\]

\[ OF_c \leq (1 + \beta_r) OF_b \]

\[ 0 \leq \beta_r \leq 1 \]

Equations (2)–(10a), (11a)–(15b).

The RS strategy aims to increase the chance of positive effect of uncertain parameter on the objective function. In this strategy, the uncertainty of wind power generation is the desired event. Since only an increase in wind power generation has a desired effect on the objective function, the proposed model can be defined as a single-level problem, which is shown as follows:

\[ \alpha_o = \min \alpha \]

\[
\sum_{i=1}^{NU_i} \left( P_{i,t} + \Delta P^U_{i,t,s} - \Delta P^D_{i,t,s} \right) + \sum_{r=1}^{N_M} P^f_{r,t}(1 + \alpha) 
- \sum_{j=1}^{NJ} D_{j,t,s} = \sum_{j=1}^{NJ} PF_{r,t,s} 
\]

\[ OF_c = \sum_{i=1}^{NT} \sum_{i \in iNG} \left[ F^c_i(P_{i,t}) + SU_{i,t} + SD_{i,t} \right] C^{DRU}_{i,t} + C^{FRD}_{i,t} 
+ \sum_{i=1}^{NT} \sum_{i \in iNC} \left[ F^c_i(P_{i,t}, H_{i,t}) + SU_{i,t} + SD_{i,t} \right] C^{DRU}_{i,t} + C^{FRD}_{i,t} 
+ \sum_{i=1}^{NT} \sum_{i \in iNS} \sum_{s=1}^{\pi_s} \left[ F^c_i(\Delta P^U_{i,t,s}, \Delta P^D_{i,t,s}) \right] \right]
\]

\[ OF_c \leq (1 - \beta_o) OF_b \]

\[ 0 \leq \beta_o \leq 1 \]

Equations (2)–(10a), (11a)–(15b).

### IV. CASE STUDY AND SIMULATION RESULTS

The proposed model has been implemented on a case study in order to evaluate the performance of the model. The studied test system is shown in Fig. 4, which is a six-bus system, including a CHP unit, two thermal plants, and a wind power generation unit. The power load demands are connected to buses 3, 4, and 5, and the heat load demand is connected to the CHP unit. The cost coefficients of the CHP unit and thermal plants are provided in Table II. The characteristics of FOR of the CHP unit, which is shown in Fig. 2, are adopted from [10] and scaled for achieving a 205-MW CHP unit. In addition, Table III includes technical characteristics of the generation units. The required up-/downward flexible ramping reserve for each time interval is adopted from [6]. The offer for up-/downward flexible ramping reserve cost of the CHP and thermal units considered as 20% of the first-order cost coefficient of each unit [6]. The forecasted energy demands and wind power production are shown in Fig. 5. The parameters of transmission lines are adopted from [25]. Two
Fig. 5. Forecasted energy demand and wind power.

Fig. 6. Flexible ramping reserve of generation units in case 1.

Fig. 7. Power generation scheduling of the plants with and without FRPs in case 1.

cases are considered in order to verify the high performance of the proposed model. The running time for all two cases is 8.4 and 11.9 s, respectively. The two studied cases are as follows.

A. Case 1

In this case, the FRPs have been investigated in the proposed two-stage stochastic NCUC problem. The uncertainties of electric and heat loads have been considered in the proposed two-stage NCUC problem. The forecasted error of the electric and heat loads follows a normal distribution function with a 10% standard deviation. The MCS has been developed for generating 1000 scenarios. The number of generated scenarios has been decreased to five suitable scenarios utilizing the fast-backward method in GAMS/SCENRED [26]. The scheduling of flexible ramping reserve by the generation units have been demonstrated in Fig. 6. As can be seen in this figure, the whole upward ramping is provided by CHP unit between \( t = 1 \) and \( t = 15 \). On the other hand, a part of upward ramping is supplied by expensive thermal unit G1 between \( t = 13 \) and \( t = 19 \) due to the FOR of the CHP plant, which results to the increment of the daily operation cost of the system. In addition, total upward ramping is supplied by the CHP unit between \( t = 20 \) and \( t = 24 \) by decrement of system electric load.

Fig. 7 shows the effect of consideration of FRP on power generation scheduling of the plants. As can be seen in this figure, it is economical to assign a part of power dispatch of the CHP unit to upward ramp by decreasing the power generation of this unit, which causes an increment in power generation of G1. Increasing the power generation of G1 due to consideration of FRPs results in the higher operation cost. The operation cost without FRPs is obtained as $115,991.88, whereas the operation cost is equal to $119,990.99 with FRPs that shows a 3.4% increase in the daily operation cost with FRPs. Table IV describes the effect of consideration of FRPs on the served load in real-time dispatch due to variations of net load. It is assumed that the net load is increased by 15% in real-time dispatch. As can be seen, although considering flexible ramp products increases the operation cost of the day-ahead market, it leads to a decrease in load shedding in \( t = 9 \) and \( t = 10 \), which enhances the system’s
reliability. In fact, considering flexible ramp products, the G1 unit is participated in $t = 9$ and $t = 10$ to increase the flexibility of the CHP unit to provide FRPs for handling net-load variabilities in real-time dispatch.

Figs. 8 and 9 depict the effect of variations of the heat load on hourly dispatch and upward ramping provided by the CHP and G1 units. As it is evident, increasing the heat load by 40% results in the lower power production of the CHP plant, which is related to the FOR limitation of the CHP unit. Accordingly, the sum of power generated and upward ramping of the CHP plant has been decreased in 1.4 heat load, which is effective in increasing the power generation and upward ramping of G1. The effect of heat load variations on the system operation cost is provided in Table V. As can be seen in this table, the increment of the heat load caused to higher operation cost of the non-CHP units is due to the mutual dependence of the power and heat networks.

<table>
<thead>
<tr>
<th>Operation cost of non-CHP units ($\text{S}$)</th>
<th>60%</th>
<th>100%</th>
<th>140%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP ($\geq 140%$)</td>
<td>21928.564</td>
<td>24901.57</td>
<td>25707.432</td>
</tr>
<tr>
<td>G1 ($\leq 60%$)</td>
<td>22825.564</td>
<td>24901.57</td>
<td>25707.432</td>
</tr>
<tr>
<td>G1 ($\leq 140%$)</td>
<td>22825.564</td>
<td>24901.57</td>
<td>25707.432</td>
</tr>
<tr>
<td>CHP ($\leq 60%$)</td>
<td>22825.564</td>
<td>24901.57</td>
<td>25707.432</td>
</tr>
</tbody>
</table>

B. Case 2

In this case, the proposed hybrid stochastic–IGDT model has been analyzed for modeling the uncertainty of wind power generation and heat and power loads. The robustness parameter $\beta_r$ has been increased from 0 to 0.04 by 0.01 step in order to evaluate different strategies of RA operation. The basic operation cost $OF_b$ has been considered as the operation cost in case 1 as $119990.99$. Fig. 10 demonstrates the optimal robustness function $\alpha$ versus the robustness parameter $\beta_r$. As seen in this figure, the critical operation cost $\alpha$ is increased by increasing $\beta_r$, which means that ISO considers a vast range of the error forecasts of wind power generation in real-time dispatch (i.e., second stage of the proposed model).

The effect of $\beta_r$ on the wind power generation under RA strategy is depicted in Fig. 11. As can be seen, by increasing $\beta_r$, the generated wind power reduces, which leads to an increase in power generation of thermal units and the daily operation cost. The critical operation cost for $\beta_r = 0.01$ and $\beta_r = 0.04$ is equal to $121190.9$ and $124790.63$, respectively, which defines that ISO decides on a more robust strategy against the forecast error of wind power generation in real-time dispatch for $\beta_r = 0.04$. In fact, in this strategy, ISO reduces the effect of wind power uncertainty on unbalancing generation and consumption in the real-time dispatch by increasing the day-ahead operation cost. Such unbalance can result in power market price spike or disrupting the reliability of the system in real-time. The robust power production of CHP and G1 for different robustness parameters is shown in Fig. 12. As can be seen in this figure, the power
This article introduced a network-constrained market clearing of joint energy and flexible ramping reserve for integrated heat and power systems. A novel two-stage hybrid IGDT–stochastic NCUC for the introduced market clearing was presented considering uncertainties of heat and power demands and wind power generation, which were handled using the MCS method and IGDT, respectively. The proposed model considered both RS and RA strategies enabling ISO to provide flexible decision versus uncertainties in real-time dispatch. The effect of consideration of FRPs in day-ahead market on production scheduling of the plants and operation cost of the system was investigated. In addition, the effect of FOR of the CHP units on their cooperation in energy and flexible ramping reserve markets and system operation cost was analyzed. The simulation results demonstrated the following points.

1) Although considering FRPs led to an increment in operation cost of the day-ahead market by 3.4%, but it had a positive impact on reliability improvement by decreasing the load shedding in the real-time dispatch by 100%.

2) The power and flexible ramping reserve provided by the CHP unit was a function of heat load variations, so that, by increasing heat load, the power and reserve provided by the CHP unit were decreased by 0.8% and 3.9%, respectively.

3) The introduced hybrid approach facilitated the system operator to take benefit of both stochastic and IGDT methods, simultaneously.

V. Conclusion

This article introduced a network-constrained market clearing of joint energy and flexible ramping reserve for integrated heat and power systems. A novel two-stage hybrid IGDT–stochastic NCUC for the introduced market clearing was presented considering uncertainties of heat and power demands and wind power generation, which were handled using the MCS method and IGDT, respectively. The proposed model considered both RS and RA strategies enabling ISO to provide flexible decision versus uncertainties in real-time dispatch. The effect of consideration of FRPs in day-ahead market on production scheduling of the plants and operation cost of the system was investigated. In addition, the effect of FOR of the CHP units on their cooperation in energy and flexible ramping reserve markets and system operation cost was analyzed. The simulation results demonstrated the following points.

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REFERENCES


