Decentralized Coordinated Dispatch of Multi-microgrid Integrated Energy System Considering Source-Load Uncertainty

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Abstract. Multiple microgrids are connected to the regional electric power distribution system (EPS) and natural gas distribution system (NGS) to form a multi-microgrid integrated energy system (MMIES), where each stakeholder’s game behaviour and renewable energy uncertainty increase the complexity of dispatch decisions. In view of this, a decentralized coordinated dispatch model of MMIES considering source-load uncertainty is proposed in this paper. Firstly, based on fuzzy theory, the forecasts of wind/PV output and system load are described by fuzzy parameters, and consequently fuzzy chance constraints based on credibility theory are established. Secondly, for multi-stakeholders including EPS, NGS, and microgrid operator which consists of multiple microgrids, a decentralized dispatch model is established with the goal of maximizing each stakeholder’s interest considering network security constraints. Then, the fuzzy chance constraints are turned into their clear equivalent forms based on trapezoidal membership parameters, and the analytical target cascading algorithm is designed to decouple the coordination variables and solve the decentralized dispatch model collaboratively. Finally, an example of MMIES is carried out to verify the feasibility and effectiveness of the proposed method. Simulation results show that the method considers the source-load uncertainty and each stakeholder’s interest and realizes the reliable and economic optimal operation of MMIES.

1. Introduction
With the development of economy and society, multiple microgrids (MGs) in the same area are interconnected and integrated into the higher-level distribution network (DN) to form a multi-microgrid integrated energy system (MMIES). The interest game between different stakeholders and the uncertainty of renewable energy will have a greater impact on the optimal operation of MG and the safe and economic dispatch of DN [1]. Therefore, it is urgent to study the optimal dispatch strategy of MMIES.

At present, there have been literature studying the economic dispatch of MG [2-4]. In Ref. [2], linearization technology was applied to deal with non-linear terms, and a mixed integer linear programming (MILP) method for MG energy optimization was proposed. In Refs. [3, 4], the influence of electric power interaction between MGs on the economic dispatch of multi-microgrid system was studied. But the above literature does not involve DNs. In fact, DN and MG are subordinate to different stakeholders, and the interest and the operation security of DN will affect the actual dispatch decision of MMIES. For the collaborative optimal dispatch of different stakeholders, the decentralized coordinated dispatch model can be established. And analytical target cascading (ATC) is often used as
a decomposition and coordination algorithm for such problems because of its flexibility, easy selection of parameters, and strict theoretical proof of convergence [5]. For example, in Ref. [6] the electric power distribution system (EPS) and the multi-MGs were regarded as one stakeholder, respectively, and the power along the EPS-MG tie line was decoupled based on ATC to achieve independent parallel solution of the two.

The above analysis reveals the following two issues that need further research: (1) the decentralized coordinated dispatch of MMIES less considers the power interaction between MGs and the security constraints of DN; (2) stakeholders considered in the decentralized coordinated dispatch of MMIES are not comprehensive, and the interest of the natural gas distribution system (NGS) are not involved. Besides, due to the increasing penetration of renewable energy sources such as wind and PV in MGs, the uncertainty of their output forecasts will have a greater impact on the model calculation [7]. Therefore, it is necessary to analyse the uncertainty of forecasts of wind/PV output and system load.

In view of the above problems, this paper proposes a decentralized coordinated dispatch model of MMIES considering source-load uncertainty. This model uses fuzzy parameters to characterize the uncertainty of wind/PV output and system load, considers comprehensively the interests of multi-stakeholders, such as EPS, NGS and microgrid operator (MGO) that consists of multi-MGs, and the security constraints of DN, and achieves the independent modelling and the coordinated solution of each stakeholder based on the ATC algorithm. Finally, the feasibility and effectiveness of the method proposed in this paper is verified through the example simulation.

2. Multi-microgrid Integrated Energy System

2.1. Decentralized Coordinated Dispatch Framework and Mathematical Modelling

The decentralized coordinated dispatch framework of MMIES is shown as figure 1. EPS and NGS provide electric power (EP) and natural gas power (NGP) to each MG through EPS-MG and NGS-MG tie lines, respectively. While MGs are connected in series through electric power channels to form the MGO. EPS, NGS and MGO are subordinate to different stakeholders. Because there is no direct energy transaction between EPS and NGS, and the conflict of interests between the two is reflected in the competition for energy sales revenue; therefore, EPS and NGS are classified as the DN side, and MGO is on the MG side. The DN-side stakeholders pursue maximum sales revenue and optimize DN-MG interactive power while meeting security constraints of DN. Meanwhile, MGO aims to minimize the total cost and optimize the DN-MG and MG-MG interactive power and internal device output.

![Figure 1. Decentralized coordinated dispatch framework of MMIES.](image-url)

The MG structure is shown in the example system in Section 5. The main devices includes: wind turbine (WT), PV, micro-gas turbine (MT), waste heat boiler (WH), gas boiler (GB), electric chiller (EC), absorption chiller (AC), electric storage (ES), heat storage (HS) and gas storage (GS). Where, models of MT, WH, GB, EC and AC can be found in [3]; models of ES, HS, GS can be found in [8]; MT adopts the combined heat and power working mode, and its power generation efficiency is approximately a cubic function of the output electric power [3].
2.2. Source-Load Uncertainty Analysis

The forecasts of wind/PV output and load are uncertain. Existing forecasting methods will produce errors that are not statistical. Therefore, it is more reasonable to use fuzzy parameters to characterize wind/PV output and load [7]. Firstly, this paper converts the ambiguity of wind/PV output and load into the ambiguity of constraints, establishes fuzzy chance constraints based on credibility theory, and controls risk through the confidence level. And then, the fuzzy chance constraints are turned into their clear equivalent forms based on trapezoidal membership parameters, which can transform the original optimization problem with fuzzy parameters into a mixed integer programming problem and facilitate the solution. Relevant theories are detailed in Ref. [7]. Sections 3.2.4 and 3.2.5 below are their specific applications in this paper.

3. Decentralized Dispatch Model of MMIES Considering Source-Load Uncertainty

3.1. Distribution Network Side

The DN-side model is shown in equation (1), where security constraints of DN include power/flow balance constraints, node voltage/barometric pressure constraints, and branch capacity constraints. See Ref. [9] for details. The steady-state power flow calculation of EPS and NGS adopt the forward-backward sweep method and the Newton-node method, respectively.

\[
\begin{align*}
\max F_\psi = & \sum_{t=1}^{T} \sum_{\psi} c_\psi P_{t,\psi}^{\psi,i} \\
\text{s.t.} & P_{t,\psi}^{\psi,i} \leq P_{t,\psi}^{\psi,i} \leq P_{t,\psi}^{\psi,i} \text{ & security constraints of DN}
\end{align*}
\]

where: \( F_\psi \) – energy sales revenue of DN \( \psi \) to MG in dispatch period \( T \), \( \psi \in \{ \text{EPS,NGS} \} \). \( m \) – number of MGs connected to DN \( \psi \). \( P_{t,\psi}^{\psi,i} \) – interactive power between DN \( \psi \) and MG \( i \) at time \( t \), where for EPS, the positive value indicates EPS sells electricity, while the negative value means EPS purchases electricity, and NGS does not consider buying gas from MGs. \( c_\psi \) – price of DN-MG interactive power.

3.2. Microgrid Side

The MG-side model is shown in equation (2). The objective function is the minimum total cost of all MGs \( F_{MGO} \), including operation-maintenance costs \( F_{om} \), DN-MG interaction costs \( F_{int} \), MG-MG interaction costs \( F_{ch} \), and carbon emissions costs \( F_{ec} \), where \( F_{ch} \) ignores the energy transmission loss between MGs (because the distance between MGs is short). Constraints are mainly credibility-based fuzzy chance constraints (CFCCs) of the system and other conventional constraints. The former is shown in Section 3.2.1. The latter includes energy conversion device constraints, fuel unit climbing constraints, energy storage constraints, wind/PV output constraints, DN-MG interactive power constraints, and MG-MG interactive power constraints, which are detailed in Refs. [4, 6, 8].

\[
\begin{align*}
\min F_{MGO} = & F_{om} + F_{int} + F_{ch} + F_{ec} \\
= & \sum_{t=1}^{T} \sum_{i=1}^{m} \lambda_\psi P_{t,\psi}^{\psi,i} + \sum_{\psi} F_\psi + \sum_{t=1}^{T} \sum_{i=1}^{m} k_\psi P_{t,\psi}^{\psi,i} + e \cdot \sum_{t=1}^{T} \sum_{i=1}^{m} \sum_{\psi} \beta_\psi P_{t,\psi}^{\psi,i} \\
\text{s.t.} & \text{credibility-based fuzzy chance constraints & Others}
\end{align*}
\]

where: \( P_{t,\psi}^{\psi,i} \) – output power of device \( \theta \) in MG \( i \) at time \( t \). \( \lambda_\psi \) – operation-maintenance cost of device \( \theta \) per unit power at time \( t \), \( \theta \in \{ \text{WT, PV, MT, WH, GB, AC, EC, ES, HS, GS} \} \). \( k_\psi \) – price of MG-MG interactive electric power. \( P_{t,\psi}^{\psi,i} \) – total amount of interactive electric power between MG \( i \) and its
associated MGs at time \( t \). \( \beta_\psi \) – equivalent emission coefficient of power purchased by MG from DN \( \psi \). \( c \) – processing cost per kg of CO2.

3.2.1. Credibility-Based Fuzzy Chance Constraints of the System. The CFCCs of the system include the CFCCs of the system power balance and those of the system spare capacity. The former is shown as equation (3)-(6). As for the latter, the energy of MGO all comes from EPS and NGS, so the latter CFCCs only need to consider electricity spare and natural gas spare. That is, replace \( P_{\text{EPS},i} \) in equation (3) and \( P_{\text{NGS},i} \) in equation (6) with its upper limit, respectively, and replace ‘\( \leq 0 \)’ in \( \{ \} \) of equation (3)-(6) with ‘\( \leq 0 \)’. Note that the uncertainty of forecasts of wind/PV output and load has been considered in CFCCs, so there is no need to assume the system spare capacity additionally.

\[
\begin{align*}
\text{Cr} \left\{ \tilde{L}_{e,j} - \sum_{\psi} \tilde{P}_{\text{MT},j}^{\psi,i} - P_{\text{ES},j}^{\psi,i} - P_{\text{EPS},i} - P_{\text{NGS},i}^{\psi,i} + P_{\text{EC},i} = 0 \right\} \geq \alpha \\
\text{Cr} \left\{ \tilde{L}_{e,j} - \lambda^{\text{EC}} P_{\text{EC},i}^{\psi,i} - \lambda^{\text{AC}} P_{\text{AC},i}^{\psi,i} = 0 \right\} \geq \alpha \\
\text{Cr} \left\{ \tilde{L}_{h,j} - \eta^{\text{GB}} P_{\text{GB},j}^{\psi,i} - P_{\text{WH},i} - \eta^{\text{MT}} (1 - \eta^{\text{MT}}) P_{\text{MT},i}^{\psi,i} (\eta^{\text{MT}})^{-1} + P_{\text{AC},i}^{\psi,i} = 0 \right\} \geq \alpha \\
\text{Cr} \left\{ \tilde{L}_{g,j} - P_{\text{GS},i}^{\psi,i} - P_{\text{NGS},i}^{\psi,i} + P_{\text{MT},i}^{\psi,i} (\eta^{\text{MT}})^{-1} + P_{\text{GB},j}^{\psi,i} = 0 \right\} \geq \alpha 
\end{align*}
\]

where: \( \alpha \) – confidence level. \( \text{Cr} \{ \} \) – credibility of events in \( \{ \} \). superscript \( i \) – MGi. subscript \( t \) – time \( t \). \( \tilde{L}_{e,j} \), \( \tilde{L}_{h,j} \), \( \tilde{L}_{g,j} \) – fuzzy parameters of electric, cold, heat and gas load; taking \( \tilde{L}_{e,j} \) as an example, its quadruple is represented as \( (L_{e,j}^{1}, L_{e,j}^{2}, L_{e,j}^{3}, L_{e,j}^{4}) \). \( \tilde{P}_{\text{MT},j}^{\psi,i} \) – fuzzy parameters of wind/PV output \( (P_{i1}^{\psi,i}, P_{i2}^{\psi,i}, P_{i3}^{\psi,i}, P_{i4}^{\psi,i}) \). \( P_{\text{MT},i}^{\psi,i} \) – output electric power of MT. \( P_{\text{ES},j}^{\psi,i}, P_{\text{WH},i}, P_{\text{GS},i}^{\psi,i} \) – power of ES, HS and GS, where the positive value indicates discharging, while the negative indicates charging. \( P_{\text{EC},i}^{\psi,i}, P_{\text{AC},i}^{\psi,i}, P_{\text{GB},j}^{\psi,i} \) – input power of EC, AC and GB. \( \eta^{\text{MT}}, \eta^{\text{WH}}, \eta^{\text{GB}}, \lambda^{\text{EC}}, \lambda^{\text{AC}} \) – the power generation efficiency and the heat loss coefficient of MT. \( \eta^{\text{WH}}, \eta^{\text{GB}}, \lambda^{\text{EC}}, \lambda^{\text{AC}} \) – energy conversion efficiency/energy-efficiency ratio of WH, GB, EC and AC.

3.2.2. Solution to Credibility-Based Fuzzy Chance Constraints of the System. The CFCCs of the system are turned into their clear equivalent forms by means in [7]. Taking equation (3) as an example, its clear equivalent form is shown as equation (7). Other CFCCs’ clear equivalent forms can be obtained by analogy and are omitted here.

\[
(2 - 2\alpha) \left[ L_{e,j}^{1} - \sum_{\psi} P_{i1}^{\psi,i} \right] + (2\alpha - 1) \left[ L_{e,j}^{3} - \sum_{\psi} P_{i3}^{\psi,i} \right] - P_{\text{MT},i}^{\psi,i} - P_{\text{ES},j}^{\psi,i} - P_{\text{EPS},i}^{\psi,i} - P_{\text{EC},i}^{\psi,i} = 0
\]

4. Decentralized Coordinated Dispatch Solution Method Based on ATC

4.1. Analytical Target Cascading Algorithm
In this paper, ATC algorithm is applied to achieve decentralized coordinated dispatch of MMIES. Firstly, the coordination variables between different stakeholders, namely \( P_{\text{MT},i}^{\psi,i} \) which indicates the EPS-MG interactive electric power and the NGS-MG interactive natural gas power specifically, are decoupled into a pair of virtual load and virtual power supply, respectively. Then the original main problem of optimal dispatch is constructed as a two-level sub-problem. And the penalty function, whose coefficient is abbreviated as PFC, is introduced into the objective function of each level of the sub-problem model to achieve the coordination between the upper and lower levels. Finally, the
optimal solution is obtained by repeated iterations between the two levels. The solution process is shown in figure 2. The convergence of the ATC algorithm has been strictly theoretically proven in [5] and will not be repeated here. In this paper, the convergence criterion is set as follows: (1) At the $k^{th}$ iteration, the difference between the virtual load of DN and the virtual power supply of MG should meet the accuracy requirements; (2) the overall benefit of the system should be optimal.

![Figure 2. ATC-based solution process of decentralized coordinated dispatch.](image)

4.2. Model Linearization

Since the model of MT is nonlinear, the decentralized coordinated dispatch of MMIES mentioned above belongs to the mixed integer nonlinear programming (MINLP) problem. Using the method in [2] to deal with the nonlinear terms, the MINLP problem is transformed into a MILP problem, so that Yalmip is used to call the solver Gurobi to solve easily.

5. Case Analysis

5.1. Illustration of the Example System

In this paper, a multi-MG system [4] in Tianjin is used for reference and appropriately modified to form the example system as shown in figure 3, which includes IEEE33-node EPS, 11-node low-pressure NGS, and three MGs. Note that the dotted line in figure 3 indicates the electric power channel between MGs, which is not connected to the EPS-MG tie line. The simulation parameters are set as follows: the relevant parameters of DN come from Ref. [9]; the efficiency and operation-maintenance cost of devices in MG come from Ref. [8]; the parameters of trapezoidal membership come from Ref. [7]; the wind/PV output forecasts, system load forecasts, and other relevant parameters come from Ref. [4]. The energy transaction prices are set as follows: 1) the price of NGS-MG interactive gas is ¥2.2/m$^3$; 2) the price of EPS-MG interactive electricity and that of MG-MG interactive electricity come from [4], where the price of electricity sold by MG to EPS is lower than that purchased by MG from EPS [4], which is to protect EPS interest. Note that to protect interests of DN-side stakeholders, the prices of energy purchased by EPS and NGS from the upper energy provider must be lower than those of energy sold to MG, which is set to ¥0.35/(kW·h) and ¥1.2/m$^3$, respectively.

5.2. Construction and Analysis of Comparison Strategies

To verify the feasibility and effectiveness of the method proposed in this paper, the following two strategies are set for comparative analysis:

(1) Strategy 1: adopting the conventional centralized dispatch model of MMIES.

(2) Strategy 2: adopting the decentralized coordinated dispatch model of MMIES in this paper.

where: the model of strategy 1 aims at the overall optimal economy of MMIES without considering the differentiated interest of each stakeholder. The relevant parameters of ATC are detailed in Ref. [6].
The initial values of coordination variables are obtained from the independent optimal dispatch results of each MG. Set $\alpha=0.95$. The simulation results are as follows.

![Figure 3. Topology of the multi-microgrid integrated energy system.](image)

The total cost of EPS/NGS in table 1 consists of the purchase cost of EPS/NGS from grid/gas station and the sales revenue of EPS/NGS to MG. According to table 1, it can be found that from Strategy 1 to 2, the total cost of EPS decreases, while the total costs of NGS, MGO, and system all increase. This implies that the centralized dispatch model sacrifices the interest of EPS to optimize the overall interest of the system. While the decentralized coordinated dispatch model considers the interests of different stakeholders, making the three stakeholders achieve the cooperative optimal operation through interest game, which is more in line with the actual situation.

![Figure 4. MMIES spare capacity change at different confidence levels of Strategy 2.](image)

Table 1. Stakeholder interests of different strategies.

| Strategy | EPS sales revenue ($\times 10^4$ Yuan) | EPS total cost ($\times 10^4$ Yuan) | NGS sales revenue ($\times 10^4$ Yuan) | NGS total cost ($\times 10^4$ Yuan) | MGO total cost ($\times 10^4$ Yuan) | System total cost ($\times 10^4$ Yuan) |
|----------|--------------------------------------|------------------------------------|--------------------------------------|------------------------------------|------------------------------------|--------------------------------------|
| 1        | 1.0445                               | 0.6410                             | 2.6636                               | 2.6462                             | 4.2980                             | 7.5851                               |
| 2        | 1.2040                               | 0.5625                             | 2.5786                               | 2.6848                             | 4.3731                             | 7.6204                               |

| $\alpha$ | 0.65 | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 | 1.00 |
|----------|------|------|------|------|------|------|------|------|
| System total cost of Strategy 1 ($\times 10^4$ Yuan) | 7.2656 | 7.3191 | 7.3716 | 7.4241 | 7.4770 | 7.5306 | 7.5851 | 7.6376 |
| System total cost of Strategy 2 ($\times 10^4$ Yuan) | 7.2974 | 7.3475 | 7.4017 | 7.4562 | 7.5109 | 7.5657 | 7.6204 | 7.6753 |

5.3. Comparison of Dispatch Results at Different Confidence Levels

Table 2 and figure 4 show the comparison of the system cost and spare capacity at different confidence levels, which changes from 0.65 to 1.

Table 2. Comparison of the system cost at different confidence levels.

| $\alpha$ | 0.65 | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 | 1.00 |
|----------|------|------|------|------|------|------|------|------|
| System total cost of Strategy 1 ($\times 10^4$ Yuan) | 7.2656 | 7.3191 | 7.3716 | 7.4241 | 7.4770 | 7.5306 | 7.5851 | 7.6376 |
| System total cost of Strategy 2 ($\times 10^4$ Yuan) | 7.2974 | 7.3475 | 7.4017 | 7.4562 | 7.5109 | 7.5657 | 7.6204 | 7.6753 |
It can be seen from Table 2 and Figure 4 that the confidence level \( \alpha \) is negatively correlated with system economy and is positively correlated with system spare capacity. This is because the confidence level reflects the reliability of the electricity and natural gas supply of the MMIES. The larger the value of \( \alpha \) is, the more abundant the system spare capacity is, so the higher the system reliability is, and the greater the system cost is.

6. Conclusion
This paper proposes a decentralized coordinated dispatch method for MMIES considering source-load uncertainty. The simulation results of the example system show that:

1. The decentralized coordinated dispatch framework of MMIES and ATC-based solution process can effectively consider the interests of different stakeholders, and finally realize their cooperative optimal operation through the interest game between different stakeholders. Compared with the centralized dispatch, this method is less economical but more in line with the actual situation.

2. The confidence level \( \alpha \) is negatively correlated with system economy and is positively correlated with system spare capacity. Decision makers need to measure the value of \( \alpha \) according to the actual situation to balance the economy and reliability of the system.

Acknowledgements
The authors are grateful for the support of the National Natural Science Foundation of China (No. 51577068).

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