Collaborative Optimal Operation of AC/DC Hybrid Microgrid with High Proportion of Renewable Energy

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Abstract. Complexity of collaborative optimal dispatching and uncertainty of system are enhanced with the increase ratio of renewable energy in AC/DC hybrid microgrid. The prediction error of the output of renewable energy as a fuzzy variable is treated in this paper. Then a fuzzy chance constrained collaborative optimal model of AC/DC hybrid microgrid considering economy and flexibility is established. In view of the problems that both uncertain programming and mixed integer programming are contained in the model, where conventional algorithms have difficulty in solving it, the thought of fuzzy simulation into the neural network algorithm is introduced in this paper and the uncertainty of the source side by training the neuron to simulate the uncertainty is solved. Finally, the discrete binary particle swarm optimization to solve the integer programming is introduced. Based on the field data of a certain AC/DC hybrid microgrid demonstration project in Zhejiang Province, the effectiveness of the model and algorithm are verified.

1. Introduction
In the AC/DC hybrid microgrid, the access of a large amount of renewable energy represented by wind power generation and photovoltaic (PV) power generation brings obvious adverse effects to the stable operation of microgrid. Meanwhile, the complex topological structure and various operation modes of AC/DC microgrid put forward higher requirements for the theoretical research of collaborative optimal operation. Taking uncertainty into account is an effective measure to deal with the problem of intermittent output. The existing literature on the uncertainty of renewable energy output mainly focuses on the stochastic uncertainty of the prediction error of renewable energy, that is, the uncertainty factor is a random variable obeying a certain specific probability distribution. However, due to the ambiguity of meteorological forecast, the prediction error of renewable energy generation based on meteorological forecast does not obey these distributions obviously. Therefore, it is more realistic to select the prediction error as fuzzy variable. Aiming at the randomness of wind power generation, a stochastic dynamic economic dispatching model with wind farms considering generating unit combination based on the prediction of wind speed was established in literature\cite{1-2}. In \cite{3-4}, the optimal operation model of microgrid was established on the premise of considering the randomness and ambiguity of renewable energy output, but the loss cost of energy storage was not taken into account in the operating cost. This paper applies the theory of fuzzy chance programming to the day-
ahead optimal dispatching of the AC/DC hybrid microgrid with high proportion of renewable energy, which improved the accuracy of the dispatching scheme.

2. Fuzzy chance constrained optimal model

In the uncertainty theory, ambiguity is the uncertainty of the result caused by the inaccuracy of the research object state itself. Fuzzy chance constrained programming is similar to stochastic chance constrained programming [5]. Due to the existence of uncertain factors, the constraints are satisfied under certain confidence. Different from the stochastic chance constrained programming, the confidence level of the fuzzy chance constrained programming is described by the credibility \( C_r \), and the credibility should be no less than the level set by the decision maker. A typical model of fuzzy chance constrained programming is shown in equation (1).

\[
\begin{align*}
\max \bar{f} \\
\text{s.t.} \\
C_r \{ f(x, \xi) \geq \bar{f} \} \geq \beta \\
C_r \{ g_i(x, \xi) \leq 0 \} \geq \alpha
\end{align*}
\]  

(1)

Where, \( \alpha \) and \( \beta \) are the level of credibility given by the decision maker; \( \max \bar{f} \) is the optimistic value of the objective function \( \beta \); \( x \) is the decision vector; \( \xi \) is the fuzzy vector.

When the microgrid containing a high proportion of renewable energy is injected into the main network, it will bring obvious uncertainty to the stable operation of the main network. Distinguishing between the day-ahead electricity purchase-sale prices and the intraday is an effective measure to reduce the adverse effects on the microgrid. The specific price strategy is as follows: the intraday pool purchase price of unplanned surplus power of microgrid is lower than the day-ahead, and the intraday power purchase price of the unplanned deficit power of microgrid is higher than the day-ahead.

Obviously, in order to increase the operation economy and reduce the punishment caused by unplanned power adjustment, microgrid operators should strive to improve the accuracy of the optimal dispatching, and make reasonable start-stop plan of the unit and scheduling scheme under the premise of fully considering the prediction error of renewable energy. Considering the output uncertainty of wind power and PV power is an effective measure to improve dispatching accuracy.

3. Fuzzy collaborative optimal model of ac/dc hybrid microgrid with high proportion of renewable energy

Fig.1 shows the topology of the AC/DC hybrid microgrid constructed in this paper. It can be seen that the AC/DC hybrid microgrid can be mainly divided into three parts: AC zone, DC zone and AC/DC power interface. The microgrid with high proportion of renewable energy also brings some
challenges: microgrid needs to schedule and coordinate more equipment during operation, which puts higher requirement on the performance of the energy management system and increases the difficulty of the operation control of microgrid. In addition, under the high permeability of wind power penetration, flexibility becomes a key indicator of operating characteristics of the system, reflecting the adjustment ability of the grid to balance supply and demand and the ability to absorb renewable energy. Flexibility refers to the ability of the grid to configure resources to cope with changes in the payload. Therefore, a new method for optimizing the operation of AC/DC hybrid microgrid considering uncertainty and flexibility is urgently needed.

Operating Cost Model of AC/DC Hybrid Microgrid consists of five parts, which are the power purchase cost of the utility grid $C_G$, the operation model of MT $C_{MT}$, the composite cost model of energy storage $C_{ES}$, the loss cost of AC/DC power flow section $C_{loss}$ and the equipment maintenance cost $C_{om}$.

\[
C_G = \Delta T \sum_{i=1}^{T} p_G^i c_G^i
\]
\[
C_{MT} = \sum_{i=1}^{T} \left[ c_{MT} \Delta T \frac{p_{MT}}{LHV_{MT}} \right]
\]
\[
\eta_{MT} = a + b \frac{p_{MT}}{LHV_{MT}} + c \left( \frac{p_{MT}}{LHV_{MT}} \right)^2 + d \left( \frac{p_{MT}}{LHV_{MT}} \right)^3
\]
\[
C_{ES} = \Delta T \left( P_{ES}^t \sum_{i=1}^{T} \left( 1 - \eta_{ES} \eta_{ES}^t \right) c_E^t + \frac{C_{ES}}{Q_{ES}^t} \left( \eta_{ES}^t \right) \right)
\]
\[
C_{loss} = \Delta T \sum_{i=1}^{T} \left[ 1 - \eta \left( P_{PFC}^i \right) \right] P_{PFC}^i
\]
\[
\eta = 0.226 \beta^2 - 0.478 \beta^2 + 0.326 \beta + 0.908
\]
\[
\beta = \frac{P_{PFC}^i}{P_{PFC}^R}
\]
\[
C_{om} = \Delta T \sum_{i=1}^{T} \sum_{j=1}^{N} \left( K_j p_{DEA,i}^j \right)
\]

The power system evaluates flexibility based on a certain time scale, which is also the most difficult to quantify among its four characteristics. And the source side uncertainty and load side uncertainty have different effects on the microgrid flexibility.

This paper models the flexibility of microgrid scheduling mainly for the source side uncertainty. The penalty amount caused by abandoned wind power and PV power is as follows.

\[
C_{loss} = \Delta T \sum_{i=1}^{T} c_{\theta} \cdot \Delta P_{\theta,i}, \ \theta \in \{WT, PV\}
\]

Where $c_{\theta}$ is the unit penalty amount corresponding to the abandoned wind power and PV power. $\Delta P_{\theta,i}$ is the power of abandoned wind power and PV power at time $t$.

3.1. Objective Function

Combining the above models, the fuzzy chance constrained optimal model of composite costs of AC/DC hybrid microgrid can be constructed, as shown in equation (2).

\[
\min \left\{ \mathcal{C} \left[ C_G + C_{MT} + C_{ES}^+ \right] \geq \beta \right\}
\]

Where $C_G$ is the cost of the utility grid, $C_{MT}$ is the operation cost of MT, $C_{ES}$ is the composite cost of energy storage, $C_{loss}$ is the loss cost of AC/DC power flow section, $C_{om}$ is the equipment maintenance cost, $\beta$ is the penalty amount of abandoned wind power and PV power, $\mathcal{C}$ is the constraint probability.
Where $\beta$ is the credibility given by the decision maker in advance; $\bar{C}$ is the $\beta$ optimistic value of the composite operating cost;

And the constraints are as follow.

\[
\begin{align*}
\text{a.} & \quad C_r \left\{ P_{\text{MT}} + P_{\text{MT}} + P_{\text{titd}} = \sum_{i=1}^{l} P_{\text{PFC},i} + P_{\text{ACL}} + \frac{P_{\text{bus}}}{\theta_{\text{acl}}} \right\} \geq \alpha \\
\text{b.} & \quad C_r \left\{ P_{\text{ES}} + \sum_{i=1}^{l} P_{\text{PFC},i} + P_{\text{PV}} = P_{\text{ACL}} + \frac{P_{\text{bus}}}{\theta_{\text{acl}}} \right\} \geq \alpha \\
\text{c.} & \quad \left\{ \begin{array}{l}
S_{\text{acl}}^{+1} = S_{\text{acl}}^{-1} + \left( \mu_{\text{sh}} \eta_{\text{sh}} + \mu_{\text{dis}} \eta_{\text{dis}} \right) \frac{P_{\text{es}}}{\theta_{\text{sh}}} \Delta T \\
-\bar{P}_{\text{es}} \leq P_{\text{es}} \leq \bar{P}_{\text{es}} \\
S_{\text{min}}^{\text{soc}} \leq S_{\text{soc}} \leq S_{\text{max}}^{\text{soc}} \\
S_{\text{soc}}^{\text{initial}} = S_{\text{soc}}^{\text{end}} \\
\text{d.} & \quad \text{onoff} \left( t \right) P_{\text{MT}, \text{min}} \leq P_{\text{MT}} \leq \text{onoff} \left( t \right) P_{\text{MT}, \text{max}} \\
\text{e.} & \quad P_{\text{PFC}} \leq \bar{P}_{\text{PFC}} \\
\text{f.} & \quad \text{Pr}(Z \leq 0) = \text{Pr}(X \leq Y) = \text{Pr}(\sum_{i \in S} X_i \leq \sum_{i \in D} Y_i) \leq \theta \\
\end{array} \right. \\
\end{align*}
\]

4. Hybrid intelligent algorithm based on fuzzy simulation

Based on the above objective function and constraints, the fuzzy chance constrained optimal model [6] of AC/DC hybrid microgrid can be summarized in equation (6).

\[
\begin{align*}
\text{min} & \quad \bar{C} \\
\text{s.t.} & \quad C_r \left\{ \left( P_{\text{d}} , P_{\text{f}} \right) \right\} \leq \bar{C} \geq \beta \\
& \quad C_r \left\{ g \left( P_{\text{d}} , P_{\text{f}} \right) \leq 0 \right\} \geq \alpha
\end{align*}
\]

Where, $P_{\text{d}}$ is the decision variable and $P_{\text{f}}$ is the fuzzy variable. Different from the conventional optimal model, the model (6) becomes difficult to solve due to the inclusion of the chance constraint, so the fuzzy simulation can be used to generate the sample data, and the neural network is used to find the substitution function of the chance constrained function. Considering that the model contains integer variables 0 and 1, the discrete binary particle swarm optimization [7] is used to solve the equivalent model.

4.1. Simulation Verification Based On Demonstration Project

Optimal model of the AC/DC hybrid microgrid is solved under the conditions of credibility of 0.75, 0.85 and 0.95 respectively. Figure.2-4 show the simulation results.

![Figure 2. Output scheduling of the utility grid](image-url)
Figure 2 shows the curve of exchange power between the microgrid and the utility grid. It can be seen that the microgrid still purchases electricity from the utility grid when the installed capacity of wind power and PV power is close to the load. The purchased power is the smallest at around 7:00, while the largest at around 22:00. With the increase of credibility, the amplitude of the curve of between the microgrid and the utility grid is increased. This is because the permissible error is becoming smaller and the fluctuation is increasing in the AC/DC Hybrid Microgrid. In order to ensure the reliability, it is necessary to increase electricity purchase from utility grid.

![Figure 3. Output curves of energy storage and TOU power price](image)

Fig. 3 shows the output curves of energy storage under different credibility. It can be seen that the output of energy storage has a significant correlation with the TOU power price. When the price is low, the energy storage is charged, and when the price is high, the energy storage is discharged. The essence is to transfer the peak load to the valley, which effectively reduces operating costs. At the same time, we can find that the energy storage’s output is similar under the three kinds of credibility, but the fluctuation of storage energy output is large when the credibility is low.

![Figure 4. Curves of SOC in energy storage](image)

Fig. 4 shows curves of SOC in energy storage. The initial and final SOCs in energy storage during operation are both set to 0.535. We can see that the SOC in energy storage can be always maintained within the upper and lower limits during operation, and there is no frequent fluctuation, thereby effectively reducing losses of electric storage lifetime. From the magnification of local details, it can be clearly seen that the two curves with confidence intervals of 0.85 and 0.95 are quite close, and the variation of energy storage is approximately the same.

Tab. 1 shows every operating cost of the AC/DC hybrid microgrid under different credibility. It can be seen that under the same credibility, the vast majority of composite costs is the power purchased from the utility grid, followed by the equipment maintenance cost and the operating cost of MT, and the operating cost of energy storage is the least. With the increase of credibility, the cost of power...
purchased from the utility grid and the fuel cost of MT increase significantly in composite cost. So the utility grid can set different confidence intervals based on the importance of the load and other relevant factors to get the corresponding composite cost.

| Table 1. Composite costs of fuzzy optimization |
|-----------------------------------------------|
| Credibility | 0.75 | 0.85 | 0.95 |
|-----------------|-------|-------|-------|
| Total operating cost/Yuan | 47320 | 47685 | 49226 |
| Power purchase cost/Yuan | 45752 | 45972 | 47670 |
| Operating cost of energy storage/Yuan | 184 | 184 | 184 |
| Fuel cost of MT/Yuan | 602 | 758 | 966 |
| Equipment maintenance cost/Yuan | 782 | 771 | 802 |

5. Conclusion
The fuzzy uncertainty of the prediction error of renewable energy and the flexibility of grid dispatching is considered comprehensively in this paper. Furthermore, this paper proposed a collaborative optimal operation model of AC/DC hybrid microgrid based on fuzzy chance constraints, and combined the fuzzy-neural network and discrete binary particle swarm optimization to solve the model. Based on the project field data, the simulation was carried out under different credibility. The simulation results showed that the comprehensive operating cost has a positive correlation with the credibility. This paper only considered the uncertainty of the source side at present, and the research work on the uncertainty of load forecasting will be further carried out.

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