Research on DC Cross-regional Accommodation Model Based on Scene Analysis

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Abstract: In order to cope with the impact of uncertainty of the renewable energy forecasting in two regions on the cross-regional accommodation of renewable energy, a DC cross-regional accommodation model based on scene analysis is established. Firstly, the ARMA model, scene reduction and scene combination concept are used to construct the scene set describing the uncertainty of the renewable energy forecasting in two regions. Then, the model is used to obtain the unit start-stop plan in two regions and the DC line transmission plan with the goal of smallest renewable energy power abandonment statistically. Finally, based on the measured data of renewable energy power generation, the unit power generation schedule with the goal of smallest renewable energy power abandonment in the actual operation of the power grid is obtained. The validity of the model is verified by a cross-regional system example of actual data reconstruction in a province.

1. Introduction

With the increasing installed capacity scale and penetration rate of renewable energy, some parts of China are limited by local accommodation capacity and cannot eliminate renewable energy power completely. It is an important solution that renewable energy cross-regional accommodation through DC lines currently[1][2]. However, with the expansion of the installed capacity of renewable energy, the error value of renewable energy forecasting is gradually expanding for the uncertainty of renewable energy forecasting, which is likely to seriously affect the effectiveness of renewable energy cross-regional accommodation. Meanwhile the related research on renewable energy cross-regional accommodation concentrates on the optimization of DC line transmission components[3], DC line peak shaving[4][5], and two-region coordination[6][9], etc. How to deal with the impact of renewable energy cross-regional accommodation for the uncertainty of renewable energy forecasting in two regions has rarely been studied.

According to the renewable energy historical forecasting error data and forecasting data, the references[10] uses the ARMA model and the synchronous back-reduction method[11] to construct a renewable energy forecasting scene set, which can roughly describe the actual energy output curve and probability. The renewable energy forecasting uncertainty is transformed into a deterministic scene and the probability of occurrence of the scene and then the statistically optimal unit power generation schedule is obtained to promote renewable energy accommodation. However, this method is currently
used in single-region power grids and is less used for two-region or multi-region power grids. This is to propose a concept of scene combination, cross-combining the renewable energy forecasting scene sets of each region, and constructing a renewable energy forecasting scene set describing the uncertainty of two-region or multi-region renewable energy forecasting.

Based on the above research, this paper will use ARMA model, scene reduction and scene combination concept to construct a scene set describing the uncertainty of two-region renewable energy day-ahead forecasting, and establish a DC cross-regional accommodation model based on scene analysis to obtain the unit start-stop plan in two regions and the DC line transmission plan with the goal of smallest renewable energy power abandonment statistically to cope with the impact on the effectiveness of renewable energy cross-regional accommodation for renewable regional energy forecasting uncertainty.

2. Model Framework

2.1. Uncertainty description process of new energy forecasting

Considering the renewable energy forecasting error sequence is usually stationary sequence\(^8\), the ARMA model is used to fit the renewable energy forecasting error sequence, which can be solved directly by using calculation tools and is simple and convenient. The specific functions are as follows:

\[
\Delta p_g^t = \sum_{i=1}^{p} \alpha_i \Delta p_g^{t-i} + \varepsilon_t - \sum_{j=1}^{q} \beta_j \varepsilon_{t-j}
\]

\[
\Delta p_g^0 = 0, \varepsilon_t = 0, a < 0, b < 0
\]

Where \(\Delta p_g^t\) is the forecasting error of the renewable energy station \(g\) at \(t\), \(p, q\) are the order of the autoregressive and moving average parts of the ARMA model, \(\alpha, \beta\) are the parameter sequences of the ARMA model, \(\varepsilon\) is the gaussian of the variance \(\sigma^2\) white noise.

Combined with the white noise sampling in the ARMA model, a basic scene with many renewable energy forecasting scenes with equal probability can be generated, which is not conducive to the stochastic optimization model. Therefore, this paper uses the heuristic-based synchronous back-reduction method\(^{11}\) to reduce the number of the renewable energy forecasting base scene, and reduce the input data volume of the stochastic optimization model to accelerate the model solution. See the references\(^{11}\) for specific scene reduction methods.

If the basic scene of two regions are combined directly, a huge number of renewable energy forecasting basic scenes in two regions with equal probability will be generated, which makes it difficult to scene reduction. Therefore, this paper uses the method of reducing the basic scenario set of renewable energy forecasting for each region, and then combining the two regional scenes to construct the scene set of renewable energy forecasting for each region.

2.2. Model framework

The framework of model based on scene analysis is shown in figure 1. The model is composed of DC line operation model, sending area and receiving area accommodation model. The DC line,
sending area and receiving area are taken as the research objects. The start-stop state and power generation of units in two areas, as well as the operation state and transmission power of DC line are taken as optimization variables. Combining the load curve of two areas and the scene set of renewable energy forecasting, the unit start-stop plan in two regions and the DC line transmission plan are optimized though the model.

2.3. Model framework
The process of model optimization is divided into two steps: the uncertainty treatment of renewable energy forecasting in two regions (steps 1-3) and the optimization of the unit start-stop plan in two regions and the DC line transmission plan (steps 4). The specific contents are as follows:

a) Combining the historical error data of renewable energy forecasting, a series of historical error data like weather in the same time period of forecasting in this area (sending and receiving regions) was selected. The expected values at each time point are calculated to obtain the expected series of renewable energy forecasting errors in this time period.

b) Combining the renewable energy forecasting error expectation sequence, the ARMA model is used to fit the data sequence, and the least squares method is used to solve the parameters of the ARMA model. Then the standard deviation of the white noise sequence is calculated, and the function of fitting the renewable energy forecasting error expectation sequence is obtained.

c) Multiple sets of white noise samples are substituted into the ARMA model to generate the renewable energy forecasting base scene set. In order to reduce the amount of model calculation, the scenario reduction is performed on the basic scene set by using the scene reduction method to obtain the renewable energy forecasting scene set of each region.

d) The scene sets of renewable energy forecasting in both sending and receiving regions are combined to generate scene sets describing the uncertainty of renewable energy forecasting in the two regions. Combining the two-area load curve, the two regions units start-stop plan and transmission plan of are optimized by using the DC cross-regional accommodation model based on scene analysis, and the two regions units output plan are obtained with the measured data of the renewable energy power.

3. Model Establishment

3.1. Objective Function
In order to promote the renewable energy accommodation, the objective function of the DC cross-regional accommodation model is the minimum expected value of the renewable energy abandonment in two regions. The specific formulas are as follows:

\[
\min \sum_{s=1}^{S} \sum_{t=1}^{T} p_s (\Delta P_{st}^{\Delta} + \Delta P_{nt}^{\Delta}) \Delta t
\]

Where \( N_s \) is the time length of model simulation, \( \Delta t \) is the time resolution of model simulation, \( S \) is the number of combined scene for two regions renewable energy forecasting scene, \( p_s \) is the probability of occurrence of scene \( s \) of renewable energy forecasting, \( \Delta P_{st}^{\Delta} \), \( \Delta P_{nt}^{\Delta} \) are the renewable energy abandonment power of the sending and receiving regions in scene \( s \) at \( t \).

The renewable energy abandonment power refers to the power that is not emitted by renewable energy stations in the region due to the influence of internal and external obstacles. In this paper, only the peaking factor is considered for the abandonment factor, and the rest of the factors are not considered.

3.2. Constraints
In order to ensure the safe operation of the cross-regional power grid, the model needs to meet the system operation constraints, unit operation constraints, renewable energy output constraints and DC
line operation constraints, and inter-scene constraints in the sending and receiving regions under each scene. The first four constraints are the same as the stochastic optimization model[8] and the DC line operation equivalent model[4], which are not described in detail here. Inter-scene constraints are set to satisfy the operation constraints of units in two regions when different scenes are converted. Specifically, the unit start-up and shutdown plans are consistent in each scene and the unit output of adjacent time nodes in any two scenes satisfies the climbing constraints. The specific constraints are as follows:

\[
\begin{align*}
    u'_{s_1,k} &= u'_{s_2,k} \\
    r^d_k &\leq p_{s_2,k} - p_{s_1,k} \leq r^u_k \\
    \forall s_1, s_2 &\in S \\
    k &= 1, 2, \ldots, K
\end{align*}
\]

Where \( K \) is the number of cross-regional power grid units, \( s_1, s_2 \) are two scenes in the renewable energy forecasting scene set of two regions, \( u'_{s_1,k} \), \( u'_{s_2,k} \) are the start and stop states of the unit \( k \) at \( t \) in the scene \( s_1 \) and the scene \( s_2 \) respectively, \( p_{s_2,k} \) is the power of unit \( k \) at \( t \) in scene \( s_1 \), \( p_{s_1,k} \) is the power of unit \( k \) at \( t-1 \) scene \( s_2 \), \( r^u_k \), \( r^d_k \) are the upward climbing rate and the downward climbing rate of unit \( k \) respectively.

3.3. Model solving method
Combining the objective function and constraints of the model, it can be seen that the DC cross-regional accommodation model based on scene analysis is a mixed integer linear programming problem, which can be solved by commercial software (such as CPLEX package)[12].

4. Case Study
The validity of the model is verified by a cross-regional system example of actual data reconstruction in a province in China.

4.1. Examples of basic data
The total installed capacity of units in the sending region is 22892MW, of which the total installed capacity of renewable energy is 11532MW, the total installed capacity of thermal power is 14880MW, and the installed permeability of renewable energy is 50.38%. Thermal power units are divided into heating units, conventional units and fast start-up and shutdown units. There are 20 heating units with a total installed capacity of 11400 MW, including 1 1060 MW unit, 8 660 MW units, 5 600 MW units, 4 350 MW units and 2 330 MW units. There are 8 conventional units with a total installed capacity of 2950 MW, including 600 MW units, 2 350 MW units and 5 330 MW units. There are 2 fast start-up and shutdown units with a total installed capacity of 530 MW, including 330 MW units and 1 200 MW units.

The total installed capacity of units in the receiving region is 2570MW, of which the total installed capacity of renewable energy is 7329MW, the total installed capacity of thermal power is 18380MW, and the installed permeability of new energy is 28.51%. Thermal power units are divided into heating units, conventional units and fast start-up and shutdown units. There are 28 heating units with total installed capacity of 13320MW, including 1 1060 MW unit, 3 660 MW units, 8 600 MW units, 10 350 MW units and 6 330 MW units. There are 12 conventional units with total installed capacity of 4000MW, including 2 350 MW units and 10 330 MW units. There are 4 fast start-up and shutdown units with total installed capacity of 1060MW, including 4 330 MW units and 2 200 MW units.

The capacity of DC line is 4000MW, the minimum transmission power is 1000MW, the maximum transmission power is 4000MW, the adjustment times of outgoing power is limited to 6 times, the
minimum stabilization time is 1 hour, the adjustment range of power per hour is limited to 2000 MW, the minimum transaction power is 67.2 GWh, the maximum transaction power is 86.2 GWh, and the initial transmission power is 2000 MW. The types of thermal power units used in the sending and receiving regions are the same. The specific parameters of thermal power units are shown in Table 1.

Table 1. The operating parameter of units in two regions

| Unit type | Maximum technical output (MW) | Minimum Technical Output (MW) | Climbing rate (MW/min) | Minimum downtime duration (h) | Minimum startup duration (h) |
|-----------|-------------------------------|-------------------------------|------------------------|-----------------------------|-----------------------------|
| 1         | 200                           | 100                           | 2                      | 2                           | 2                           |
| 2         | 330                           | 165                           | 3.3                    | 8/2                         | 8/2                         |
| 3         | 350                           | 175                           | 3.5                    | 8/24                        | 8/24                        |
| 4         | 600                           | 300                           | 6                      | 8/24                        | 8/24                        |
| 5         | 660                           | 330                           | 6.6                    | 8/24                        | 8/24                        |
| 6         | 1060                          | 530                           | 10.6                   | 24                          | 24                          |

In Table 1, 8/2 means that when the thermal power is used as a regular unit, the minimum duration of 8h, as quick stops the unit used, the minimum duration of 2h. 8/24 refers to the unit when the unit is used as a regular, minimum duration 8h, used as a heating unit, the minimum duration of 24h.

4.2. Load data and new energy data of example

Combining the actual load data of the two regions, the load level of the two regions in the calculation example is set as shown in Figure 2. The maximum load demand of the two regions is 8124 MW and 16978 MW respectively.

Figure 2. Two-region load level

Combining the installed capacity of renewable energy in the two regions, the day-ahead forecasting curve and theoretical generation curve of renewable energy in the two regions are set as shown in figure 3.

Figure 3. Two-region renewable energy generation data

4.3. Scenario set construction of renewable energy forecasting in two regions

The renewable energy historical forecasting error series for a similar period of time in two regions is
selected to obtain the renewable energy forecasting error expectation series as shown in figure 4.

According to Fig.3 and Fig.4, the scene set of renewable energy forecasting in two regions are constructed by using ARMA model and scene reduction technology, as shown in figure 5. The probability of occurrence of each scene is shown in table 2. The scene set of renewable energy forecasting in two regions are combined to form a scene set of renewable energy forecasting in two regions with nine scenes.

![Figure 4. Renewable energy day-ahead forecasting error sequence in two regions](image)

![Figure 5. Renewable energy source forecasting scene set in the sending end area](image)

Table 2. The probability of occurrence for each scene in the renewable energy forecasting scenario in the two regions

| Probability       | scene 1   | scene 2   | scene 3   |
|-------------------|-----------|-----------|-----------|
| the sending region| 23.0%     | 33.7%     | 43.3%     |
| the receiving region| 31.1%     | 52.2%     | 16.7%     |

4.4. Model validity verification

In order to verify the effectiveness of the model in dealing with uncertainty of renewable energy forecasting, two optimization methods are compared, which are as follows:

Optimization Method 1: According to the two regions renewable energy day-ahead forecasting data, the cross-regional accommodation model is used to optimize the two regions the units power generation schedule and the DC transmission plan, and the renewable energy abandonment situation is calculated based on the renewable energy theoretical generation curve.

Optimizing method 2: According to the scene set of renewable energy forecasting in two regions, the unit start-stop plan and DC transmission plan are optimized by using the DC cross-regional accommodation model based on scene analysis, and the abandonment situation of renewable energy is calculated based on the renewable energy theoretical generation curve.

According to the data of load, unit and renewable energy in two regions, the DC transmission plan and renewable energy abandonment situation under the two optimization methods are solved as shown in figure 6.
In order to better describe the renewable energy accommodation under the two optimization methods, the renewable energy abandonment and abandonment rate in the sending region under the two methods are counted, and the results are shown in Table 3.

Table 3. The renewable energy abandonment and abandonment rate under three methods

| methods | theoretical energy production (MWh) | energy abandonment (MWh) | abandonment rate (%) |
|---------|-------------------------------------|--------------------------|----------------------|
| 1       | 69984.82                            | 5756.76                  | 8.23                 |
| 2       | 69984.82                            | 0                        | 0                    |

According to the basic data of the example, the thermal power units in the two regions are mainly heat-supply units, and the operation status of the units generally has fixed opening constraints, which makes the uncertainty of renewable energy forecasting in the two regions affect the operation of AC-DC interconnected system mainly reflected in the DC transmission plan.

According to the analysis of figure 3, figure 6 and table 2, there are extreme cases where the renewable energy forecasting in the sending region is too small and the renewable energy forecasting in the receiving region is too large in the 0:00-18:00 period, which causes the DC transmission power is low in the 0:00-3:00 time period and the 5:00-12:00 time period of method 1. That will reduce the effectiveness of renewable energy cross-regional accommodation. Especially in the 1:00-2:00 time period and the 6:00-11:00 time period, there is a large amount of "abandoning wind and abandoning light" phenomenon in the sending region, and the renewable energy abandonment reaches 5576.76 MWh, accounting for the theoretical power 8.23%.

According to the combined scene set describing the uncertainty of renewable energy forecasting in the two regions, Method 2 uses the DC cross-regional accommodation model based on scene analysis to obtain the statistically optimal the DC transmission plan. As shown in figure 5, the DC line transmission power is improved in the 0:00-3:00 time period and the 5:00-12:00 time period comparing with the method 1, which greatly promotes the cross-regional accommodation of renewable energy and eliminates the surplus renewable energy power completely in the sending area. This method greatly reduced the impact of the uncertainty of the renewable energy forecasting on the DC transmission plan.

5. Conclusion
In this paper, a DC cross-regional accommodation model based on scene analysis is proposed. The ARMA model, scene reduction and scene combination concept are used to construct a scene set describing the uncertainty of two-region renewable energy day-ahead forecasting. The model is used to obtain the unit start-stop plan in two regions and the DC line transmission plan with the goal of smallest renewable energy power abandonment statistically, which can promote the cross regional accommodation of renewable energy considering the uncertainty of renewable energy day-ahead forecasting.
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References
[1] LIU Zhenya, ZHANG Qiping, DONG Cun, et al. Efficient and security transmission of wind, photovoltaic and thermal power of large-scale energy resource bases through UHVDC projects [J]. Proceedings of the CSEE,2014,34(16): 2513-2522.
[2] XIN Songxu, BAI Jianhua. Study on the options of wind power cross regional transmission modes in China[J]. Electric Power, 2015,48(09): 9-13.
[3] XU Dan, WANG Bin, ZHANG Jiali, et al. Integrated transmission scheduling mode for wind-photovoltaic-thermal power by ultra-high voltage direct current system[J]. Automation of Electric Power Systems,2016,40(06): 25-29,57.
[4] CUI Yang, ZHAO Yu, QIU Lijun, et al. Coordinated scheduling method of wind-thermal power transmitted by UHVDC system for improving peak shaving margin of receiving end power grid[J]. Automation of Electric Power Systems, 2018,42(15):126-132.
[5] HAN Hongwei, TU Mengfu, ZHANG Huiling, et al.Day-ahead generation scheduling method considering adjustable HVDC plan and its analysis[J]. Automation of Electric Power Systems,2015,39(16): 138-143.
[6] ZHENG Haiwang, XIA Qing, DING Maosheng, et al. A new mode of HVDC tie-line operation optimization for maximizing renewable energy accommodation[J]. Automation of Electric Power Systems,2015,39(03): 36-42.
[7] WANG Bin, XIA Ye, XIA Qing, et al. Model and methods of generation and transmission scheduling of interregional power grid via HVDC tie line[J]. Automation of Electric Power Systems,2016,40(03): 8-13,26.
[8] DONG Cun, LIANG Zhifeng, LI Xiaofei, et al. Study on Power Optimization of the Trans-Regional UHVDC Delivery Channels in Promoting Renewable Energy Accommodation Capacity[J]. Electric Power, 2019, 52(4): 41-50.
[9] REN Jianwen, XU Yingqiang, YI Chen. Cross Regional Wind Power Consumption Model Considering Power Adjustment of DC Tie-Line[J]. Electric Power Construction,2017,38(11):129-135.
[10] LEI Yu, YANG Ming, HAN Xue-shan. A two-stage stochastic optimization of unit commitment considering wind power based on scenario analysis[J]. Power System Protection and Control, 2012, 40(23): 58-67.
[11] Razali M N, Hashim H A, Backward reduction application for minimizing wind power scenarios in stochastic programming, 2010 4th International Power Engineering and Optimization Conference (PEOCO), Shah Alam, 2010, 430-434.
[12] CHEN Haoyong, WANG Xifan. A Survey of Optimization Methods for Unit Commitment[J]. Automation of Electric Power Systems, 1999(04):51-56.