Study on the evaluation model of new energy real-time consumption capacity considering dynamic constraints of network sources

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Abstract. In order to accurately evaluate the real-time consumption capacity of new energy considering the dynamic coordination of network sources in real-time scale, a new energy real-time consumption capacity evaluation model considering the dynamic constraints of network sources is established. Firstly, according to the operation plan of thermal power unit, the transmission plan of tie line, the regulation margin of transformer ratio and the capacity of each node's reactive device, the dynamic constraint of network source is set. Then, according to the grid parameters, the real-time prediction of new energy station operation and the real-time prediction of each node load demand, the line power flow security, node power balance, node voltage security and new energy station operation constraints are set. Finally, two optimization objectives of new energy active power maximum and minimum consumption are set up, and a new energy real-time consumption capacity evaluation model considering the dynamic constraints of network sources is established, which takes the active and reactive power of thermal power unit, the active and reactive power of tie line, the transformer transformation ratio, the reactive capacity of reactive device switching, and the active and reactive power of new energy as decision variables. The validity of the model is verified by 4-node system.

1. Introduction

With the continuous expansion of the scale of new energy installation, the priority consumption of new energy power generation has become an important work of the dispatching agency, and accurate evaluation of the current power grid's new energy consumption capacity is the current research focus [1-12]. At present, scholars have made some researches on the assessment of new energy consumption capacity under the day ahead, day inside and real-time time scales. Different from the day ahead and day inside time scale, the assessment of new energy consumption capacity under the real-time time scale must further consider the influence of node voltage security, line power flow security, and...
dynamic coordination of network sources on the basis of power balance and peak load regulation capacity of power grid. However, most of the related researches do not consider the factors of thermal power units, transformers, reactive power devices, and real-time dynamic coordination of tie lines, which reduces the accuracy of real-time energy consumption capacity evaluation and is not conducive to the real-time optimal consumption of new energy.

In this paper, according to the operation plan of thermal power unit, the transmission plan of tie line, the regulation margin of transformer ratio and the capacity of each node reactive device, the dynamic constraints of network source are set firstly. Then, according to the grid parameters, the real-time prediction of new energy station operation and the real-time prediction of each node load demand, the line power flow security, node power balance, node voltage security and new energy station operation constraints are set. Finally, two optimization objectives of the maximum and minimum active power consumption of new energy are set up, and a new energy real-time consumption capacity evaluation model considering the dynamic constraints of network sources is established, which takes the active and reactive power of thermal power units, the active and reactive power of tie lines, the transformer transformation ratio, the reactive capacity of reactive devices, and the active and reactive power of new energy as decision variables, solves the new energy real-time consumption capacity evaluation model considering the dynamic coordination of network sources, and provides data support for real-time optimal consumption of new energy.

2. Model Establishment

2.1. Model framework

![Figure 1. Framework of new energy real-time consumption capacity evaluation model considering dynamic constraints of network sources](image)

The new energy real-time consumption capacity evaluation model considering the dynamic constraints of the grid source takes the maximum and minimum active power of the new energy as the optimization objective. On the basis of satisfying the dynamic constraints of the grid source and the static constraints of the grid source, using the external point method or commercial software to solve the model, the active and reactive power of the thermal power unit, the active and reactive power transmission regulation of the tie line and the transformer transformation ratio regulation can be obtained at the real-time scale to optimize the real-time consumption plan of new energy and promote the real-time optimal consumption of new energy.
2.2. Model objectives and constraints

2.2.1. Model objectives. In order to evaluate the new energy consumption capacity of each node, the maximum and minimum sum of the active power of each node is taken as the optimization objective, and the specific formula is as follows:

$$\max \sum_{n=1}^{N} \left( \sum_{i=1}^{n_I} p_{wn}^{i} + \sum_{j=1}^{n_J} p_{pn}^{j} \right)$$

(1)

$$\min \sum_{n=1}^{N} \left( \sum_{i=1}^{n_I} p_{wn}^{i} + \sum_{j=1}^{n_J} p_{pn}^{j} \right)$$

(2)

Where, $N$ is the number of simplified grid nodes; $n_I$ is the number of wind farms connected to the grid under node $n$; $n_J$ is the number of photovoltaic power stations connected to the grid at node $n$; $p_{wn}^{i}$ is the active power of wind farm $i$ under node $n$; $p_{pn}^{j}$ is the active power of photovoltaic power station $j$ in the next period under node $n$.

2.2.2. Model constraints. Model constraints mainly include static constraints and dynamic constraints. Among them, the static constraints of grid sources include the constraints of node power balance, new energy generation, power flow security and voltage security; the dynamic constraints of power grid include the constraints of thermal power unit operation, tie line operation, reactive power device operation, transformer regulation, and the details are as follows:

a) Power balance constraints of each node

$$\sum_{i=1}^{n_I} p_{wn}^{i} + \sum_{j=1}^{n_J} p_{pn}^{j} + \sum_{f=1}^{n_F} p_{wn}^{f} - \sum_{l=1}^{n_L} p_{xn}^{l} = u_n \sum_{m=1}^{N} \left( G_{nm} \cos \delta_{nm} + B_{nm} \sin \delta_{nm} \right)$$

(3)

$$\sum_{i=1}^{n_I} q_{wn}^{i} + \sum_{j=1}^{n_J} q_{pn}^{j} + \sum_{v=1}^{n_V} q_{wn}^{v} + \sum_{f=1}^{n_F} q_{wn}^{f} - \sum_{l=1}^{n_L} q_{xn}^{l} = u_n \sum_{m=1}^{N} \left( G_{nm} \sin \delta_{nm} - B_{nm} \cos \delta_{nm} \right)$$

(4)

Where, $n_F$ is the number of thermal power units connected to the grid at node $n$; $n_V$ is the total number of reactive power devices connected to the grid under node $n$; $p_{wn}^{f}$ is the active power of thermal power unit $f$ under node $n$; $p_{xn}^{l}$ is the active power of the tie line $l$ under node $n$; $p_{dn}$ is the active demand of time period under node $n$; $q_{pn}^{j}$ is the reactive power of photovoltaic power station $j$ in the next period under node $n$; $p_{wn}^{i}$ is the active power of wind farm $i$ under node $n$; $q_{wn}^{v}$ is the reactive power of reactive device $v$ under node $n$; $q_{wn}^{f}$ is the reactive power of thermal power unit $f$ under node $n$; $q_{xn}^{l}$ is the reactive power in the next period under the tie line $l$ under node $n$; $u_n, u_m$ are the effective value of voltage under $n$ and $m$ respectively; $\delta_{nm}$ is the phase angle difference between $n$ and $m$ nodes in the next period; $G_{nm}, B_{nm}$ are the real part and the imaginary part of the admittance matrix.

b) New energy generation constraints

$$\sigma C_{wn}^{i} + P_{wn}^{i} \geq p_{wn}^{i} \geq \max(P_{wn}^{i} - \sigma C_{wn}^{i}, 0)$$

(5)

$$\sigma C_{pn}^{j} + P_{pn}^{j} \geq p_{pn}^{j} \geq \max(P_{pn}^{j} - \sigma C_{pn}^{j}, 0)$$

(6)
\[
Q_{\text{wn}}^{\text{max}} \geq q_{\text{wn}} \geq Q_{\text{wn}}^{\text{min}}
\]

\[
Q_{\text{pn}}^{\text{max}} \geq q_{\text{pn}} \geq Q_{\text{pn}}^{\text{min}}
\]

Where, \(P_{\text{wn}}^i, P_{\text{pn}}^j\) are the prediction value of active power of wind farm \(i\) and photovoltaic power plant \(j\) under node \(n\) respectively; \(\sigma\) is the real-time prediction error rate of new energy stations; \(C_{\text{wn}}^i, C_{\text{pn}}^j\) are the installed capacity of wind farm \(i\) and photovoltaic power plant \(j\) under node \(n\) respectively; \(Q_{\text{wn}}^{\text{max}}, Q_{\text{wn}}^{\text{min}}\) are the maximum and minimum reactive power extremum of wind farm \(i\) under node \(n\) respectively; \(Q_{\text{pn}}^{\text{max}}, Q_{\text{pn}}^{\text{min}}\) are the maximum and minimum reactive power extremum of photovoltaic power plant \(j\) under node \(n\) respectively.

c) Power flow safety constraints

\[
p_{nm} = u_n u_m (G_{nm} \cos \delta_{nm} + B_{nm} \sin \delta_{nm}) - u_n^2 G_{nm}
\]

\[
q_{nm} = u_n u_m (G_{nm} \sin \delta_{nm} - B_{nm} \cos \delta_{nm}) - u_n^2 B_{nm}
\]

\[
\sqrt{p_{nm}^2 + q_{nm}^2} \leq S_{nm}
\]

Where, \(P_{nm}, Q_{nm}\) are the active and reactive power transmitted by the line between \(n\) and \(m\) nodes respectively; \(S_{nm}\) is the limit capacity of line transmission between \(n\) and \(m\) nodes.

d) Voltage safety constraints

\[
u_n^{\text{max}} \geq u_n \geq u_n^{\text{min}}
\]

Where, \(u_n^{\text{max}}, u_n^{\text{min}}\) are the maximum and minimum extremum of the effective value of voltage under node \(n\), generally 0.95-1.05.

e) Operation constraints of thermal power units

\[
P_{hn}^{f,\text{max}} \geq p_{hn}^f \geq P_{hn}^{f,\text{min}}
\]

\[
Q_{hn}^{f,\text{max}} \geq q_{hn}^f \geq Q_{hn}^{f,\text{min}}
\]

\[
R_{hn}^{fu} \geq p_{hn}^f - p_{hn}^f \geq R_{hn}^{fd}
\]

Where, \(P_{hn}^{f,\text{max}}, P_{hn}^{f,\text{min}}\) are the maximum and minimum active power of thermal power unit \(f\) under node \(n\) respectively; \(Q_{hn}^{f,\text{max}}, Q_{hn}^{f,\text{min}}\) are the maximum and minimum reactive power of thermal power unit \(f\) under node \(n\) respectively; \(R_{hn}^{fu}, R_{hn}^{fd}\) are the maximum up and down climbing speed of thermal
power unit \( f \) under node \( n \) respectively; \( P_{fn} \) is the current active power of thermal power unit \( f \) under node \( n \).

\[ f) \text{ Tie line operation constraints} \]

\[ \alpha P_{xn} \geq P_{xn} - P_{xn} \geq \beta P_{xn} \]  

\[ \sqrt{P_{xn}^2 + Q_{xn}^2} \leq S_{xn} \]  

Where, \( P_{xn} \) is the active power planned to be delivered in the next period of the tie line \( l \) under node \( n \); \( \alpha, \beta \) are the real-time transmission power adjustment margin of the tie line \( l \) under node \( n \); respectively; \( S_{xn} \) is the limit transportation capacity of the tie line \( l \) under node \( n \).

\[ g) \text{ Reactive device operation constraints} \]

\[ Q_{vn}^{\text{max}} \geq Q_{vn} \geq Q_{vn}^{\text{min}} \]  

Where, \( Q_{vn}^{\text{max}}, Q_{vn}^{\text{min}} \) are the maximum and minimum extremum of the reactive power of reactive device \( v \) under node \( n \) respectively.

\[ h) \text{ Transformer regulation constraints} \]

\[ k_{mn} \in \left( k_{mn}^0, k_{mn}^1, \ldots, k_{mn}^{\text{gear}} \right) \]  

Where, \( k_{mn}^0, k_{mn}^1, \ldots, k_{mn}^{\text{gear}} \) are the regulating transformation ratio of the transformer between \( n \) and \( m \) nodes respectively.

2.3. Model solution

The evaluation model of new energy real-time consumption capacity considering the dynamic constraints of network sources is a large-scale nonlinear problem in mathematical nature, which can be solved by the external point method or commercial software.

3. Example Analysis

3.1. Basic data

As shown in Figure 2, this paper selects a 4-node system as an example, in which the left side is the system wiring diagram and the right side is the equivalent circuit represented by admittance \( S_{B}=100 \text{MW}, U_{B}=U_{N} \). Set node 1 as the balance node, the rated capacity active power of grid connected thermal power unit is 55MW, the minimum active power is 30MW, the real-time adjustment limit is 10MW, and the power factor is 0.9-0.96; node 2 is PV node, with installed capacity of 100MW and power factor of -0.95-0.95; node 3 is the contact node, and node 4 is the PQ node, the transformer capacity between the two nodes is 63MW, the rated voltage is 110 / 38.5kv, and the voltage is adjusted in five grades (± 2 * 2.5%); the maximum input capacity of grid connected capacitor of node 2 is 20MV *A; the maximum input capacity of grid connected capacitor of node 4 is 10 MV *A; the equivalent load adjustment amplitude of tie line of node 1 is 0.80-1.20; the ultimate transmission capacity of the three lines is 20 MV *A, 50 MV *A and 30 MV *A respectively.
3.2. Result analysis

According to the transmission plan of tie line, operation plan of thermal power unit, transmission plan of tie line, active power prediction of wind farm and real-time prediction of load demand of each node, combined with the tap position of transformer in the current time system and the input capacity of reactive devices of each node, the system operation at the next time is calculated as shown in Table 1.

| Active power of thermal power unit ($G_1$) | 0.478 | Reactive power of thermal power unit ($G_1$) | 0.144 | Power factor of thermal power unit ($G_1$) | 0.957 | Active power of wind farm ($G_2$) | 0.2 | Active power of tie line ($S_{L1}$) | 0.15 | Tie line reactive power ($S_{L1}$) | 0.1 | Load active power ($S_{L2}$) | 0.5 | Load reactive power ($S_{L2}$) | 0.3 |
|------------------------------------------|-------|--------------------------------------------|-------|------------------------------------------|-------|-------------------------------|---|-----------------------------|---|-----------------------------|---|-----------------------------|---|-----------------------------|---|

According to the analysis in Table 1, without considering the real-time prediction error of wind farm and load, the regulation of thermal power unit, transformer and reactive power device in the system can realize the full consumption of wind power based on meeting the grid security constraints and voltage stability. However, compared with the minimum error of load real-time prediction, the real-time prediction error rate of wind power is generally less than 20%, which has great uncertainty. Therefore, it is necessary to evaluate the real-time capacity of the system to absorb new energy. Now the paper selects three error scenarios of 5%, 10% and 20% to calculate and compare the evaluation results of the proposed model (method 1) and the conventional model (method 2) according to the results in Table 1, so as to verify that the model has the function of accurately evaluating the real-time consumption capacity of new energy. The specific results are shown in Table 2.

| Prediction error | 5% ($0.2\pm0.05$) | 10% ($0.2\pm0.1$) | 20% ($0.2\pm0.2$) |
|------------------|-------------------|-------------------|-------------------|
| Method           | 1                 | 2                 | 1                 | 2                 | 1                 | 2                 |
| Maximum consumption | 0.25          | 0.25              | 0.3               | 0.3               | 0.396             | 0.378             |
| Minimum consumption       | 0.15          | 0.15              | 0.122             | 0.1               | 0                 | 0.078             |
According to the analysis in Table 2, when the real-time prediction error rate of the wind farm is below 5%, the evaluation results of the proposed model and the conventional model are the same, the system does not have the risk of load rejection and power abandonment due to the real-time prediction error of the wind farm. When the real-time prediction error rate of the wind farm reaches 10%, the evaluation results of the model proposed in this paper are inconsistent with those of the conventional model. Because the transmission power of the tie line is coordinated, the minimum dissipation capacity of the model proposed in this paper can reach 0.1. If the tie line power regulation is not adopted, the system will have load rejection risk due to the real-time prediction error of the wind farm. When the real-time prediction error rate of the wind farm reaches 20%, the evaluation results of the model proposed in this paper are not consistent with those of the conventional model. Although the model proposed in this paper coordinates the generation power of the thermal power unit and the transmission power of the tie line at the same time, the maximum absorption capacity is only 0.396 due to the limitation of the transmission capacity of line $L_i$. The system will have the risk of power abandonment due to the real-time prediction error of the wind farm, while the conventional model is not enough due to the insufficient considering the dynamic coordination of network sources. The evaluation results show that the system will have the risk of load rejection and power abandonment.

4. Conclusion
In this paper, a new energy real-time consumption capacity evaluation model considering the dynamic constraints of network sources is proposed, which can accurately evaluate the new energy real-time consumption capacity considering the dynamic coordination of network sources on the real-time scale, providing data support for optimizing the new energy real-time consumption plan and promoting the real-time optimal consumption of new energy.

Acknowledgments
This work was financially supported by Research and Application on the fluctuation of power output characteristics of photovoltaic leader base based on the foundation cloud chart fund.

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