A Novel Generation Expansion Planning Model Considering Constraints on Regulation Capacity and Regulation Speed

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Abstract. New energy is experiencing rapid development in the world, but the curtailment problem of new energy power output is serious in some countries, due to the mismatch between new energy development and power system development. This paper proposes an improved generation expansion planning model, taking the constraints on regulation capacity and regulation speed into consideration. A case study is carried out based on the IEEE 30 Bus system to verify the effectiveness of the model. The results show that the planning result will be more reasonable by virtue of the proposed model.

Introduction

Generation Expansion Planning (GEP) aims to figure out the optimal expansion scheme of generation units within the planning period in terms of overall cost, on basis of the demand forecast results. Since GEP is a very crucial issue in power system, it has already become a conventional research topic. The core part of GEP model lies in the constraints to ensure the generation capacity will meet the requirements of power and electricity.

With the development of new energy generation in recent years, a number of researchers have made some modifications on GEP model. Ref. [1] built a novel GEP model taking into account the development policy of renewable energy. Ref. [2] carried out the research on multi-objective GEP considering the influences of new energy on power systems. Ref. [3] conducted the study on the GEP model considering the uncertainties of wind power under the background of electricity market. Ref. [4] modified the GEP model to incorporate flexible generation units to promote the utilization of wind power. Ref. [5] proposed a novel planning model considering wind power units and large-scale energy storage together. These researches are all very meaningful. However, constraints on regulation capacity and regulation speed have not been taken into consideration, which may lead to the curtailment of variable new energy generation because the integration capacity for new energy is not enough.

Based on this background, this paper puts forward a novel GEP model considering regulation capacity constraint and regulation speed constraint. Apart from meeting the requirements of power demand and electricity demand, satisfying the peak load regulation problem caused by new energy generation is also a core issue in the GEP. The results of this model will make the development of new energy generation more coordinated with that of the power system.

The Coordinated Generation-Transmission Expansion Planning Model

As a mathematical optimization problem, the model of GEP consists of an objective and several constraints. The objective is usually to minimize the overall cost of the construction and operation of power generation units. Since the low-carbon development goal of power systems in many countries, the carbon emission cost is also considered in the objective function in this paper, which will promote the development of clean energy and restrain the expansion of fossil generation. The objective function is shown in Eq. (1).
where $\Omega_g$ is the set of generation candidate units; $x_i$ is the decision variable of the construction result of unit $i$, which is a 0-1 variable; $C_i$ is the capacity of unit $i$; $G_i$ is the construction cost per unit of capacity of unit $i$; $\Omega_T$ is the time length of planning period; $O_i$ is the operation cost per unit of electricity generation of unit $i$; $H_{it}$ is the utilization hour of unit $i$ in year $t$; $\Omega_D$ is the set of exist generation units; $Pr_C$ is the carbon emission price; $E_i^{CO_2}$ is the carbon dioxide emission factor of unit $i$.

Constraints in GEP model usually contains the power supply-demand balance constraint, the electricity supply-demand balance constraint, generation expansion scale constraint, power source structure constraint, carbon and pollution emissions constraint, etc. Eq. (2) shows the power supply-demand balance constraint, which ensures that the total generation capacity after expansion can meet the maximum power load demand in the target year.

$$\sum_{i \in \Omega_g} x_i \cdot C_i \cdot G_i + \sum_{i \in \Omega_g} \sum_{l \in \Omega_D} x_i \cdot O_i \cdot C_i \cdot H_{il} + \sum_{i \in \Omega_g} \sum_{l \in \Omega_D} O_i \cdot C_i \cdot H_{il} \geq (1 + \eta) \cdot P_f,$$

where $\eta$ is the reserve factor; $P_f$ is the forecast on maximum power load demand in the target year.

Eq. (3) illustrates the electricity supply-demand balance constraint, which makes sure that the total electricity generation after expansion can meet the electricity demand in the target year.

$$\sum_{i \in \Omega_g} x_i \cdot C_i \cdot H_{it} + \sum_{i \in \Omega_D} C_i \cdot H_{il} \geq E_f,$$

where $E_f$ is the forecast on electricity demand in the target year.

Eq. (4) shows the generation expansion scale constraint, which puts an upper limit on the number of new-built generation units.

$$\sum_{i \in \Omega_g} x_i \leq X_{max},$$

where $X_{max}$ is the maximum number of new-built generation units.

Eq. (5) illustrates the power source structure constraint, which means the power source structure in the target year can meet certain goal, for example, the ratio of renewable power generation.

$$\frac{\sum_{i \in \Omega_g} x_i \cdot C_i + \sum_{l \in \Omega_D} C_i}{\sum_{i \in \Omega_g} x_i \cdot C_i + \sum_{l \in \Omega_D} C_i} \geq \rho_w,$$

where $\Omega_w$ is the set of variable new energy generation unit; $\rho_w$ is the target of the ratio of new energy.

Eq. (6) expresses the carbon dioxide emission constraint of the power system. Similarly, Eq. (7) and (8) shows the constraint on sulfur dioxide and nitrogen oxides, respectively.

$$\sum_{i \in \Omega_g} \sum_{l \in \Omega_D} x_i \cdot E_i^{CO_2} \cdot C_i \cdot H_{il} + \sum_{i \in \Omega_g} \sum_{l \in \Omega_D} E_i^{CO_2} \cdot C_i \cdot H_{il} \leq Tem_{CO_2},$$
To cope with the GEP problem considering the development of variable new energy, some modifications should be made on the planning model to ensure that the power source structure is suitable for the development of new energy with adequate regulation capacity and regulation speed. Therefore, these two constraints are added in our model. Eq. (9) shows the regulation capacity constraint that makes sure the total regulation capacity of all the generation units after expansion can meet the requirement of regulation caused by the variation of load demand and new energy generation.

\[
\sum_{i \in \Omega_i} \left( x_i \cdot R_i \cdot C_i \right) + \sum_{i \in \Omega} \left( R_i \cdot C_i \right) \geq \beta \cdot P_{f_i} + \sum_{i \in \Omega_i} x_i \cdot C_i + \sum_{i \in \Omega} C_i
\]  

(9)

where \( R_i \) is the regulation depth factor of unit \( i \); \( \beta \) is the peak-valley difference rate of the load demand in the system.

Eq. (10) expresses the regulation speed constraint which ensures the maximum regulation speed of all the generation units after expansion can meet the requirement of regulation caused by the variation of load demand and new energy generation.

\[
\sum_{i \in \Omega_i} \left( x_i \cdot \delta_i \cdot C_i \right) + \sum_{i \in \Omega} \left( \delta_i \cdot C_i \right) \geq \delta_D \cdot P_{f_i} + \sum_{i \in \Omega_i} x_i \cdot \delta_i \cdot C_i + \sum_{i \in \Omega} \delta_i \cdot C_i
\]  

(10)

where \( \delta_i \) is the regulation speed factor of unit \( i \); \( \delta_D \) is power variability speed of the load demand in the system.

**Case Study**

A numerical study is carried out on the IEEE 30 Bus system that contains 30 bus nodes and 41 branches. The information on existing generation units, power grid and load demand at each node can be found in Ref. [6]. In order to make the test system more suitable for this study, Unit 3 is set to be gas power unit, while Unit 2 is set to be cogeneration coal-fired unit. The candidate units are shown in Table 1. The planning is carried out for the target year. The time length of the planning period is 10 years. The maximum power load demand at each node in the target year is forecasted to be 50% higher than the initial year, and the electricity demand in the target year is 2000GWh. The reserve rate is 30%. The peak-valley difference rate of the load demand is 35%, and the power variability speed of the load demand is 0.2%/min. The maximum number of expansion unit is 5. The carbon emission price is 52 yuan/ton. The upper limit on carbon dioxide emission, sulfur dioxide emission and nitrogen oxides emission is 2 million tons, 10000 tons and 5000 tons, respectively. Two scenarios are set to study the effects of the modifications of the GEP model in this paper. In Scenario 1, the regulation capacity constraint and the regulation speed constraint are not taken into account, while these two constraints are considered in Scenario 2.
Table 1. Information on generation unit candidates.

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Node</th>
<th>Power Source</th>
<th>Capacity (MW)</th>
<th>Regulation Capacity Rate (%)</th>
<th>Regulation Speed (%/min)</th>
<th>Carbon Dioxide Emission Factor (kg/MWh)</th>
<th>Sulfur Dioxide Emission Factor (kg/MWh)</th>
<th>Nitrogen Oxides Emission Factor (kg/MWh)</th>
<th>Utilization Hour</th>
<th>Construction Cost (10000 yuan/MW)</th>
<th>Operation Cost (yuan/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>24</td>
<td>Coal</td>
<td>100/200/300</td>
<td>50</td>
<td>2</td>
<td>880</td>
<td>4.88</td>
<td>2.26</td>
<td>4500</td>
<td>360</td>
<td>400</td>
</tr>
<tr>
<td>G2</td>
<td>25</td>
<td>Coal</td>
<td>100/200/300</td>
<td>50</td>
<td>2</td>
<td>880</td>
<td>4.88</td>
<td>2.26</td>
<td>4500</td>
<td>372</td>
<td>400</td>
</tr>
<tr>
<td>G3</td>
<td>14</td>
<td>Gas</td>
<td>100/200/300</td>
<td>80</td>
<td>10</td>
<td>460</td>
<td>0.04</td>
<td>0.70</td>
<td>3000</td>
<td>322</td>
<td>600</td>
</tr>
<tr>
<td>G4</td>
<td>19</td>
<td>Gas</td>
<td>100/200/300</td>
<td>80</td>
<td>10</td>
<td>460</td>
<td>0.04</td>
<td>0.70</td>
<td>3000</td>
<td>322</td>
<td>600</td>
</tr>
<tr>
<td>G5</td>
<td>27</td>
<td>Wind</td>
<td>50/100/150</td>
<td>100</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2000</td>
<td>950</td>
<td>20</td>
</tr>
<tr>
<td>G6</td>
<td>29</td>
<td>Wind</td>
<td>50/100/150</td>
<td>100</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2000</td>
<td>850</td>
<td>20</td>
</tr>
</tbody>
</table>

The model is constructed and solved on the platform of GAMS (the General Algebraic Modeling System) 0. The Solver in BONMIN (Basic Open-source Nonlinear Mixed Integer programming). The planning result in Scenario 1 and Scenario 2 is shown respectively in Table 2 and Table 3.

Table 2. Results of generation expansion planning in Scenario 1.

<table>
<thead>
<tr>
<th>Unit to be Built</th>
<th>Power Source</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>Coal</td>
<td>100</td>
</tr>
<tr>
<td>G5</td>
<td>Wind</td>
<td>150</td>
</tr>
<tr>
<td>G6</td>
<td>Wind</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 3. Results of generation expansion planning in Scenario 2.

<table>
<thead>
<tr>
<th>Unit to be Built</th>
<th>Power Source</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3</td>
<td>Gas</td>
<td>100</td>
</tr>
<tr>
<td>G4</td>
<td>Gas</td>
<td>100</td>
</tr>
<tr>
<td>G5</td>
<td>Wind</td>
<td>50</td>
</tr>
<tr>
<td>G6</td>
<td>Wind</td>
<td>150</td>
</tr>
</tbody>
</table>

As shown in the above tables, the total generation expansion capacity is 400 MW in both Scenario 1 and Scenario 2. The planning result in Scenario 1 include 100 MW coal power and 300 MW wind power, while the result in Scenario 2 include 200 MW gas power and 200 MW wind power. In terms of wind power, G5 and G6 are selected in both scenarios. The capacity of wind power expansion in Scenario 1 is higher than that in Scenario 2, because the constraints on regulation capacity and speed of the power system are not considered in Scenario 1. However, the wind power capacity in Scenario 1 may be too much to be integrated as a result of the relative shortage of regulation ability in the power system, which is similar to the practical situations in some regions in China where the wind curtailment problem is quite serious. On the contrary, the wind power integration can be ensured in Scenario 2, because the regulation capacity and regulation speed can meet the requirement of wind power development, even though the wind power capacity in this scenario is lower. When it comes to the conventional generation units, gas power units are selected in Scenario 2, rendering the power system better performances in terms of regulation capacity and regulation speed, which matches the scale of wind power.

In order to show the differences on wind power integration between the two scenarios, the integration capacity for wind power of the power system is calculated with the approach proposed in ref. [6]. The results are listed in Table 4, where $C_{wpi1}$ refers to the integration capacity for wind power determined by the regulation capacity of the power system, $C_{wpi2}$ refers to the integration capacity for wind power determined by the regulation speed of the power system, and $C_{wpi}$ indicates the
integration capacity for wind power after comprehensive consideration of $C_{wpi_1}$ and $C_{wpi_2}$. It is evident that the integration potential for wind power is only 79 MW in Scenario 1, while the planned wind power capacity is 300 MW, which means wind power curtailment will be serious if the planning result is adopted. On contrast, the integration capacity for wind power is in accordance with the scale of wind power expansion in Scenario 2.

Table 4. Estimated capacity of wind power integration.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$C_{wpi_1}$ (MW)</th>
<th>$C_{wpi_2}$ (MW)</th>
<th>$C_{wpi}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>103.7</td>
<td>79.0</td>
<td>79.0</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>213.6</td>
<td>199.0</td>
<td>199.0</td>
</tr>
</tbody>
</table>

Conclusion

This paper proposes a novel GEP model considering the constraints on regulation capacity and regulation speed of the power system, in order to render the power system sufficient integration capacity for variable new energy generation such as wind power and solar power. The case study on IEEE 30 Bus system verifies the effectiveness of the model. The results show that the improved GEP model can obtain a more reasonable planning result, making the scale of variable new energy development more coordinated with the integration capacity for new energy in the power system. Accordingly, the efficiency of investment will be enhanced.

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References


