Comprehensive Assessment Method of New Energy Consumption Considering Steady and Dynamic Active Power Equilibrium Constraints

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Keywords: New energy consumption capability, Peak load regulation, Frequency stability, Frequent regulation of units.

Abstract. With the increase of the proportion of new energy sources, the peak load capacity and frequency stability of power grid have become the main constraint factors for the new energy consumption. This paper presents a comprehensive assessment method of new energy dissipation capacity under the constraints of steady and dynamic equilibrium conditions such as peak regulation, frequency stability and unit regulation performance. The new energy permeability of the power grid considering the connection line peak regulation is calculated, and the life loss under the frequent regulation of the unit is calculated by the relationship between the stress and the life to analyze the influence of the new energy acceptance capacity; the frequency stability is regarded as an important constraint condition, then the new energy consumption level under different types of disturbance such as general disturbance and serious fault is analyzed. The analysis reveals the interaction constraints under different factors and improves the systematicness and adaptability of the assessment of new energy consumption capacity.

Introduction

In recent years, new energy continues to develop rapidly, and its penetration in the power grid is increasing. Due to its randomness and instability, it leads to the lack of power grid peak regulation capacity and causes the problems of frequency safety and stability, which becomes the resistance to the development of new energy[1].

Numerous studies [2,3,] have demonstrated that new energy consumption has been studied from the aspects of peak load regulation, frequency stability, static voltage stability and network constraints. In the aspect of peak regulation, the acceptance capacity of wind power is calculated by analyzing the conventional power supply, the output range and the contact line force plan, according to the difference between peak load and valley load[4]. Peak shaving capability has always been an important constraint on the new energy consumption. At present, the related research has been relatively mature.

Frequency security and stability is the focus of research in recent years, and gradually become an important constraint for new energy consumption. The penetration of high proportion of new energy reduces the moment of inertia of the system and has a greater impact on frequency regulation[5,6]. The work discussed in [7] takes the system frequency recovery as a dynamic stability constraint, and determines the penetration of a photovoltaic power station under the condition of dynamic stability, that is the frequency limit of no more than 49.5Hz. According to the wind speed data, the wind power fluctuation is simulated, and the penetration limit of wind power is analyzed with the frequency fluctuation limit of ±0.2Hz in [8]. The maximum accessible capacity of the wind farm is determined by the combination of frequency constraint method and time domain simulation analysis on the basis of ensuring the stable operation of the system taking frequency as a dynamic constraint condition in [9,10]. However, the study of the frequency stability and frequency deviation allowable values of different types of disturbances is not comprehensive. In addition, the disturbance magnitude of
different power grids is different and is constantly changing. Therefore, various types of disturbance and magnitude of disturbance need to be considered as a whole.

The large-scale access of new energy has significantly increased the regulation pressure of conventional units, so the life loss of the unit itself has also been taken into account in the operation of the power grid. Taking 600WM steam turbine as an example, the relationship between frequent load fluctuation and life loss of thermal power unit is studied in [11], which also points out that the increase of load fluctuation rate is caused by the new energy dissipation greatly aggravates the life loss. In [12], the life loss of the unit in the frequent adjustment process is estimated from two aspects of temperature change and thermal stress taking the power grid containing wind power as an example, and then a scheduling plan is formulated. Most of the existing studies have neglected the problem of inadequate regulation capacity caused by the high proportion of new energy. Therefore, it should be considered in the overall capacity to eliminate.

In view of the lack of overall analysis of different types of disturbances and the limitation of unit adjustment capacity to new energy dissipation in frequency stability problems, this paper selects frequency stability and unit adjustment capacity as the criterion of dynamic balance, and uses peak regulating capacity as a steady state balance constraint, referring to the progress of evaluating the maximum capacity of new energy from peak shaving, and then proposes a comprehensive assessment method of new energy consumption considering steady and dynamic active power equilibrium constraints.

**Comprehensive Evaluation Method under Multiple Constraints**

**Comprehensive Evaluation Method**

The basic idea of the comprehensive evaluation of power grid energy dissipation capacity is to consider the different disturbances such as general disturbances and serious faults as frequency stability constraints, to add new energy, thermal power, load and contact lines as peak constraint, and to analyze and evaluate the new energy permeability taking into account the constraints of the control capacity of the units. Figure 1 presents the evaluation method.

**Peak Shaving Constraint**

The new energy has unique resource characteristics, such as volatility and a certain degree of reverse peak characteristics, increasing the peak regulating pressure of the power grid, thus it limits the level of new energy consumption.

In this section, a new energy admission capacity analysis method, which considers the peak capacity of the contact line, is adopted. The new energy is set to zero at the peak load, and the starting capacity of the thermal power unit is solved through the active power balance under the condition of...
the known peak load, the transmission power of the contact line and the reserve capacity. At this time, it is assumed that the new energy is full in the low load of the load, and the minimum output value of the conventional unit is determined according to the output range of the thermal power unit, and the new energy output is solved with the low valley load. Finally, the maximum permeability of new energy is determined under the condition of a certain amount of abandoned wind and solar energy. It should be noted that the new energy penetration rate is used as an index to evaluate the capacity of new energy consumption in this paper.

1) The peak load is set to $P_{L_{\text{max}}}$, it needs to be met in Eq.1,

$$P_{L_{\text{max}}} = P_{G_{\text{max}}} - P_{\text{Tie}}$$  \hspace{1cm} (1)

where $P_{\text{Tie}}$ is transmission power of contact line, then the maximum output of the thermal power unit $P_{G_{\text{max}}}$ can be calculated. Thus, the power supply reserved for a certain reserve capacity is computed by Eq.2.

$$P_{GM} = P_{G_{\text{max}}} + P_{\text{res}}$$  \hspace{1cm} (2)

where $P_{\text{res}}$ is reserve capacity

2) When the load is at a low point, total power of thermal power and new energy $P_{G_{\text{min}}}$ can be modelled by Eq.3.

$$P_{G_{\text{min}}} - \gamma P_{\text{Tie}} = P_{L_{\text{min}}}$$  \hspace{1cm} (3)

where $P_{L_{\text{min}}}$ is minimum load, and $\gamma$ denotes power adjustment coefficient of contact line. Maximum new energy output is yielded by

$$P_{\text{new}} = P_{G_{\text{min}}} - \beta P_{GM}$$  \hspace{1cm} (4)

where $\beta$ is minimum force coefficient and $\beta P_{GM}$ refers to minimum output of thermal power unit. Then the maximum permeability of new energy is computed by

$$P_{pvp} = \frac{P_{\text{new}}}{P_{L_{\text{max}}} + P_{\text{Tie}}} / (1 - \rho)$$  \hspace{1cm} (5)

where $\rho$ is discarding rate of wind and solar energy.

**Regulation Capacity Constraint of Unit**

The rapid fluctuation of new energy output will inevitably lead to frequent regulation of conventional units, especially thermal power units. During the actual operation, the rotor is subjected to alternating thermal stress in the process of regulation. After a certain cycle, the fatigue crack will appear on the surface of the metal and gradually expand to fracture, and the cycle is called the crack cycles [20]. The greater the stress, the fewer the cycles and the more serious the life loss. This section adopts a method to estimate the life loss of unit life, through the calculation of stress, crack cycles can be solved, and the relationship between them can be expressed by the following formula.

$$N_C = (\frac{0.25E_y \ln \frac{1}{1-\varphi}}{\sigma_a - \sigma_{ao}})^2$$  \hspace{1cm} (6)

where $N_C$ is crack cycles, $E_y$ denotes elasticity modulus of material, $\varphi$ refers to section shrinkage coefficient of material, and $\sigma_{ao}$ is limit value of fatigue strength. Then the stress of calculating point($\sigma_a$) can be computed by Eq.7,
\[ \sigma_m = \frac{E \alpha}{1 - \mu} \Delta m \]  

(7)

where \( \alpha \) is coefficient of expansion of rotor material, \( \mu \) refers to Poisson ratio, \( \Delta m \) denotes temperature difference, which has the following relation with the temperature rise rate (\( \eta \)).

\[ \Delta m = \frac{\eta}{4a} R^2 \]  

(8)

where \( a \) is material conductance coefficient, and \( R \) refers to metal thickness on the radius of the rotor.

After obtaining \( N_c \), the life loss adjusted once can be estimated by Eq. 9,

\[ d_c = 1 / N_c \]  

(9)

Then, according to the linear damage accumulation rule, the total loss rate of the unit after frequent adjustment is obtained by adding the life loss caused by each adjustment.

In order to make the steam turbine run safely and economically during the service period of the unit, it is necessary to allocate the frequently adjusted life as a constraint to limit the acceptance of new energy.

**Frequency Stability Constraint**

The dynamic role of the governor of thermal power units should be taken into account in the analysis of frequency stability. Figure 2 shows the system model block diagram of generator-load with speed governor effect.

*Figure 2. Block diagram with speed governor.*

\[ \Delta P_D \]  

\[ \Delta f \]  

\[ \Delta P_G \]  

In the above figure, \( \Delta P \) is amount of unbalance power, \( \Delta P_D \) denotes the power change of generator unit, \( \Delta P_G \) refers to the load change, \( T_G \) is time constant of speed governor, \( K_G \) indicates the regulation effect coefficient of generator unit, \( T_J \) denotes the inertia time constant of generator unit and \( K_D \) refers to the load regulation effect coefficient.

The wind turbine and photovoltaic generating units cannot provide inertia support, which results in the system's equivalent rotational inertia decline. And according to Fig.2, it can be inferred that the decrease of moment of inertia will lead to a decrease in the system's ability to resist unbalance disturbance and make the problem of frequency stability more prominent. In view of the relevant technical specifications and general operating experience, in order to study the new energy dissipation capacity under the frequency stability constraints, the requirements for the frequency stabilization of the power grid are as follows.

1) When the power grid is slightly disturbed, such as any motor trip, DC single pole fault, and the power fluctuation of a large new energy base, the frequency deviation should meet the operation requirements of the power grid (generally not more than 0.2Hz).

2) When a serious fault such as a N-2 fault occurs, including the DC bipolar locking, the generator set removal, and the connection line disconnection, a larger power imbalance will occur. At this time, the control measures (such as cutting, cutting load) are taken into consideration, after which the action...
of high frequency protection or low frequency load reduction cannot be caused, that is, the frequency deviation does not exceed the allowable value (usually 1.0Hz).

3) Under-frequency load shedding and high-frequency generator trip are taken to make the system frequency back to the allowable range and keep the system from breaking down in frequency when the extreme fault such as substation completely shutting down or losing large capacity power plant occurs. This article focuses on the first two requirements, and the frequency stability problem under extreme fault will be further studied. The corresponding frequency range is required for each frequency stable setting value as shown in Figure 3.

Assessment of Consumption Ability

Assessment of Consumption Ability Considering Peak Shaving

In this paper, the power grid supplies constant power by contact line \( \gamma = 1 \), and the transmission power of the contact line is set to 0.3. When the load is highest, the thermal unit has the maximum output, of which the per unit is set to 1. According to the formula of the last section, the peak load is calculated to 0.7. Then the valley load is estimated to be about 0.5 according to the typical daily load curve. The typical daily load curve is shown in Figure 4.

The minimum technical output of the thermal power unit is 0.4 and the reserve capacity is 5% of the total capacity, and then the maximum permeability of the new energy can be calculated to 40% by the formula in section 2.2 under the condition of setting up the 5% discarding rate of wind and solar energy.
Assessment of Consumption Ability Considering Unit Regulation

In general, about 10% of the life loss of the unit is allocated to the load fluctuation of the unit[17]. For wind power, because of the low probability of large fluctuations in small minute magnitude, this paper takes the time interval between 10 and 20min to do the following simulation. With the new energy fluctuation, the thermal power unit reduces the load with the change rate of -2.5% by 24min from the initial state, and then increases the load by 21min with 2.5% load change rate, then increases by 16min with the rate of 3.5% change, and finally reduces the load by 10min with the 5% load change rate. According to the material parameters in [20], the life loss of each stage can be obtained as shown in Table 1.

Table 1. Life loss under different load changing process.

<table>
<thead>
<tr>
<th>Load change rate</th>
<th>-2.5%</th>
<th>+2.5%</th>
<th>+3.5%</th>
<th>-5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life loss [%]</td>
<td>6.9*10^{-5}</td>
<td>6*10^{-5}</td>
<td>6.3*10^{-5}</td>
<td>7.5*10^{-5}</td>
</tr>
</tbody>
</table>

The service life of the unit is 20 years, the annual operation is 310 days, and the same unit adjustment process in one day is calculated by 6 times. According to the linear cumulative principle mentioned in the previous article, the total life loss can be estimated as follow, (6.9*10^{-5}+6*10^{-5}+6.3*10^{-5}+7.5*10^{-5})×310×20×6=9.93%, which is close to the assigned limit of life.

According to the above analysis, a general estimation can be made, the higher the ratio of new energy, the greater the regulation range of the unit, and the more serious the life loss. When the load change rate of the thermal power unit does not exceed 5%/min, the life loss is in the acceptable range. The new energy permeability is limited by this value, when the time scale is small, for example, fluctuating 6 times in 10min, the power fluctuation of the new energy is small and set to 3%/min, then the new energy permeability is estimated to be 62.5% with the regulation load rate of the thermal power unit not exceeding 5%; When the time scale is larger, for example fluctuating 6 times in 1 hour, the amplitude of the new energy power fluctuation increases, which is set to 8%, and the new energy permeability can be estimated by the same standard as 38.5%.

Assessment of Consumption Ability Considering Frequency Stability

One generator with centralized load model is simulated by PSD-BPA, in which the generator reserve capacity is 5%, the inertia time constant is 8 seconds, and the active frequency factor of the load is 1.0. The frequency variation process of general disturbances and severe failures is simulated, in order to analyze the limitation of frequency stability to the capacity of new energy consumption.

1) Calculation and analysis of general disturbance

The power grid of different scale may produce different power imbalance when the general disturbance occurs. This section selects 3 kinds of power vacancies, which are 1%, 1.5% and 2%, to simulate the general disturbance, and the maximum frequency change does not exceed 0.2Hz as the standard. The result is shown in Figure 5:
In the case of 1%, 1.5%, and 2% power vacancy, the corresponding new energy permeability is 57.6%, 36.2% and 24%, when the frequency deviation allowable value 0.2Hz is the limit condition.

2) Calculation and analysis of serious fault

When serious faults occur, it is necessary to consider the difference in power shortage due to the different scale of the grid. Serious failure usually configures the security control device, but the security control setting will often leave a certain amount of imbalance, usually 2% to 3% and the larger value 3% is selected here. This section sets three power vacancies 15%, 20% and 25% to simulate serious faults, and the corresponding 12%, 17% and 22% load after 300ms delay. In order to make the low frequency load shedding not move, the minimum frequency threshold is set at 49.0Hz, and the simulation results are shown in Figure 6.

Taking 1.0Hz as the permissible limit of frequency deviation, the permeability of new energy is limited to 60.6%, 48% and 35%, respectively, in the case of 15%, 20%, 25% power vacancies.

**Comprehensive Evaluation**

Summarize the new energy penetration rates determined under different constraints in the previous sections as shown in Table 2:

<table>
<thead>
<tr>
<th>constraints</th>
<th>peak regulation</th>
<th>regulating ability of unit</th>
<th>general disturbance</th>
<th>serious fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability range</td>
<td>40%</td>
<td>38.5%-62.5%</td>
<td>24%-57.6%</td>
<td>35%-60.6%</td>
</tr>
</tbody>
</table>

Figure 5. Frequency variation curves under different disturbances.

Figure 6. Frequency variation curves due to different loss of generation under severe faults.
According to the above table, the range of new energy permeability defined by each factor is intersecting, that is, each constraint restricts the capacity of new energy to a certain extent and considering only one constraint is obviously limited. For example, for areas with large DC feed or large power units, the difficulty of frequency control is high, and frequency stability will be the main factor limiting new energy consumption. In the case of bad environmental conditions, the regulation capability of the unit may become the main constraint because the regulation speed of thermal power unit is difficult to adapt to the rapid change of new energy output. Meanwhile, the peak load capacity obviously becomes the main constraint in areas where the electrodes are unbalanced. Therefore, the comprehensive evaluation method proposed in this paper can reasonably and comprehensively analyze the capacity of new energy consumption.

Conclusion

In this paper, based on the effects of peak regulating capacity, unit regulation performance and frequency stability on the level of new energy consumption, a set of comprehensive evaluation methods for new energy dissipation capacity is proposed, which considers steady state and dynamic active power balance constraints. In terms of peak load regulation, new energy penetration is calculated according to the load, tie line and unit output range. Considering the unit's regulating ability, the life loss of the units is calculated by the stress change of the unit's frequent adjustment, and then the scale of the new energy acceptance is restrained. And take the problem of frequency stability into account, and the new energy dissipation capacity under the disturbance constraints is analyzed based on the different types of disturbance such as general disturbance and serious fault and the corresponding frequency deviation allowable value.

The results show that, due to the difference of the magnitude of disturbance, the randomness and volatility of the new energy and the change of the load characteristics, different constraints restrict each other and may limit the level of new energy consumption to a certain extent. The comprehensive evaluation method proposed in this paper can comprehensively and continuously assess the new energy capacity of the power grid, which makes up for the shortcomings of the previous system deficiencies.

At present, in the actual operation of the power grid, the load peak and valley difference is large and the regulation capacity of the unit is still lacking. Obviously, it is difficult to achieve a relatively high ratio for the new energy consumption. Therefore, the future research focus and development direction is to strengthen the flexibility transformation of the unit, popularize the load demand side management strategy and energy storage technology, and vigorously develop new energy friendly technologies such as virtual synchronizer, so as to improve the level of new energy consumption.

References


