Research on Optimization of Power System Regulation Capacity Based on New Energy Installed Capacity

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Abstract. As the proportion of new energy continues to increase, the safety and stability of the power system faces severe challenges. Many a flexible resource should be established to ensure that the regulating ability of the power system is enough, so as to cope with the load fluctuations caused by the grid-connected new energy. This article analyses the technical characteristics of various flexible resources, and which aspect that each flexible resource can contribute to the regulating ability of the power system. On this basis, this paper proposes a quantitative analysis method of the improvement of power system regulating ability based on the consumption model of new energy, using the addition of new energy grid-connected capacity as a quantitative indicator to evaluate the improvement of system regulating ability contributed by each type of flexible resource. Combined with calculation examples, a quantitative analysis of usual flexibility resources is carried out.

1. Introduction

On September 22, 2020, Chinese President Xi Jinping announced at the General Debate of the Seventy-fifth United Nations General Assembly that China will increase its nationally determined contributions and adopt more powerful policies and measures to achieve the CO2 emission capacity by 2030. Peak, strive to achieve carbon neutrality before 2060. The common characteristics of the power system in most areas of China are that they are mainly consisted of thermal power and lack hydropower which has good regulation performance. In the context of large-scale connection and increasing proportion of new energy, flexible resources are becoming increasingly scarce because of the fluctuation of load and the ever-increasing peak-to-valley gap. Without enough flexibility resources and planning, the contradictions during the "14th Five-Year Plan" period will be difficult to reconcile. Therefore, to find out the contribution of various flexible resources on the improvement of regulating ability of power system is not only an urgent need for the security and stability of power system, but also an important precondition for the subsequent increasing of new energy sources and the transformation of the power system.

1.1. Power System Regulating Ability

At present, there is no clear standard for the definition of power system regulating ability at home and abroad. North American Electric Reliability Corporation (NERC) defines the power system regulation capability as the ability to use system resources to respond to load changes[1], The International Energy Agency (IEA) believes that the regulation capability of the power system refers to the ability of the system to react quickly when the load or power generation of the power system fluctuates under certain operating conditions[2].
2. Analysis of Technical Characteristics of Usual Flexible Resources

2.1. Power Generation Resources

Flexible resources on the power generation side refer to traditional power generation resources other than intermittent renewable energy, mainly including thermal power and hydropower. Some of the thermal power plants that can respond quickly can provide high-quality flexibility. At the same time, the flexibility of thermal power units can be modified as their minimum output level can be adjusted through technical solutions, which can also provide more flexibility. Some hydropower plants with good regulating performance have all the functions including power generation, peak regulation, frequency regulation, and backup [3]. They can quickly respond to load changes and are economical. However, due to the impact of resource endowments, their construction locations are limited. As the rate of intermittent renewable energy power generation continues to increase, it is necessary to set and configure multiple types of flexible resources on the power generation side. After analysing their technical, the development and utilization combination can be determined based on the actual situation of the power grid. The technical characteristic of usual thermal units are given in the following table.

2.2. Demand-side Resources

With the development of the power system, relying solely on the power supply side to meet the increasing load and short-term peak power consumption will cause the cost of power generation and supply continuing to rise, which is extremely unfavourable to the rational use of social resources [4]. There is a certain potential to develop demand-side resources by demand-side management. Demand response (DR), due to the introduction of market regulation mechanisms, has a high degree of user participation, rich forms of participation, and effective energy-saving effects. Broadly speaking, demand-side response can be defined as the market participation behaviors of users in the electricity market responding to price signals or incentive mechanisms to change the normal electricity consumption pattern. In the future, with the advancement of power marketization, user-side flexibility resources will be of greater significance to the improvement of system flexibility. In addition, with the continuous popularization of electric vehicles and the development of V2G (Vehicle to grid), a large number of researches on electric vehicles and their impact on the power system have been carried out. Electric vehicles are also an important resource for providing flexible services on the demand side [5].

| Working Period | Type                  | Technical characteristic | Min Output | Max Output |
|---------------|-----------------------|--------------------------|------------|-----------|
| Heating season| Coal-fired unit       |                          | 40%        | 100%      |
|               | Gas-fired unit        |                          | 70%        | 90%       |
| Non-heating season| Coal-fired unit |                          | 40%        | 100%      |
|               | Gas-fired unit        |                          | 30%        | 100%      |
| Whole year    | Coal-fired            |                          |            |           |

2.3. Energy-storage Resources

Energy storage of power system refers to the facilities and mechanisms which can turn electrical energy in the power system into other forms of energy through physical or chemical means. They are also able to converted the physical or chemical energy into electrical energy to be input into the power system when needed. Due to the fast response speed and comprehensive technical characteristics of energy
storage, it has been widely used in power systems, such as peak shaving, flexible ramping, energy supply, frequency modulation, operating standby, and black start. By configuring a reasonable amount of energy storage facilities, it is possible to improve the controllability of the output power even take the intermittent renewable energy and suppress power fluctuations into account. From the perspective of providing flexibility, energy storage enriches the regulating ability of power system operation by shifting the time of power supply and demand.

**Table 2. Technical catachrestic of energy storage.**

| Storage Type         | Continual time | Life Time | Energy Consumption Scatter rate(%) | Energy Density(W·h/l) | Power Density(W/l) | Efficient(%) | Response time |
|----------------------|----------------|-----------|-----------------------------------|-----------------------|-------------------|--------------|--------------|
| Pumped storage       | 4-10h          | 30-60 years | ≈0                                | 0.2-2                 | 0.1-0.2            | 70-85        | Sec-Min level |
| Compressed air storage | 2-30h          | 20-40 years  | ≈0                                | 2-6                   | 0.2-0.6            | 40-75        | Sec-Min level |
| Flywheel storage     | Sec-Hour level | 0-1000 times | 1.3-100                           | 20-80                 | 5000              | 70-95        | 10-20ms       |
| Superconducting storage | MS-min Level | 10000 times | 10-15                             | 6                     | 1000-4000         | 80-95        | <100ms        |
| Lithium battery      | 1h-8h          | 2500-4400 times | 0.05-20                          | 150-300              | 120-160           | 70-90        | 10-20ms       |
| Lead-acid batteries  | 1min-8h        | 6-40 years | 0.1-0.3                           | 50-80                 | 90-700            | 80-90        | <s           |
| Flow battery         | 2-10h          | 0-1400 times | 0.2                               | 20-70                 | 0.5-2             | 60-85        | 10-20ms       |

2.4. Grid-side Resources

The electric power network is the key way to realize the flexibility of the power system. Reasonable power grid planning and construction can ensure the security of power supply, enhance the power system's ability to integrate renewable energy generation, attract investment from various power market participants, and ensure the good operation of the power market. Flexible AC Transmission System (FACTS) is a new technology that has emerged in recent years. It applies the latest development achievements of power electronics technology and modern control technology to achieve flexible and rapid control of AC transmission system parameters and even network structure, in order to achieve reasonable distribution of transmission power, reduce power loss and power generation costs, and greatly improve system adjustability, Stability and reliability.
3. Utility Analysis Method of Power System Regulation Capacity Improvement Based on New Energy Limit Consumption Model

3.1. Calculation Process
As shown in Figure 1, the calculation of the addition of the new energy installed capacity can be divided into three steps. The first step is to combine the actual endowment of flexible resources of the target system and set an addition capacity step for the flexible resources that need to be analysed. The second step is to set up the simulation scene. In the set benchmark scenario, increase the new energy installed capacity in equal steps to form a simulation scenario. The third step is to simulate the set scene of the power system. Gradually increase the grid-connected new energy installed capacity in 10MW steps until the annual wind and solar abandonment rate of the system reaches 5%. And then stop iteration and output the new total installed capacity of new energy as a measure of the improvement of the power system regulating ability of the regulating resources. [6]

Figure 1. Program flow chart.

3.2. New Energy Limit Consumption Model
- Objective function
The simulation uses a unit combination model that does not contain network topology constraints and is based on security constraints. The objective function is that the total power generation cost of the system in the time period T (heating period and non-heating period) is minimized, including the operating and power generation cost of thermal power units, Start-up costs and penalty costs for abandoning new energy. When the penalty factor is large, abandoning wind and solar will be subject to a large amount of fines. Since the goal is to have the lowest total operating cost of the system, the model will also avoid abandoning wind as much as possible. So the simulation result will show the situation that the new energy technology is well consummated.

\[
\min F = \sum_{i=1}^{T} \sum_{i=1}^{N} [U_{i,t}(a_iP_{i,t} + b_i) + U_{i,t-1}(1-U_{i,t})S_{i,t}] + \sum_{i=1}^{T} \rho_1 P_{c1,t} + \sum_{i=1}^{T} \rho_2 P_{c2,t}
\]

Where: \(T\) is the number of periods; \(N\) is the number of thermal power units; \(U_{i,t}\) is the operating state variable of the unit during the period, \(U_{i,t} = 0\) represents shutdown, \(U_{i,t} = 1\) represents operation; \(P_{i,t}\) is the power variable of the thermal power unit during the period; \(a_i\) is the marginal energy consumption cost parameter of the unit; \(b_i\) is the no-load of the unit Cost parameter; \(S_{i,t}\) is the start-up cost of the unit;
\( \rho_1 \) and \( \rho_2 \) respectively represents the penalty coefficient for abandoning wind power and photovoltaic; \( P_{e1,t} \) and \( P_{e2,t} \) respectively is the amount of wind abandonment and solar abandonment of the system during the time period.

- Thermal power units constraints
  Constraints on the upper and lower limits of output:
  \[
  U_{i,t} P_{i,\text{min}} \leq P_{i,t} \leq U_{i,t} P_{i,\text{max}}
  \]  
  \( U_{i,t} \) is the pumping efficiency of the pumped storage unit.

Where: \( P_{i,\text{min}} \) and \( P_{i,\text{max}} \) are the minimum and maximum technical output of the unit respectively.

Minimum start and stop time constraints:
\[
\begin{align*}
(U_{i,t-1} - U_{i,t})(T_{i,t-1} - T_{i,\text{on}}) & \geq 0 \\
(U_{i,t} - U_{i,t-1})(T_{i,t-1} - T_{i,\text{off}}) & \geq 0
\end{align*}
\]

Where: \( T_{i,\text{on}} \) and \( T_{i,\text{off}} \) are the minimum continuous operation and shutdown time of the unit respectively.

Ramping constraints:
\[
\begin{align*}
P_{i,t-1} - P_{i,t} & \leq \Delta P_{i,\text{down}} \\
P_{i,t} - P_{i,t-1} & \leq \Delta P_{i,\text{up}}
\end{align*}
\]

Where: \( \Delta P_{i,\text{up}} \) and \( \Delta P_{i,\text{down}} \) are the upper and lower climbing limits of the unit respectively.

- Energy storage constraints
  Constraints on the upper and lower limits of absorbing and generating power:
  \[
  \begin{align*}
  0 & \leq P_{pi,t} \leq U_{pi,t} P_{pi,\text{max}} \\
  0 & \leq P_{gi,t} \leq U_{gi,t} P_{gi,\text{max}} \\
  U_{pi,t} U_{gi,t} & = 0
  \end{align*}
  \]
  Where: \( P_{pi,t} \) and \( P_{gi,t} \) are the pumping and generating power of the pumped-storage unit during the time period respectively; \( U_{pi,t} \) and \( U_{gi,t} \) are the operating state variables of the pumped-storage unit during the time period, \( U_{pi,t} = 1 \) representing shutdown, \( U_{gi,t} = 1 \) representing pumping, and representing power generation.

Energy storage capacity constraints:
\[
E_{i,\text{min}} \leq E_{i,t} \leq E_{i,\text{max}}
\]

Where: \( E_{i,t} \) is the energy storage capacity of the pumped storage unit during the period of time, and \( E_{i,\text{min}} \) and \( E_{i,\text{max}} \) is the minimum and maximum energy storage limit.

Intraday balance constraint:
\[
\begin{align*}
\sum_{t=1}^{24} (P_{pi,t} - \eta_t P_{gi,t}) & = 0
\end{align*}
\]

Where: \( \eta_t \) is the pumping efficiency of the pumped storage unit.
4. Calculation Results and Analysis
This paper takes the power system in a certain area in northern China as an example, and calculates the influence of thermal power flexibility transformation units, pumped storage units, and 3-hour energy storage included in the grid reform on the system's regulation capacity. The calculation results and analysis are shown below.

- Flexible transformation of thermal power units
The calculation example is based on the data of a power grid in northern China. Based on the basic scenario, the abandonment rate of wind energy is controlled under 5% when the thermal power unit's flexible transformation capacity is added from 4500MW to 10500MW with 500MW as the step length. The figure below is the calculation result:

Table 3. Additional capacity of new energy under different transformation capacities.

| Flexible transformation of thermal power units | Additional capacity /MW | Step /MW | Additional capacity of new energy every 1000MW /MW | Abandonment rate /% |
|-----------------------------------------------|-------------------------|---------|-----------------------------------------------|---------------------|
| Basic scenario                                | 4500                    | -       | -                                            | 4.92%               |
| Simulation scene                              | 5500                    | 1000    | 3246                                         | 4.94%               |
|                                               | 6500                    | 1000    | 3023                                         | 4.93%               |
|                                               | 7500                    | 1000    | 3121                                         | 4.96%               |
|                                               | 8500                    | 1000    | 2826                                         | 4.96%               |
|                                               | 9500                    | 1000    | 2830                                         | 4.94%               |
|                                               | 10500                   | 1000    | 3211                                         | 4.96%               |
| Average                                       |                         |         | 3042                                         | 4.95%               |

Average wind curtailment rate: 4.95%

Figure 2. Additional capacity of new energy under different transformation capacities.
It can be seen from the above chart that the increase in the flexible transformation capacity of thermal power units will obviously promote the increase in the additional installed capacity of new energy, and the two are in a linear relationship. Under the current boundary conditions, when the wind abandonment rate is controlled at 4.9%-5%, the additional wind power installed capacity supported by the flexible transformation capacity of 1,000 MW of thermal power will be about 3000 MW. In summary: The ratio of the flexible transformation capacity of thermal power units to the additional capacity of new energy is 1:3.

- **3h electrochemical energy storage**

Based on the basic scenario, the calculation example uses 300MW as the step length to calculate the corresponding wind abandonment rate when the newly-built 3h electrochemical energy storage capacity is from 300MW (a new set of electrochemical energy storage) to 1200MW (a new set of electrochemical energy storage). The figure below is the calculation result:

| Table 4. Additional capacity of new energy under different energy storage capacities. |
|---|---|---|---|
| **3h electrochemical energy storage** | **Additional capacity /MW** | **Step /MW** | **Additional capacity of new energy every 300MW /MW** | **Abandonment Rate /%** |
| Basic scenario | Flexible transformation of thermal power | 4500MW | - | - | 4.92% |
| Simulation scene | 300 | 300 | 425 | 4.95% |
| | 600 | 300 | 429 | 4.98% |
| | 900 | 300 | 303 | 4.98% |
| | 1200 | 300 | 218 | 4.95% |
| Average | 343.75 | - | 4.965% |

**Figure 3.** Additional capacity of new energy under different energy storage capacities.
It can be seen from the above chart that the newly-built electrochemical energy storage can promote the increase of new energy installed capacity to a certain extent. The newly built 300MW 3h energy storage can add 425MW of wind power installed capacity; compared with the newly built 300MW energy storage, the newly built 600MW 3h energy storage can add 429MW of wind power installed capacity; compared to the newly built 600MW energy storage, the newly built 900MW 3h energy storage It can add 303MW of wind power installed capacity; similarly, the newly built 1,200 MW 3h energy storage can add 218MW of wind power installed capacity. In summary:
The ratio of additional capacity of 3h electrochemical energy storage to the additional capacity of new energy is 1:2.2.

- Pumped storage units
Based on the basic scenario, the calculation example uses 300MW as the step length to calculate the corresponding wind abandonment rate when the capacity of the newly-built pumped storage unit ranges from 300MW (newly built a pumped storage unit) to 1200MW (newly built 4 pumped storage units); Based on the 4 pumped storage units, the situation of a new pumped storage power station (1200MW) was further estimated. The figure below is the final calculation result:

| Pumped storage units | Additional capacity /MW | Step /MW | Additional capacity of new energy every 300MW /MW | Abandonment Rate /% |
|---------------------|-------------------------|---------|-----------------------------------------------|-------------------|
| Basic scenario      |                         |         |                                               |                   |
| Flexible transformation of thermal power 4500MW | - | - | - | 4.92% |
| Simulation scene   |                         |         |                                               |                   |
| Add pumped units    | 300                     | 300     | 485/300MW                                     | 4.93%            |
|                     | 600                     | 300     | 621/300MW                                     | 4.93%            |
|                     | 900                     | 300     | 974/300MW                                     | 4.94%            |
|                     | 1200                    | 300     | 540/300MW                                     | 4.94%            |
| Total               | 2400                    | -       | 2620/1200MW                                   | 4.935%           |
| Add pumped station  | 2400                    | 1200    | 2670/1200MW                                   | 4.96%            |
| Average             | 661.25/300MW            |         |                                               | 4.94%            |

It can be seen from the above chart that the newly built pumped storage units and pumped storage power stations can promote the increase of new energy installed capacity. Under the current boundary conditions, when the wind curtailment rate is controlled at 4.9%-5%, the new wind power installed capacity that can be absorbed by each new 300MW pumped storage unit is about 661.25MW; the newly built 1200MW pumped storage power station can absorb The newly added wind power installed capacity is about 2660MW; the two sets of data are consistent. In summary, in the basic scenario:
The ratio of additional capacity of pumped storage unit capacity to the additional capacity of new energy is 1:2.20.
Figure 4. Additional capacity of pumped units under different energy storage capacities.

5. Conclusion

From the above analysis, it can be seen that when the flexibility of the power system is insufficient, it is best to give priority to the flexible transformation of thermal power units. The ratio of the flexible transformation capacity of thermal power units to the additional new energy capacity is 1:3. The newly-built 3h energy storage and the newly-built pumped-storage power station have a similar improvement effect, and the ratio of newly-built capacity to additional new energy capacity is 1:2.2. On the one hand, considering the large difference in cost between new electrochemical energy storage and new pumped storage units, it can be concluded that when the demand for flexibility is small, the construction of 3h electrochemical energy storage should be considered first. When the demand for flexibility is large, consideration should be given to building large-capacity pumped-storage power stations. On the other hand, this result also shows that the demand for flexibility of the current power system is concentrated on a smaller time scale (less than 3h). Although pumped storage can be used for 6 hours of continuous pumping or power generation, which is much higher than the 3h of energy storage, flexibility is not fully utilized.

In a word, for power systems that lack flexibility, the flexibility of thermal power generation units should be modified first, and then a new electrochemical energy storage or pumped storage power station should be decided based on the lack of flexibility.

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