Fast Frequency Response Capability of Large-Scale Clustered Access to the New Energy at the Sending End in Power Grid

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Abstract. Recently, the proportion of the new energy in the Northwest China Power System has been growing, occupying the space of conventional power units with rotational inertia. The operation with safety and power system stability is facing great challenges. Facing the increasing shortage of traditional frequency modulation resources, it is urgent to carry out the use of wind power and photovoltaic (PV) to involve in the system frequency modulation method. From the perspective of the power grid operation demand, this paper proposes the optimization scheme of fast frequency control parameters of the new energy power generation. The primary frequency modulation method of the new energy and conventional unit power supply cooperate and relay on the time scale. Through the application in the actual power station, the results show that the grid has sufficient primary frequency modulation ability, and the frequency security of the large power grid at the transmission end is effectively improved.

Keywords. New energy, perturbation capability, time scale, primary frequency modulation

1. Introduction

Nowadays, the new energy grid in Northwest China has been developing considerably. Since June 2021, 127.69 million kW of the new energy was installed in Northwest China, of which, 68.61 million kW is wind power and 59.08 million kW is photovoltaic [1, 2]. The grids in Northwest China are the ones with the largest new energy installation and the largest number of DC transmission returns among regional grids in China, and the features of the power grid at the sending end with high percentage of new energy are obvious [3-5]. After a large number of new energy clusters are linked to the grid, the whole grid presents high degree of power electronic characteristics, problems of the power system stability are prominent, and the safe and stable operation of the power system is facing great challenges [6, 7].

This paper mainly introduces the program of typical wind power plants and photovoltaic (PV) power plants to involve in the fast frequency response of the grid, and
analyses of the fast frequency response capability of PV power plants and wind power plants with field tests. The experimental results showed that PV power plants and wind power plants could involve in the grid fast frequency response, and the new energy cooperates with conventional units to involve in the grid frequency modulation, which presents good application prospects.

2. Ways for the New Energy to Involve in the Fast Frequency Response of the Power Grid

2.1. The Way the Wind Turbines Involving in the Fast Frequency Response of the Grid

The frequency modulation method of wind turbine mainly includes the reserved spinning reserve and the wind turbine rotational kinetic energy utilization, specifically including the inertia response control (the wind turbine rotational kinetic energy utilization), speed control (the reserved spinning reserve) and the pitch angle control (the reserved spinning reserve) [8-10]. The implementation methods and disadvantages of different frequency modulation methods are shown in Table 1.

<table>
<thead>
<tr>
<th>Implementation method</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Inertial response control</td>
<td>Fast throughput of wind turbine inertial energy storage through wind turbine electromagnetic torque control Easy to cause secondary frequency drop in the system</td>
</tr>
<tr>
<td>Rotational speed control</td>
<td>Wind turbine load-shedding operation control Complex to implement, and real-time operation of wind turbines generate abandoned power</td>
</tr>
<tr>
<td>Pitch angle control</td>
<td>During steady-state operation, the pitch angle of the wind turbine is increased appropriately and the system frequency change rate is introduced as input to modulate the pitch angle change of the wind turbine Pitch angle control speed is slow and subject to mechanical wear and tear</td>
</tr>
</tbody>
</table>

The comparison in Table 1 shows that the coordination of the three methods for frequency modulation were applied to improve the system stability.

Single machine + full-field optimal control: The optimized combination of single machine frequency modulation mode is carried out in combination with the operating conditions of each wind turbine, which makes use of both the rapidity of the inertia response and the continuity of the pitch angle control. The typical design can be seen in Figure 1.

The model of primary frequency modulation instruction link in wind farm is shown in Figure 2. The model adopts the first-order inertia and the nonlinear to represent various parts of the primary frequency modulation command implementation. In Figure 2, $P_{PFC,wt}$ is the wind power frequency-active droop characteristic function; $f_0$ is the rated frequency, taken as 50Hz, move the frequency measurement in the output direction; $T_{med}$ is the frequency measurement equivalent inertia time; $r_e$ is the rate limit of the frequency modulation power command; $\tau$ denotes the delay time of issuing an frequency modulation power command; $f$ denotes the power system frequency; $e$ denotes the natural constant of the pure delay in the power system frequency; $P_{m}$ denotes the primary FM power command for wind farms; $\Delta P_{wt,m}$ denotes the primary FM power distribution.
instruction of the mth typhoon power unit; \( \Delta P_{wt-ad} \) denotes the adjustable real power margin for the wind farm; \( \Delta P_{wt-ad,m} \) denotes the adjustable real power margin for the mth wind turbine generator; FM denotes the frequency measurement; FCPC refers to the calculation link for the primary FM power command; FCPD refers to the distribution link for the primary FM power command; FCPT refers to the delay link of issuing a FM power command; FCPSL refers to the speed limit link of the primary FM power command of the wind turbine generator.

![Diagram of primary frequency modulation instruction link in wind farm](image)

*Figure 1.* Single machine + full-field optimized control implementation.

\[
f(t) = \frac{1}{1 + T_{med}} \Delta f_{\text{WT}}(\Delta f) + P_{\text{FCPC}}(\Delta f) + \frac{1}{1 + T_{dis}} \Delta P_{\text{FCPSL}}
\]

*Figure 2.* Model of primary frequency modulation instruction link in wind farm.

Since the model of primary FM instruction of wind farm starts from the level of wind farm, and the distribution of primary FM power instruction mainly has a significant impact on the response time, the first-order inertial link is needed to realize the power system level simulation, and the wind power plant primary frequency modulation command model was improved, as shown in Figure 3. In Figure 3, \( T_{dis} \) is the equivalent inertia time of the primary frequency modulation power command allocation.

![Diagram of improved primary frequency modulation command model](image)

*Figure 3.* Improved primary frequency modulation command model for wind power plants.

When the control object remains unchanged, i.e., when the single machine control architecture and performance of the wind turbine unit remains unchanged, in the equivalent model of wind farm frequency response of variable speed wind turbines with primary frequency modulation command, the parameters which affect the primary frequency modulation performance of wind farms in the model mainly include \( T_{med} \), \( \tau \), \( T_{dis} \), and \( r_a \).
2.2. Ways for Photovoltaic Power Generation to Involve in the Rapid Frequency Response of the Power Grid

2.2.1 Active Power-Droop Control Strategy

As shown in Figure 5 below, the active power-frequency droop characteristic curve is set. The curve is set according to the active power-frequency static characteristics of the synchronous generator set when the active power is set. This curve can reflect the trend of the frequency droop control of photovoltaic power generation. The real power output of the PV generator set is expressed in equation (1) [11, 12].

\[
P = P_0 - k(f - f_d) \cdot P_n
\]

in the formula \( f_d \) means the frequency response action value; \( k \) means the frequency adjustment coefficient at 1/Hz; \( P_n \) means the maximum output power of PV power generation under any light intensity, that is, the sagging coefficient varies with the light intensity; \( P_0 \) means the initial power value.

![Figure 4. Real power-frequency droop curve.](image)

![Figure 5. Active power-frequency droop control strategy.](image)

The optimized inverter control strategy is shown in Figure 5. After the power error signal passed through the PI controller, the \( d \)-axis current reference value \( i_{dref} \) is generated. The standby power of PV power generation can be defined as the ratio of active power variation to active power \( \sigma \% \), the PV power generation unit outputs (1- \( \sigma \% \)) of active power under the power-limited operation state of PV power generation, \( \sigma \% \) is presented as equation (2).

\[
\sigma \% = \frac{\Delta P}{P_n}
\]

In the equation (2), \( \Delta P \) is the standby power of photovoltaic power generation under any illumination.
2.2.2. Virtual Inertia Control Strategy

The phase-locked loop control strategy of the PV power generation unit is shown in Figure 6. The grid frequency can be represented by \( f \); the grid frequency \( f \) is shown in equation (3). In equation (4), Derive the grid frequency and get the grid frequency change rate \( \frac{df}{dt} \). Based on the change rate of the grid frequency, the active power increment \( \Delta P_{pv} \) of the PV generation unit is obtained, where \( H_{ph} \) denotes the virtual inertia time constant of PV generation.

\[
 f = \frac{U_s}{2\pi} \left( k_p + \int k_i dt \right) \quad (3)
\]

\[
 \frac{df}{dt} = \frac{U_s \cdot k_i}{2\pi} \quad (4)
\]

\[
 \Delta P_{pv} = 2H_{ph} \frac{df}{dt} = 2H_{ph} \frac{U_s \cdot k_i}{2\pi} \quad (5)
\]

The frequency response is realized by linearly changing the active power reference value according to the system frequency deviation and frequency change rate, as shown in Figure 7.

2.2.3. Technical Indicators of the PV Power Plant Fast Frequency Response

For the frequency step perturbation with the change of regulation target no less than 10% of the rated output, the comparison of primary frequency modulation performance between the droop control in combination with the virtual inertia control and the single control method is presented in Table 2.
Table 2. Comparison of the primary frequency modulation performance of PV power plant with different technical scheme.

<table>
<thead>
<tr>
<th>Technical scheme</th>
<th>Response lag time/s</th>
<th>Response time/s</th>
<th>Modulation time/s</th>
<th>Modulation accuracy/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single method</td>
<td>0.50-2.00</td>
<td>2.00-5.00</td>
<td>2.00-15.00</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Integrated control</td>
<td>0.25-1.80</td>
<td>1.60-4.50</td>
<td>1.80-10.00</td>
<td>&lt;0.8</td>
</tr>
</tbody>
</table>

As is shown in Table 2, in comparison with the single scheme, the integrated control scheme significantly reduced the response lag time, the response time and the modulation time. Meanwhile, due to the improvement of the modulation accuracy, it effectively improved the response performance of the primary frequency modulation of the PV power plant and enhanced the support ability of the power system frequency.

3. Results and Analysis of the Fast Frequency Response of the New Energy Involved in the Power Grid

According to the above control methods of the wind power and PV response frequency, in June 2021, 285 new energy wind power plants and PV power plants with a total output of 2043 MW were selected by the Northwest China Power Grid to carry out a frequency modulation response experiment, taking a wind power plant and a PV power plant in Shaanxi as examples for illustrative analysis.

3.1. Fast Frequency Response Function Examination of Wind Farm

During the test, the wind power plant dropped from 33.3 MW to 30.96 MW, the fast frequency action delay was less than 2 s, the fast frequency response time was 3.1 s, less than 10 s, and the action effect was good. The system frequency started to rise from 50.03 Hz, and the highest system frequency rose to 50.127 Hz, and the frequency returned to normal after 14 s, and the wind power plant returned to normal value, as shown in Figure 8.

![Figure 8](image)

Figure 8. A wind farm’s primary frequency modulation reaction in Shaanxi.

3.2. PV Power Plant Fast Frequency Response Function Test

The response of a PV power plant with output of 4.9 MW in Shaanxi is as follows: The PV power station’s primary frequency modulation function is normally put into operation. During experiments, the power of PV power plants decreased from 4.9 MW to 4.28 MW,
the fast frequency action delay was 1.2s, less than 2s, and the fast frequency response time was 2.1s, less than 5s, and the action effect was good. The system frequency started to rise from 50.03Hz, and the highest system frequency rose to 50.127 Hz, after 14s, the frequency returned to normal and the PV power returned to normal, too, as presented in Figure 9.

The above experiments showed that the active output of the new energy station has a good primary frequency modulation performance under the premise of leaving space for regulation. Through the analysis and comparison of various types of new energy primary frequency modulation actions during the actual tests and experiments, it was concluded that the action delay of wind farms’ fast frequency was fewer than 2s, the time of it was fewer than 10s; in the meantime, the action delay PV power plant’s fast frequency was fewer than 2s, the time of it was fewer than 5s. After fast frequency transforming, the unconventional energy station not only has achieved demanded standards, but had good operation characteristics.

4. The Measured Results

To further improve the frequency modulation performance, Northwest China Power Grid also tested the fast frequency response of conventional units and new energy in coordination with the grid.

System conditions: New power grid energy is 8.64 million kW, load is 11.15 million kW, DC is 11.1 million kW, and initial system frequency is 50.026Hz.

The system frequency rose from 50.026 Hz to 50.122 Hz at the highest, as shown in Figure 10. The frequency was restored to about 50 Hz by the system secondary frequency modulation.

During DC blocking transient process, the later stage mainly shows the system primary frequency modulation response. The new energy and conventional power have good ability of primary frequency modulation response in time scale and relay action. Through different action thresholds, the new energy station has realized the coordination with conventional power thermal power units and hydropower units, improved the frequency stable degree of Northwest China Power Grid system.
(a) Participation of thermoelectric generating set units in the primary cooperative frequency modulation response

(b) Participation of hydropower units in the primary cooperative frequency modulation response

(c) PV power plants participation in a collaborative frequency modulation response

(d) Participation of wind farms in a collaborative frequency modulation response

Figure 10. Primary frequency modulation effect of multi-type power echelon coordination.

5. Conclusion

This paper conducts experiments and analyses about the function of the unconventional energy station’s fast frequency response:

1. The measured data of wind farms and PV power plants are used for analysis, through data analysis, the ability of new energy stations to respond quickly to frequency under frequency disturbance is reflected.

2. Several PV power plants and wind power plants were selected in the Northwest to analyze the frequency regulation performance, the data analysis shows that the use of wind power and photovoltaic fast frequency regulation differentiated settings can better coordinate the fast frequency regulation capabilities of various types of power sources, and realize the coordination of fast frequency regulation behaviors of different types of which effectively promotes the rapid frequency modulation of the frequency after the large power grid accident, and improves the safety prevention and control level of the large power grid frequency at the transmitting end.

Acknowledgements

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References


