Study on Grid-connected Operation Performances Evaluation of Photovoltaic Power Stations

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Abstract. To achieve the grid-connected operation performances evaluation of photovoltaic power stations, a grid-connected operation performance index system and the comprehensive evaluation method on photovoltaic power station grid-connected performances is presented. The rank sum ratio of each photovoltaic power station to reflect grid-connected performances is calculated by using the rank-sum ratio method. According to the rank sum ratio values, the comprehensive grid-connected performance of each photovoltaic power station is evaluated. The actual monitoring data of photovoltaic power stations are used to calculate performance indexes, and comprehensive evaluation on grid-connected performances of photovoltaic power station is verified. The obtained results show that the comprehensive grid-connected performance of the photovoltaic power station can be correctly evaluated by using the presented evaluation method.

Introduction

Renewable energy power generation is of great significance to adjust energy structure, increase energy supply and reduce environmental pollution. With the large-scale development of renewable energy power generation, the rapid production of photovoltaic projects has caused great hidden danger to power grid security, and the healthy development of renewable energy is also restricted.

To ensure the safety and stable operation of power grids, it is necessary for the power dispatch department to supervise and rectify the photovoltaic power station with substandard performances. For more photovoltaic power station manufacturers, the operation performance index dimensions may be different [1, 2]. At present, how to achieve comprehensive evaluation on photovoltaic power stations with multiple operation performances is an important issue [3].

The rank-sum ratio is a statistical information analysis method proposed by Fengtiao Tian [4], who is a scholar of Chinese medical field. The rank-sum ratio method can be used to evaluate the objects with parameter indexes and nonparametric indexes, and for both the relative index and the absolute index, the calculated rank sum ratio is in the range of 0 to 1. The method has characteristics of simple calculation and clear result, and it has no special requirements for index data distribution. It has been applied to the power system field such as the quantitative comprehensive evaluation of power quality, the relay protection reliability and the distribution network planning and construction project [5, 6], and good results are obtained. The application of the rank sum ratio method in the grid-connected performances evaluation of photovoltaic power stations has not been reported.

To evaluate the comprehensive operation performances of photovoltaic power stations objectively, an operation performance index system including the low voltage ride through, the power factor, the grid-connected voltage deviation and the dynamic reactive power response of the photovoltaic power
station is constructed, and a comprehensive performance evaluation method of photovoltaic power stations based on rank sum ratio method is presented.

Construction of Photovoltaic Power Station Operation Performance Index System

Different operation performances of a photovoltaic power station have different influences to power system. According to the importance of different performance indexes of the photovoltaic power station, an operation performance index system including the voltage ride through, the power factor, the grid-connected voltage deviation and the dynamic reactive power response of the photovoltaic power station is constructed.

Low Voltage Ride through Performance Index

As shown in Figure 1, the photovoltaic power station must be connected to power grid at least 0.15 second if the grid-connected voltage sags to zero, and the photovoltaic power station can be disconnected if the grid-connected voltage sags below the voltage curve.

![Figure 1. Performance requirements of low voltage ride through for the photovoltaic power station.](image)

If the grid-connected voltage sags, the time to remain connected to the grid of the photovoltaic power station is not the same when the voltage sags in different depth.

The low voltage ride through index of the photovoltaic power station is characterized by synthesizing the index of voltage sag depth, duration time and whether or not disconnected to power grid. To the disconnected photovoltaic power station, the duration time can be calculated by the difference between the actual lasting connected time and the required lasting connected time.

If the sag duration of the grid-connected voltage is less than 0.15 second, as long as the photovoltaic power station is disconnected to power grid, it is considered that the lasting operation time is 0 second no matter how much the sag depth of the grid-connected voltage. If the photovoltaic power station is disconnected to power grid when the lasting operation time is more than 0.15 second and less than 2 second, the lasting operation time before it is disconnected to the power grid can be calculated by using the allowed lasting operation time. The allowed lasting operation time can be determined according to the maximum sag depth of the grid-connected voltage and the low voltage ride through performance requirement curve.

It is assumed that a photovoltaic power station is disconnected to power grid. The number of times is $N$ when the lasting operation time is less than 0.15 second before it is disconnected, and it is $M$ when the lasting operation time is more than 0.15 second and less than 2 second. Then, the low voltage ride through performance index of the photovoltaic power station can be defined by using the average lasting operation time before it is disconnected in Eq. 1.
\[ R_{LVRT} = \left[ \sum_{i=1}^{M} (t_i - \Delta t_i) \right] / (M+N) \]  

(1)

Where, \( R_{LVRT} \) is the low voltage ride through performance index; \( t_i \) is the \( i \)th lasting operation time before it is disconnected; \( \Delta t_i \) is the allowed lasting operation time before it is disconnected under the \( i \)th sag case of the grid-connected voltage.

According to the low voltage ride through performance requirement curve of the photovoltaic power station, the allowed lasting operation time before it is disconnected to power grid can be calculated by using the ratio of the maximum sag depth of the grid-connected voltage. The greater the value of the low voltage ride through performance index, the longer the lasting operation time before it is disconnected.

**Power Factor Index**

To avoid large voltage deviation and voltage instability problems, the power system can adjust the voltage of system with reactive power devices generally. The power factor of a photovoltaic power station can be calculated with the collected active power \( P \) and reactive power \( Q \) in the photovoltaic power station.

When the active power output of a photovoltaic power station is greater than 50% of the rated power, the power factor should not be less than 0.98. When the active power output is between 20% and 50% of the rated power, the power factor should not be less than 0.95. The evaluation of power factor for photovoltaic power station can be achieved by using the calculated power factor value.

The sum of times that the power factor of photovoltaic power station whose absolute value is less than 0.95 or 0.98 is defined as the times that power factor exceeds the limit, and the ratio of it to the total calculation times of power factor is defined as the power factor index \( R_{pf} \).

**Deviation Index of Grid-connection Voltage**

The allowed deviation of grid-connection voltage for photovoltaic power stations connected to power grid by 110kV voltage levels is from -3% to +7% of rated voltage, and it is from 0% to +10% of rated voltage for the ones by 220kV voltage levels. To characterize the effectiveness of the grid-connection voltage change on the overall performance of a photovoltaic power station, the deviation index of grid-connection voltage is defined in Eq. 2.

\[ R_{adex} = \frac{3}{4} \times \left( \frac{M_{\text{acexc}}}{N_s} \times 100\% \right) + \frac{1}{4} \times \left[ \frac{1}{M_{\text{acexc}}} \sum_{i=1}^{M_{\text{acexc}}} \left( \frac{\Delta U_i}{U_N} \times 100\% \right) \right] \]  

(2)

Where, \( R_{adex} \) is the deviation index of the grid-connection voltage; \( N_s \) is the grid-connected voltage sampling times within a certain period; \( M_{\text{acexc}} \) is the times that the grid-connected voltage exceeds the limit within a certain period; \( U_N \) is the rated voltage; \( \Delta U_i \) is the \( i \)th voltage deviation value that exceeds the allowed voltage.

In Eq. 2, the weights of the voltage deviation value and the times that the grid-connected voltage exceeds the limit are set to 1/4 and 3/4 respectively, and they can be adjusted according to the actual situations.

The deviation index of grid-connection voltage is negative index. The smaller the index value, the smaller the voltage deviation.

**Dynamic Reactive Power Response Performance Index**

To fully characterize the dynamic reactive power response performance of photovoltaic power stations, the weighted sum of the percentage of the dynamic reactive power response time up to the standard, the percentage of the average relative response time deviation and the rate of the dynamic reactive current response are defined as the dynamic reactive power response performance index, and it is shown in Eq. 3. Where, the weights of each section in Eq. 3 are set to 2/5, 1/5 and 2/5 respectively.
\[
R_{qr} = \frac{2}{5} \times \left( \frac{N_Q}{N_{LHV}} \times 100\% \right) + \frac{1}{5} \times \left( \frac{1}{N_{LHV}} \sum_{i=1}^{N_{qr}} \left( \frac{30 - \Delta t_i}{30} \times 100\% \right) \right) + \frac{2}{5} \times \left( \frac{N_I}{N_{LV}} \times 100\% \right) \quad (3)
\]

In Eq. 3, \( R_{qr} \) is the dynamic reactive power response performance index; \( N_Q \) is the times that the response time of the dynamic reactive power compensation device reaches the standard; \( N_{LHV} \) is the times that the grid-connected voltage exceeds the limit; \( \Delta t_i \) is the actual response time of the dynamic reactive power compensation device after the grid-connected voltage exceeds the limit at the \( i \)th time; \( N_I \) is the times that the response time of the dynamic reactive power current reaches the standard; \( N_{LV} \) is the times that the grid-connected voltage sags.

The dynamic reactive power response performance index is positive index. The greater the index, the better the dynamic reactive power response performance.

Performance Evaluation of Photovoltaic Power Station Based on Rank-sum Ratio

The performance evaluation process of photovoltaic power station can be realized by using the rank-sum ratio method with three steps.

**Step 1**: According to the previous calculation method on grid-connected performance index of photovoltaic power station, the indexes, i.e. the low voltage ride through, the power factor, the grid-connected voltage deviation and the dynamic reactive power response within a certain period such as one month, are calculated.

**Step 2**: According to the rank-sum ratio method, the rank of each performance index of the photovoltaic power station to be evaluated is calculated. To the positive index and the negative index, they are ranked from small to large and from large to small respectively. To the indexes with the same value are ranked averagely.

**Step 3**: After the weight of each index is set, the weighted rank-sum ratio of each performance index of the photovoltaic power station to be evaluated is calculated. The grid-connected performance comprehensive evaluation of photovoltaic power stations can be realized by sorting the weighted rank sum ratios, and the evaluation results can be output.

Example Verification

Four photovoltaic power stations in an area are chosen for verification. The monitored data of each photovoltaic power station within one month are used for performance index calculation, and the results are shown in Table 1. The rank of each index is calculated by using the data in Table 1, and the results are listed in Table 2. Where, the symbol PV represents the photovoltaic power station.

Table 1. Grid-connected performance indexes results of photovoltaic power stations.

<table>
<thead>
<tr>
<th>Photovoltaic Power Station</th>
<th>( R_{LVRT} )</th>
<th>( R_{pf} )</th>
<th>( R_{adec} )</th>
<th>( R_{qr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV1</td>
<td>0.15</td>
<td>0.03</td>
<td>0.13</td>
<td>0.85</td>
</tr>
<tr>
<td>PV2</td>
<td>0.34</td>
<td>0.02</td>
<td>0.09</td>
<td>0.98</td>
</tr>
<tr>
<td>PV3</td>
<td>0.12</td>
<td>0.05</td>
<td>0.24</td>
<td>0.72</td>
</tr>
<tr>
<td>PV4</td>
<td>0.21</td>
<td>0.05</td>
<td>0.26</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 2. Grid-connected performance indexes ranks.

<table>
<thead>
<tr>
<th>Photovoltaic Power Station</th>
<th>( R_{LVRT} )</th>
<th>( R_{pf} )</th>
<th>( R_{adec} )</th>
<th>( R_{qr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>PV2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>PV3</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>PV4</td>
<td>3</td>
<td>1.5</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

In the calculation, the performance index weights of the low voltage ride through, the power factor and the dynamic reactive power response of photovoltaic power stations are set to 0.3 respectively, and the weight of the grid-connected voltage deviation is set to 0.1. According to the performance
evaluation process of photovoltaic power station, the weighted rank sum ratio (WRSR) of each photovoltaic power station to be evaluated is calculated and listed in Table 3.

Table 3. Rank-sum ratio calculation results of photovoltaic power stations.

<table>
<thead>
<tr>
<th>Photovoltaic Power Station</th>
<th>WRSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV1</td>
<td>0.6750</td>
</tr>
<tr>
<td>PV2</td>
<td>1.0000</td>
</tr>
<tr>
<td>PV3</td>
<td>0.3125</td>
</tr>
<tr>
<td>PV4</td>
<td>0.5125</td>
</tr>
</tbody>
</table>

From the results in Table 3, the comprehensive grid-connected performance of PV2 is the best, followed by PV1 and PV4, and PV3 is the worst.

According to the monitored data of photovoltaic power stations in Table 1, the values of the low voltage ride through index and the power factor index of PV2 are 0.34 and 0.02 respectively, and the values of the grid-connected voltage deviation index and the dynamic reactive power response index are 0.09 and 0.98 respectively. Among all the photovoltaic power stations, the low voltage ride through index and the dynamic reactive power response index have the maximum values, and the power factor index and the grid-connected voltage deviation index have the minimum values. Considering the power factor index and the grid-connected voltage deviation index are the negative ones, the indexes of PV2 are best. So, PV2 has the best comprehensive performance, which is consistent with the evaluation results.

The indexes of PV1 are better than those of other photovoltaic power stations except that of PV2, so the comprehensive performance of PV1 is the second. To PV3 and PV4, the low voltage ride through index and dynamic reactive power response index of PV4 are better than PV3, and both of the power factor indexes are equal. The grid-connected voltage deviation index of PV4 is worse than PV3, but its index weight is smaller than other indexes. So, the comprehensive performance of PV4 is better than PV3. After comparing and analyzing the index values of each photovoltaic power station, the results in Table 3 are consistent with the analysis.

Summary

To achieve the comprehensive evaluation on grid-connected performances of photovoltaic power stations, a grid-connected operation performance index system including the voltage ride through, the power factor, the grid-connected voltage deviation and the dynamic reactive power response of the photovoltaic power station is constructed. The rank-sum ratio method is applied to comprehensive evaluation on grid-connected performances of photovoltaic power stations, and the actual monitoring data of photovoltaic power stations are used to calculate performance indexes. The comprehensive evaluation method is verified, and results show that the grid-connected performances of photovoltaic power stations can be correctly evaluated by using the presented evaluation method.

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References

