Research on Grid-connected PV Power Station Condition Evaluation Technology Based on SCADA and Hierarchical Progression

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Abstract. This paper draws up the conditional evaluation strategy of grid-connected photovoltaic (PV) power generation stations based on the characterization of PV devices, and introduces the conditional evaluation index system includes performance and reliability of PV power generation station. This conditional evaluation statement method is based on both sides of the reliability and performance of PV devices, employ the availability, MRTBF, performance ration and power generation ability as the key evaluation index. In addition, using the operation data recorded by SCADA and recommended threshold values, in order to evaluate the operation conditional statement of grid-connected PV power generation station. Also, this paper proposed the performance degradation analysis method based on the hierarchical progression structure, and achieved the target of fast fixed position of fault PV devices. The firstly established conditional evaluation method is able to comprehensive evaluation the entirely operation statement of PV power generation station. This conditional statement evaluation method promotes the maintenance strategy of grid-connected PV power generation station, and guarantee the safe, stable and efficiency operation of stations. As a result, increase the benefits of operators of PV power generation stations and can be used to guide the PV power engineering.

1. Introduction

Large-scale and distributed grid-connected PV power generation has changed from planning to reality. In 2014, China had additional PV installed capacity of 10.6GW, and total installed capacity of 28GW. The State Council “Energy Development Strategic Action Plan (2014-2020)” proposed that domestic PV installed capacity will reach 100GW by 2020\(^{[1,2]}\). However, China grid-connected PV power plants were put into operation after 2012. The cost of power generation rapidly declined, and the demand of power station operators for product quality and refined operation and maintenance gradually highlighted. How to gradually standardize and improve operation and
maintenance and increase power generation performance and economic benefits of grid-connected PV power plants according to characteristics and requirements of grid-connected PV power plants has become a new focus in PV power generation.

In 1993, the International Energy Agency (IEA) launched the research project on performance and reliability analysis of grid-connected PV power plants (PV Power System Program Task-2), aiming to study the performance of PV power plants and reliability development of power generation equipment and influencing factors based on global database of PV power plant operation information, cost-benefit cycles and operational status evaluation indicators, ultimately forming IEC 61724 standard \[3\]. Literature \[4\] applied the hierarchy analysis to construct the project framework reflecting important characteristics of unit operating state, introducing degradation indexes, taking the fuzzy comprehensive evaluation method to establish the improved model for the wind turbine operating state assessment. Literature\[5\] introduced a complete index system from the perspective of solar energy resources and PV power generation system operation, analyzing distribution characteristics of solar resources in Wuhan for 30 years, evaluating the optimal dip angle, full-load hours and capacity factors and other indexes based on monitoring system data, analyzing power generation performance of PV power generation systems.

From the perspective of operation maintenance and repair demand, this paper introduces and integrates a complete detailed evaluation index system for grid-connected PV power plants for the first time. Based on the existing maintenance technologies and standards of PV power generation equipment, centering on the characteristics of multiple PV power generation single equipment, regional dispersion, susceptibility of hierarchical topology, operation and maintenance to the harsh environment, complete monitoring points, large amounts of operational data, this paper applies power plant real-time operation monitoring data, developing grid-connected PV power plant state assessment system with the dual dimension of reliability and power generation performance, systematically introducing evaluation indicators, calculation methods and recommended thresholds for key PV power generation equipment, proposing the stratified and progressive degradation analysis method to continuously, efficiently and accurately locate the monomer equipment witnessing performance degradation.

2. State evaluation model based on SCADA data

2.1. Reliability evaluation indicators

(1) Mean time between failures MRTBF refers to the mean working time between adjacent 2 failures of the equipment within certain time. The mean failure-free running time of the PV power generation unit is calculated according to Formula (1).

\[
MRTBF = \frac{T - T_L - T_N}{N_r + N_i}
\]  

(1)

Where, \(MRTBF\) - mean failure-free running time of the power generation unit within statistical time period, in hours, h; \(T_L\) - downtime caused by equipment routine maintenance within statistical time period, in hours, h; \(T_N\) - excluded time, downtime caused by the grid, external electrical equipment failure or other factors within statistical time period, in hour, h; \(N_r\) - number of remote reset failures caused by the equipment itself within statistical time period; \(N_i\) - number of remote reset failures failing in remote reset caused by the equipment itself within statistical time period.

(2) PV power generation unit availability \(PV_a\) refers to downtime caused by failures of PV power generation unit itself, analyzing the operation capability of the PV power generation unit in multiple time dimensions, free from influence of statistics of the PV power station failures, indicating downtime caused by failures of the power generation unit during the statistical period\[7\].

\[
PV_a = \frac{MTTF}{MTTF + MTTR} \times 100\%
\]  

(2)
Where, $MTTF$ - mean failure-free running time of the PV power generation unit within statistical time period, in hours, h; $MTTR$ - mean repair time of the PV power unit failure within statistical time period, in hours, h; $T$ - statistical time period, in hours, h; $T_L$ - downtime caused by the PV unit power outage maintenance within statistical time period, in hours, h; $T_N$ - excluded time, referring to downtime caused by nighttime or grid or external electrical equipment failures or other factors within statistical time period, in hours, h; $T_{repair, i}$ - repair time of each failure in the PV unit, in hours, h.

2.2. Power generation performance evaluation indicator

(1) PV power generation unit performance ratio $PR$ indicator, indicating the ratio between the actual output power generation and theoretical power generation of the PV power generation unit within the statistical period, calculated with the following formula:

$$Y_f = \frac{E}{P_a}$$  \hspace{1cm} (3)

Where, $Y_f$ - equivalent utilization hours, in hours, h; $E$ - the amount of electricity generated by the PV power generation unit within the statistical time period, in kWh; $P_a$ - the nominal power of PV modules of the PV power generation unit, in kW.

$$Y_r = \frac{H}{G}$$  \hspace{1cm} (4)

Where, $Y_r$ - peak sunshine hours, in hours, h; $H$ - mean effective radiation of the inclined surface received within the statistical period of PV modules of the PV power generation unit, in kWh/m²; $G$ - irradiation against the standard test conditions of PV modules, 1 kW/m².

$$PR = \frac{Y_f}{Y_r}$$  \hspace{1cm} (5)

(2) The physical meaning of the power generation capacity index $G_g$ of the PV power generation unit indicates the ratio between the actual output power and theoretical output power of the PV power generation unit, the calculation method as follows[8-10]:

$$G_g = \frac{\sum P_{Ga,i}}{\sum P_{Gp,i}} \times 100\%$$  \hspace{1cm} (6)

Where, $G_g$ - the power generation capacity index of the PV power generation unit within statistical time period, %; $N$ - within statistical time period, the PV power unit active power is the maximum output control mode, and effective data points in case the irradiance and mean power are within the normal range; $P_{Ga,i}$ - within statistical time period, the PV power unit active power is the maximum output control mode, and the irradiance and mean power are within the normal range, the actual output of the PV power generation unit active power value, kW; $P_{Gp,i}$ - theoretical power value of the PV power unit calculated with irradiance and theoretical power curves after conversion, kW.

2.3. Recommended threshold value

Considering technical parameters and actual operational statistics required by the national energy management department for advanced PV power generation equipment[11], proposing the recommended threshold value for the status evaluation indicators of grid-connected PV power plants; As shown in Table 1, the recommended threshold value is applicable to PV power generation unit status assessment results.
Table 1 The recommended threshold values of performance and reliability of PV power generation

| Reliability | Power generation performance |
|-------------|-----------------------------|
| Mean time between failures (MRTBF) | Availability (PV_a) | Energy efficiency ratio (PR) | Power generation capacity (G_g) |
| Normal: 2160h < MRTBF < 8760h | Normal: 99% < PV_a < 100% | Excellent: 0.8 < PR < 1 | Excellent: 0.8 < G_g < 1 |
| Sub-health: 360h < MRTBF < 2160h | Sub-health: 95% ≤ PV_a ≤ 99% | Good: 0.7 ≤ PR ≤ 0.8 | Good: 0.7 ≤ G_g ≤ 0.8 |
| Serious: MRTBF < 360h | Serious: PV_a < 99% | Poor: PR < 0.7 | Poor: G_g < 0.7 |

3. State assessment strategies and methods

3.1. Overall state assessment strategy
During the evaluation of PV power plants, the reliability indicators and performance index threshold values can be adjusted according to the overall operation of the same type of power generation equipment, and the key equipment should be selected. The reliability of grid-connected PV power plants is divided into normal, sub-health and serious. The performance of grid-connected PV power plants is divided into excellent, good and poor. The overall state evaluation strategy of PV power plants is shown in Table 2.

Table 2 The conditional evaluation strategy of grid-connected PV power station

| Power generation performance | Reliability | Normal | Sub-health | Serious |
|-----------------------------|-------------|--------|------------|---------|
| Excellent                   | Normal status | Sub-health state | Severe state |
| Good                        | Sub-health state | Sub-health state | Severe state |
| Poor                        | Severe state | Severe state | Severe state |

3.2. Hierarchical progressive state assessment methods
Degradation factors of the power generation performance of grid-connected PV power plants are concentrated in PV modules. Since the components are composed of a large number of distributed and converging devices connected in series and in parallel, when the state of grid-connected PV power plants is evaluated, the PV indicators can be used to first determine the PVs. The power generation performance of the power station as a whole, and then adopts the stratified and progressive method. Through the dual-dimensional evaluation indicators of reliability and power generation performance, the PV clusters with hidden dangers are located layer by layer, and the PV power generation equipment with good or poor power generation performance is combined. On-site maintenance inspection, it is proper to locate defective PV modules, finding out the cause of failures and maintaining them in time. The data source of the hierarchical progressive state assessment method is obtained through the online monitoring data of the PV monitoring system, and the hierarchical progressive state evaluation process is as shown in FIG. 1.
Fig. 1 The flow chart of hierarchical progression condition evaluation

4. Case analysis

4.1. Overall status assessment of grid-connected PV power plants

According to the total irradiance and scattering irradiance data recorded by the SCADA system of the PV power plant, Klein model of the same isotropic sky is used to calculate the peak irradiance distribution of the 10min resolution of the inclined surface of the PV power plant.

Fig. 2 shows the daily evaluation results of the overall power generation performance PR index of the PV power plant. The overall distribution of the PR index of the PV power plant from January to September is in accordance with the statistical analysis law, and the PR index mainly changes within the range of 0.75-0.9. From October to December, due to equipment maintenance and station active control, the PR index has a large fluctuation range.

Fig. 2 The daily PR index evaluation of grid-connected PV power station
4.2. PV unit status assessment

According to the power generation unit power generation capacity and failure record recorded by the PV power plant SCADA system, the availability, MRTBF, PR and power generation capacity indicators of the power generation unit in the PV power station are evaluated, and the operational status of some PV power generation units is analyzed, shown as in Table 3.

Table 3 The condition evaluation results of 1MWp PV power units in 2014

| PV unit | \( PV_a \) (%) | MRTBF (h) | PR | \( G_g \) (%) | Current state |
|---------|----------------|-----------|----|--------------|---------------|
| G017    | 94.55          | 4342      | 0.80 | 96.32        | Severe state  |
| G018    | 100            | 5344      | 0.81 | 93.70        | Normal status |
| G019    | 99.78          | 4663      | 0.81 | 99.08        | Normal status |
| G020    | 94.83          | 2004      | 0.71 | 100          | Severe state  |
| G021    | 98.99          | 2806      | 0.71 | 91.80        | Sub-health state |
| G022    | 99.16          | 2798      | 0.80 | 95.03        | Normal status |
| G023    | 99.96          | 2288      | 0.81 | 95.29        | Normal status |
| G024    | 95.26          | 953       | 0.78 | 93.40        | Sub-health state |
| G025    | 99.87          | 846       | 0.82 | 94.40        | Normal status |
| G026    | 96.74          | 1654      | 0.77 | 94.28        | Sub-health state |
| G027    | 97.70          | 967       | 0.75 | 91.26        | Sub-health state |
| G028    | 99.87          | 4656      | 0.81 | 92.44        | Normal status |
| G029    | 99.21          | 2672      | 0.80 | 96.67        | Normal status |
| G030    | 97.44          | 6012      | 0.80 | 95.25        | Normal status |
| G031    | 98.05          | 779       | 0.79 | 93.47        | Sub-health state |
| G032    | 99.07          | 2254      | 0.81 | 93.97        | Normal status |
| G033    | 97.81          | 1603      | 0.74 | 83.80        | Sub-health state |
| G034    | 99.39          | 6012      | 0.71 | 68.28        | Severe state  |
| G035    | 95.89          | 4008      | 0.70 | 79.83        | Sub-health state |
| G036    | 99.69          | 976       | 0.72 | 91.40        | Sub-health state |
| G037    | 83.25          | 2200      | 0.46 | 57.19        | Severe state  |
| G038    | 99.54          | 2168      | 0.81 | 94.92        | Normal status |
| G039    | 99.87          | 4810      | 0.80 | 96.46        | Normal status |
| G040    | 98.05          | 1334      | 0.78 | 94.57        | Sub-health state |
| G041    | 96.40          | 2149      | 0.70 | 85.64        | Sub-health state |
| G042    | 99.36          | 1603      | 0.75 | 93.42        | Sub-health state |
| G043    | 99.89          | 4155      | 0.81 | 93.60        | Normal status |
| G044    | 99.95          | 4312      | 0.82 | 100          | Normal status |
| G045    | 98.06          | 469       | 0.71 | 99.19        | Sub-health state |
| G046    | 90.92          | 752       | 0.69 | 91.84        | Sub-health state |

4.3. Analysis of performance degradation of stratified progressive power generation units

Through the stratified progressive performance degradation analysis method, the power generation performance of the G026 power generation unit is good. Combined with the state evaluation strategy of Table 2, the overall state evaluation result of the G026 PV power generation unit is sub-health state, and further analysis of the components with performance degradation is needed. And the reason. Using a typical daily data in July, using the \( G_g \) indicator of power generation capability, firstly, analyze the \( G_g \) indicator of the #3801-#3807 combiner box connected to the G026-N01 inverter on the same day, as shown in Figure 3, and find the #3807 combiner box. The power generation capacity is in a good state.
Further evaluating the Gg index of the PV string in the #3807 combiner box to guide maintenance of the power plant; Through the evaluation results, as shown in Fig. 4, it can be seen that the power generation capability of the positioning #07 and #08 PV strings in the period from 6:00 to 8:30 is significantly deviated, and maintenance is required in time. On-site maintenance personnel found failures in time based on the evaluation results and confirmed that due to the installation of other facilities on the east side of the string bracket, the sunrise stage caused shadow blocking on several PV modules in the #07 and #08 PV strings, resulting in Gg indicators low.

The statistic of PV string Gg index distribution of HL0307

5. Conclusion
This paper establishes the state-of-the-art PV power plant state assessment method and its index system based on SCADA system and stratified progressive degradation analysis method for the first time. Through the dual dimensions of reliability and power generation performance, the operational status of the commissioned power plant is evaluated in all aspects. The example proves that this method can detect the early failure of PV power generation equipment in time and prevent the deterioration of hidden defects. It has important practical significance for optimizing operation and maintenance control strategy, improving the economic efficiency of PV power plant and the reliability of PV power generation.

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