Study on the statistical characteristics of solar power

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Abstract. Solar power in China has grown rapidly recently. It exists variation of solar power due to cloudy and dusty, which is not that much of wind. The way to evaluate the statistical characteristics of solar power is important to the analysis of power system planning and operation. In this study, a multi-scale spatial and temporal framework of evaluating indices was established to describe the variation of its own natural features and the interaction between solar and load, grids. Finally, we have a case study on the variation, comparison, penetration, etc.

1. Introduction
At present, study on consolidation analysis of solar energy resources and operation information of solar power in China is still in initiative stage [1]. The power output of photovoltaic (PV) generation varies with the sunrise and sunset. The change of weather leads variations to PVs, as well. It gives rise to difficulties in power system planning and operation. It has not been formed a recognized and effective evaluation system yet. Evaluation of solar power output should start from the relationship between solar power and the power grids. By combining solar power output with its own statistical characteristics, multi-scale spatial and temporal statistical properties of the solar power generation layer by layer evaluation index system should be established [2-4].

The basic idea of analysis is: the frameworks of the index that reflect the natural characteristics of solar power and the interactive indicators that related with power grids features should be established, firstly. And then, indices classes according to the importance and coverage will be conducted based on core index and supplemented by multi-class derived index. And finally, the statistical characteristics of solar power output in typical regions will be investigated.

2. Statistical characteristics of solar power indicator framework
Statistical characteristics of solar power indicators can be divided into two categories: one is set to reflect solar energy / solar power of own characteristics indicator; the other is an indicator of the interaction between the solar power to the power grids. Index classification summarized as shown in Figure 1.
3. Indicators of natural characteristics of solar power

3.1. Power output characteristics

Variation and randomness are the main natural characteristics of solar power output / solar energy. As to solar energy resources, it is a manifestation of the natural characteristics of geographical, meteorological and topography factors. Concerned with the solar power output, the feature is based on the characteristics of solar power conversion considering solar energy resources.

Variation refers to changes of the solar power output / solar irradiation intensity, which are determined by specified sequence in multi-spatial and temporal scales, point by point. And the change rates of power output are core indicators of solar to describe variation of solar power.

1) solar power output variation: within the given period, difference of the power output $\Delta P$ of two neighboring point.

\[
\Delta P = P(t+T) - P(t)
\]  \hspace{1cm} (1)

2) solar power output change rate: the proportion of solar power output variation to the rated capacity of solar power plants.

\[
\rho\% = \frac{P(t+T) - P(t)}{P_{base}} \times 100\%
\]  \hspace{1cm} (2)

Where: $P(t+T)$ is defined as solar power output at $t+T$ time; $P(t)$ is solar power output at time $t$; $P_{base}$ is rated capacity of solar power plant. For the different time scales, $T$ is corresponding to different values.

The variation of solar power generation could be divided by time scale, such as, in seconds, minutes, hours. Meanwhile the variation could be divided by spatial scale, such as, stand-alone plants, clustered power plants and regional generations. With the viewpoint of statistical methods, there are indices of probability distribution of solar power output, forward / backward maximum variation, probability of forward / backward variation of solar power output, etc [7].
In general, variation increases with time scale increasing, while decreases with spatial scales increasing which lead to the overlap and smoothness of power output in different areas. This smoothness could be defined as confidence interval of variation coefficient R and a smoothing coefficient S.

1) Variation confidence interval $R$:

$$P(X \leq R) = p$$  \hspace{1cm} (3)

Where: $P$ is the probability; $X$ is the absolute value of solar power variation; $p$ value is a given probability.

2) Smoothing effect coefficient $S$: standard deviation of solar irradiation sequence difference (levelized with installed capacity).

$$S = \frac{\bar{\sigma}_{\text{single}} - \bar{\sigma}_{\text{cluster}}}{\sigma_{\text{single}}}$$  \hspace{1cm} (4)

where the subscript "single" and "cluster" corresponds to a single plants and clustered plants. This index is used to quantify the cluster of solar power plants with respect to the degree of smoothing on a single field of solar power variation. Variation in confidence interval $R$, for example, the index obtained by accumulating the probabilities described solar power variation in a specific area within a few minutes, which can provide reference information for the secondary frequency regulations.

3.2. Solar resource features

Resources index mainly depict the richness and distribution of solar energy resources. Solar irradiation is the core index. Commonly derived indicators also include the probability distribution of the solar irradiation and the average solar irradiation. The introduction of resource indicators are as follows:

1) Solar irradiation correlation coefficient: The correlation coefficient refers to a different location weather station metering sequence.

2) Solar energy resources disequilibrium coefficient: $I_{\text{ref}}$ is selected from maximum value of average solar irradiation in each solar power plants. Resource coefficient of each solar power plant could be determined as $a_i=I_i/I_{\text{ref}}$ by average solar irradiation in each solar power plants. And then, disequilibrium coefficient could be calculated by averaging $a_i$.

3) Active solar irradiation: solar irradiation within the effective range of the entire statistical period that contribute to power generation.

4) Probability of maximum effective solar irradiation: the occurrence probability of solar irradiation between the start of the photoelectric effect and saturation conditions, which could be noted as that the maximum effective hours and load hours over the years, as well.

5) Probability of extreme variation in solar irradiation: the probability of solar irradiation from less than / greater than the saturated conditions of solar irradiation increase / decrease to above / under the saturated condition.

3.3. Operational characteristics of solar power

Solar power operation indicators are used to evaluate the technology and economy of solar power plant facilities, which are defined as follows:

1) Curtailment / probability of solar power generation: the curtailment / probability when the curtailment of solar power occurs if the power output reaches a given ratio of installed capacity.

2) Monthly / yearly solar power generation.

3) Effective capacity of solar power: under the premise of maintaining reliability level of original power system, traditional power generation could be substituted by solar power generation, which is defined as effective capacity.

4) Annual utilization hours of solar power: annual generation of solar power divided by the rated capacity.
4. Interactive indicators

4.1. Interaction with load

1) Theoretical penetration $P_{r,th}(t)$: The ratio of the installed capacity to power load.

$$P_{r,th}(t) = \frac{P_{base}(t)}{P_{load}(t)}$$

(5)

2) Actual penetration $P_{r,ac}(t)$: Real-time solar output divided by load.

$$P_{r,ac}(t) = \frac{P(t)}{P_{load}(t)}$$

(6)

Where $P(t)$, $P_{base}(t)$, $P_{load}(t)$, is the solar power output, installed capacity and load, respectively.

Theoretical penetration is commonly used index, which reflects the development scale of integrated solar power of the region. However, the actual power output of solar power generation varies and differs from installed capacity. The integration influence of solar power might be over-estimated when theoretical penetration is used. As a result, actual penetration is suggested to be adopted in the analysis of solar power integration.

2) Peaking-load characteristics of solar power

Net load is actual load overlapped with the output of solar power, which is treated as negative load. Study on the relationship of the solar power and load mainly based on comparison of original load and net load. Peak-valley difference of net load is noted as key index.

It is assumed $P_{imax}$ and $P_{imin}$ as maximum and minimum values of original load curve, while $P'_{imax}$ and $P'_{imin}$ are maximum and minimum values of net load. $P_{Vi}$ and $P'_{Vi}$ 'denote as peak-valley difference of original and net load. $\Delta P_{Vi}$ is the change of peak-valley difference before and after solar integration. Those above-mentioned parameters have the following relationship:

$$\begin{align*}
P_{Vi} &= P_{imax} - P_{imin} \\
P'_{Vi} &= P'_{imax} - P'_{imin} \\
\Delta P_{Vi} &= P_{Vi} - P'_{Vi}
\end{align*}$$

(7)

Where, it indicates anti-peaking when $\Delta P_{Vi}$ is negative. In general, seasonal characteristics of the solar power output leads to seasonal peaking requirements. It is necessary to evaluate the influence of solar integration on peaking characteristics of power system season by season.

4.2. Interaction with grids

Integrated solar power will replace conventional power in some extent. However, the special nature features of solar power determines the difference between the level of its actual output and rated capacity. The proportion of solar power output to system load is defined as key indicators to measure the supply capacity of solar power [8-9].

Solar power output ratio (availability): Noted as a percentage of the measured active power solar to installed capacity.

$$\eta\% = \frac{P_t(t)}{P_{base}}$$

(8)

Where: $P_t(t)$ is measured solar power output at time $t$; while $P_{base}$ is the installed capacity of solar power. There is special significance in two occasions:

1) guaranteed capacity: peak load hours, 95% of the solar power generation is more than guaranteed capacity $C_g$.

2) effective output: load valley periods, 95% of solar power output is less than $C_e$. 

Guaranteed capacity reflects the capacity of solar energy that can be substantially ensure the active power during peak load period. It can provide a reference for the calculation of the power balance. Effective output is the general solar power during valley load period.

5. Case study on the evaluation of solar power output characteristic

5.1. Comparison of solar power output with different scale
This section will use power output curves of 3 locations to study the difference of power output of different scales. These regions are named as region A, B and C. Solar output curves of these regions in December 23rd to 29th are selected and normalized as shown in Figure 2.

![Figure 2. weekly solar power output curves](image)

As shown in Figure 2, the output of the power plant A varies due to weather factors. However, variation of accumulated solar power output curve of these 3 locations has decreased. Furthermore, these variations of solar power in the regional power grids are least because of the complementary effect between the various solar power plants.

By investigating annual solar output data with an interval of 15min, standard deviation of solar in regional power grids is 0.214, while the standard deviation of plant A is 0.304, and plant A+B+C is about 0.260. The smoothing effect coefficient of plant A and plant A+B+C is 0.297 and 0.176, respectively. It means that complementary effect will smooth the solar output curves when the integration capacity increases.

5.2. Variation of solar power under different time scales
The probability density of variation in solar plant A is shown in Figure 3. With increasing time scales, the distribution of probability varies from the "narrow and high" shape to "wide and low", which means the variation enhanced. The probability of forward variation is larger than that of backward variation. As a result, the determination of primary, secondary frequency regulations and reservations should take the statistical results of solar power output in multi-time scales.

![Figure 3. annual solar power output statistical properties of different time scales](image)

Statistical characteristics of the solar power plants in different seasons is shown in Figure 4. The results show solar power output variations of seasonal characteristics. During winter, variation occurs...
more frequently due to variable solar irradiation. On the contrary, the output in summer varies slight because of high irradiation.

![Figure 4](image)

**Figure 4.** solar power output characteristics in different seasons.

5.3. **Comparison on the output of solar and wind**

Wind and solar power output is different, as shown in Figure 5. The probability density curve of wind plants is kind of "high and narrow", while the probability curve of solar power plants is relatively "short and wide". This shows that wind power variation is more frequent than that of solar power, and solar power is also relatively large probability that there will be variation circumstances, such as cloudy and dust.

![Figure 5](image)

**Figure 5.** solar power and wind power output power output characteristics of FIG Comparison

5.4. **Influence of peaking-load in different seasons**

When large-scale solar power generation integrated to the power grids, the peak-valley difference will have a great impact on the power system, as shown in Figure 6. The variation of peak-valley difference is defined as the difference between original load and net load.

![Figure 6](image)

**Figure 6.** probability distribution of net load peaking-valley when large scale solar integrated
Figure 6 shows that the probability distribution curve shifts to the left direction, indicating solar power plant integrated to grid might cause anti-peaking, especially in winter and spring.

6. Conclusions
In this study, we investigated the statistical characteristics of solar power based on an evaluation indices framework. Indices were defined to describe the natural and interactive characteristics of solar power. The results showed that the combination of power output curves of power plants in different locations will get smoothed. As to variation, solar doesn’t vary that much of wind, and more frequently in short time scale. Meanwhile, it exists obvious seasonal characteristics of solar power output. Solar power generation varies more frequently in winter due to more cloudy days. Meanwhile, solar power plant might have anti-peaking effect, as wind, especially in winter and spring. It could be attributed to the low demands in some time slices of those seasons. The results of this study could be used to analyze the influence of solar power integration on power grids.

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