The Assessment of Distributed Photovoltaic Capacity Credit in Courts Considering High Penetration

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Abstract: Due to the intermittent and volatility of photovoltaic power generation, it is generally considered that there is only electricity value and no capacity value. With the high penetration of large-scale distributed photovoltaic access to low-voltage distribution network, distributed photovoltaic will gradually become an important alternative energy source. Based on the theory and experience of domestic and international photovoltaic power generation capacity credit assessment, this paper studies the correlation between distributed photovoltaic season, diurnal power generation characteristics and load. This paper also studies the characteristics of power generation system and characteristics of the power distribution system under high penetration distributed photovoltaic access. A calculation method for the capacity credit of high penetration in multi-scenario courts is proposed to provide support for precision investment.

1. Introduction

At present, the load of electricity in many courts is growing rapidly and the pressure to increase the capacity of the power distribution system is increasing. The air conditioning load is growing rapidly and the short-term capacity overrun and utilization of the distribution system are generally low. With the large-scale distributed photovoltaic high penetration access to the grid, distributed photovoltaics will gradually become an important alternative energy source. Compared with other renewable energy generation methods, the output of distributed PV is more obvious in day and night and seasonality, and these characteristics have a greater relationship and regularity with load matching. Therefore, in order to achieve economical efficiency, it is necessary to evaluate the reliability of distributed photovoltaic power generation capacity.

There are about 10 kinds of quantitative evaluations on the capacity credit of photovoltaic power generation systems in the world. The quantitative evaluation indicators of these types can be divided into four categories according to their nature. The first is the index for evaluating the equivalent capacity. The second is the indicator for evaluating the capacity credit factor for a specific period of time.
The third is the indicator for evaluating the additional measures of capacity credit. The fourth is the indicator for evaluating the ELCC (Effective Load Carry Capability, ELCC) in the capacity credit [1]. Among the four types of evaluation indicators, the last evaluation index is the best. This is because the ELCC evaluation index can directly describe the power generation utility. It can effectively make up for the shortcomings of the other three evaluation indicators. Therefore, when assessing the capacity credit of photovoltaic power generation systems, it is usually preferred to use the ELCC evaluation indicators to evaluate.

On the basis of summarizing the theory and experience of the evaluation of the capacity credit of photovoltaic power generation at home and abroad, this paper studies the characteristics of power generation system and the characteristics of power distribution system under high penetration distributed photovoltaic access, and it presents assessment indicators for high penetration in the courts.

2. The characteristics of distributed photovoltaic power generation with high penetration

The penetration rate of distributed photovoltaic refers to the ratio of the access capacity of distributed photovoltaics to the maximum load of the courts, which is used to reflect the scale of distributed photovoltaics in a certain courts. The US Department of Energy defines the high and low permeability of distributed power source: when the permeability of distributed power source is less than 15%, it is considered to be low permeability. At this penetration rate, the distributed power source access has little impact on the distribution network. When the permeability of the distributed power source is greater than 15% and less than 30%, it is considered to be moderate permeability. When the permeability of the distributed power source is greater than 30%, it is considered to be high permeability. Distributed PV high penetration, node voltage and line load rate will seriously exceed the standard limit, the temperature rise of the distribution line may cause insulation combustion, resulting in power failure of the grid [2-3]. With the development of power electronics technology, energy storage technology, relay protection devices and intelligent devices, the optimization of distribution network structure and management, the penetration rate of distributed power supply will be greatly improved [4-5].

Under the low-penetration rate of distributed photovoltaics, the capacity of the superior substation is sufficient, that is, the limitation of the active power of the external system is not considered. At this time, even if all the distributed photovoltaics are out of operation, when all the non-power components are in a non-faulty operation state, the load can be normally supplied without causing power shortage of the system. Only when the non-power components such as feeders, distribution transformers, switches, etc. are faulty, the load point will be exposed to the risk of power loss. When the system is in an isolated island, the faulty exit of the distributed PV will affect the power supply of the load in the island.

Under the high penetration rate of distributed photovoltaics, part of the load in the courts is mainly carried by distributed photovoltaics, when the non-power components such as feeders and distribution transformers are in non-faulty operation state. The reliability level of the system is determined by the matching situation between the power generation capacity of distributed photovoltaic and the power supply capacity and power load of the superior substation. When the non-power components in the power distribution system fail, the reliability level depends mainly on the system's power recovery capability and island operation capability, which involves the specific grid structure.

3. Capacity credit evaluation of distributed photovoltaic generation

Capacity credit of photovoltaic generation, also known as effective capacity, is an effective indicator of its capacity value. At present, there are two main ways to understand the capacity credit of distributed photovoltaic: (1) Considering from the load side: To maintain the reliability level of a given system, adding additional load that PV can afford, that is, Effective Load Carry Capability, ELCC; (2) Considering from the power generation side: At the same level of power supply reliability, adding Equivalent conventional Capacity (ECC) that can be replaced by photovoltaic.

The installed gross capacity is $G$, the load level is $L$, the reliability curve is $f_0d(G)$ and the original reliability is $R_0$. The greater the load in courts, the lower the reliability level. After adding distributed
photovoltaic, the reliability curve is \( f_1(G + G_D) \). At the same load level \( L \), the system reliability is improved and the reliability is \( R_1 \). At this time, if the load level is gradually increased, the system reliability is gradually reduced. When the load level is \( L' \), the reliability level reverts to \( R_0 \), as shown in figure 1.

![Figure 1. Relationship between reliability index and a shifted load demand level](image)

Its mathematical expression is as follows:

\[
R_0 = f_0(G, L) = f_1(G + G_D, L')
\]  

(1)

To find the inverse function on both sides of the upper formula, you get:

\[
L' = f^{-1}_1(G + G_D, R_0)
\]  

(2)

Therefore, the added capacity credit and Effective Load Carry Capability of distributed photovoltaic are:

\[
G_C = ELCC = \Delta L = L' - L = f^{-1}_1(G + G_D, R_0) - L
\]  

(3)

At this point, the capacity credit is:

\[
CC = \frac{G_C}{G_D} = \frac{f^{-1}_1(G + G_D, R_0) - L}{G_D}
\]  

(4)

where, \( G_D \) is the installed capacity of distributed photovoltaic, \( G_C \) is the capacity credit of distributed photovoltaic and \( ELCC \) is the capacity credit of distributed photovoltaic.

Capacity credit is based on \( ELCC \) as the evaluation criterion. When the installed capacity of distributed photovoltaic in active distribution network is high, it is necessary to consider the impact of distributed photovoltaic withdrawal from operation. The following system reliability indicators are adopted:

Loss Of Load Expectation, LOLE (time/year):

\[
LOLE = \frac{1}{N} \sum_{k=1}^{\rho} LLD_k
\]  

(5)

Loss Of Energy Expectation, LOEE (MWh/year):

\[
LOEE = \frac{1}{N} \sum_{k=1}^{\rho} ENS_k
\]  

(6)

System Average Interruption Frequency Index, SAIFI (time/household·year):

\[
SAIFI = \frac{1}{N} \sum_{k=1}^{\rho} \sum_{i=1}^{n_l} \frac{\gamma_i}{C_i} / \sum_{i=1}^{n_l} C_i
\]  

(7)

System Average Interruption Duration Index, SAIDI (hour/household·year):

\[
SAIDI = \frac{1}{N} \sum_{k=1}^{\rho} \sum_{i=1}^{n_l} \frac{\gamma_i C_i}{\sum_{i=1}^{n_l} C_i}
\]  

(8)

Expected Energy Not Supplied, EENS (MWh/year):

\[
EENS = \frac{1}{N} \sum_{k=1}^{\rho} \sum_{i=1}^{n_l} ENS_k
\]  

(9)
Average Service Availability Index:

$$\text{ASAI} = 1 - \frac{\text{SAIDI}}{8760}$$

(10)

where, \( P \) is the power generation system state simulation times, \( Q \) is the distribution system state simulation times, \( LLD_k \) and \( ENS_k \) are the \( k \)th power generation system state simulation of power shortage time and power shortage; \( \lambda_k, \gamma_k \) and \( ENS_k \) respectively the power failure times, power failure time and insufficient power supply at simulated load point \( i \) of the \( k \)th power distribution system; \( C_i \) is the number of users at each load point and \( n \) is the total number of load points.

4. Analysis of matching degree between generation power and load of distributed Photovoltaic in courts

The energy conversion efficiency and incident solar irradiance of photovoltaic panel are the decisive factors of photovoltaic power output. The output power of the photovoltaic power station is as follows:

$$P_{PV} = Y_{PV} f_{PV} \left( \frac{R_T}{R_{STC}} \right) \left[ 1 + aP (T_c - T_{STC}) \right]$$

(11)

where, \( P_{PV} \) is the actual output power of the photovoltaic power station; \( Y_{PV} \) is the rated power of photovoltaic power station under standard test conditions; \( f_{PV} \) is the loss coefficient; \( R_T \) is the actual light radiation intensity; \( R_{STC} \) is the light radiation intensity under standard test conditions, which is 1 kWh/m\(^2\); \( aP \) is the power temperature coefficient of the panels in the photovoltaic power station; \( T_c \) is the battery temperature in the power station. \( T_{STC} \) is the battery temperature under the standard test condition, which is 25°C.

The distributed photovoltaic power station in courts has the same output characteristics in the same light radiation intensity area. The normal power generation time interval of photovoltaic power station is daytime and there is no power output at night. The shortest daytime in winter in North China is 7:00~17:00 and 10 hours. The longest day in summer is 5:00~19:00 and 14 hours. Under sunny and cloudless weather, the solar irradiance is strong. The daily output curve of photovoltaic power station is "small at both ends and high in the middle", similar to the normal distribution curve, with small smooth fluctuation of output. The photovoltaic peak occurs at 12:00~15:00. The high output is close to the full power output.

Figure 2. Photovoltaic power station based on the output characteristic curve under typical fine weather

There are usually two peaks of residential load, that is, early peak and late peak. The peak-valley difference is large. The early peak occurs at about 12:00 and the heavy load occurs at about 20:00 in the evening, which is basically consistent with people's daily life.
Figure 3. Typical daily load curve of residential users

Figure 4. Annual typical load curve

The annual maximum load occurs in August and the minimum load occurs in February, showing obvious seasonality. Among which the main influencing factors are air conditioning load and the Spring Festival holiday.

Summary: (1) Seasonally, the matching degree between distributed photovoltaic power and load is high. In summer, photovoltaic output is high. In August, the load is the highest in the whole year. (2) Photovoltaic power generation has obvious diurnal characteristics. The output of photovoltaic power generation is zero during the whole dark night. (3) The matching degree between residential load and distributed photovoltaic power is the lowest.

5. Analysis of capacity credit of distributed photovoltaic generation in courts

The paper uses non-sequential Monte Carlo simulation to calculate the original system daytime reliability index $R_d$ and the night reliability index $R_y$. Adding photovoltaic power station to calculate new daytime reliability index. Taking $R_y$ and $R_d$ as targets, the system load level is adjusted to obtain the system ELCC value $\Delta L_y$.

Figure 5. Schematic diagram of the distribution network in the courts

The total system load peaked at 28.93 MW in summer and 19.92 MW in winter. The peak value of each load point are shown in the table. The number of users is one household at each load point, the time of fault isolation and load transfer is set as a constant value of one hour.

| Load point number | Load(kW) | Load point number | Load(kW) |
|-------------------|----------|-------------------|----------|
| 1, 3, 9           | 1236.9   | 15                | 3505.6   |
| 2, 4, 11          | 1141.8   | 16                | 1931.7   |
| 5, 6              | 1500     | 32                | 501.8    |

Table 1. Load data
Case1: In the summer of August, the courts is mainly dominated by residential loads. The maximum load of the courts is 28.93 MW, which occurs around the evening peak at 20:00. Since the distributed PV output is zero at this time, the capacity of the superior substation must meet the load of evening peak. The reliability index of power generation system LOLE and LOEE are both zero.

Table 2. Reliability of the courts with sufficient capacity of the substation

| Photovoltaic installed capacity (MW) | 0 | 3.18 | 6.65 | 9.84 | 13.31 | 16.49 |
|-------------------------------------|---|------|------|------|-------|-------|
| Permeability | 0 | 11% | 23% | 34% | 46% | 57% |
| SAIFI(once/year) | 2.3267 | 2.2428 | 2.1576 | 2.1263 | 2.0985 | 2.0620 |
| SAIDI(h/year) | 11.723 | 11.3004 | 10.8712 | 10.7135 | 10.5733 | 10.3894 |
| EENS(MWh/year) | 27.2759 | 25.2448 | 23.4559 | 22.7801 | 22.1878 | 21.4229 |
| ASAI | 99.8662 | 99.8710 | 99.8759 | 99.8777 | 99.8798 | 99.8814 |

From the results of various reliability indicators, we can see that: 1) when the distributed PV penetration rate is continuously improved, the system reliability is improved. And when the permeability is high enough, the improvement effect tends to be saturated. When the PV permeability is around 92%, its reliability improvement capability tends to be saturated. 2) With the increase in installed capacity, the average power supply availability of the ASAI is saturated at approximately 99.89%.

Case2: In August of summer, the courts are mainly dominated by the industrial and commercial areas. The maximum load in courts occurs at the daytime. The capacity of the superior substation meets the peak load of 25 MW at night. The system capacity is insufficient at the peak of 28.93 MW during the daytime. Considering the continuous increase of distributed PV installations and analyzing the changes in various reliability parameters of the system.

Table 3. Reliability of the courts with improved distributed PV permeability when the capacity of the superior substation is insufficient

| Distributed generation installed capacity MW | 0 | 6.65 | 13.31 | 19.96 | 26.61 |
|--------------------------------------------|---|------|------|-------|-------|
| Permeability% | 0 | 23% | 46% | 69% | 92% |
| LOLE(h/year) | 1.2879 | 0.8652 | 0.5816 | 0.3876 | 0.2824 |
| LOEE(MWh/year) | 2.0808 | 1.5069 | 1.0881 | 0.7465 | 0.5668 |
| SAIFI(once/year) | 4.6792 | 4.3987 | 4.2395 | 4.0865 | 3.9782 |
| SAIDI(h/year) | 12.869 | 12.0976 | 11.6596 | 11.2391 | 10.9412 |
| EENS(MWh/year) | 60.2166 | 53.2137 | 49.4309 | 45.9289 | 43.5263 |
|----------------|---------|---------|---------|---------|---------|
| ASAI           | 99.8535 | 99.8619 | 99.8669 | 99.8717 | 99.8751 |

| Distributed generation installed capacity MW | 33.26 | 39.92 | 46.58 | 53.23 | 60 |
|---------------------------------------------|-------|-------|-------|-------|-----|
| Permeability%                               | 115%  | 138%  | 161%  | 184%  | 207% |
| LOLE(h/year)                                | 0.1699| 0.0939| 0.0523| 0.0325| 0.0233|
| LOEE(MWh/year)                              | 0.3907| 0.2768| 0.2271| 0.1563| 0.1126|
| SAIFI(once/year)                            | 3.6121| 3.4846| 3.3964| 3.3611| 3.3570|
| SAIDI(h/year)                               | 10.3193| 9.9557| 9.7035| 9.6026| 9.5913|
| EENS(MWh/year)                              | 37.2743| 34.6916| 32.9570| 32.2750| 32.1980|
| ASAI                                        | 99.8822| 99.88635| 99.88923| 99.89038| 99.89051|

When the capacity of the superior substation cannot meet the load demand, the load needs to be reduced to ensure that the substation is not overloaded, resulting in low system reliability. As the distributed PV installed capacity increases, the system reliability gradually increases. When the installed capacity is 60 MW, the index of LOLE and LOEE used to measure the reliability of the power generation system are close to zero, that is, the distributed photovoltaic has the characteristics of the power generation system and can replace the capacity of some of the superior substations. Therefore, under the condition of meeting the load demand, the expansion of the substation can be slowed down by increasing the installed capacity of distributed photovoltaic.

6. Conclusions
1) After adding photovoltaic power plants with different installed capacity, the reliability index has been improved to different degrees. And with the increase of photovoltaic installed capacity, the reliability index tends to be gentle and has a saturation effect.

2) The greater the correlation between the distributed photovoltaic power plants in the same courts, the smaller the capacity credit. Therefore, PV power plants should be dispersed on each feeder, which can not only reduce the fluctuation range of total output and reduce the impact of failure, but also increase the capacity credit.

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