Analysis Method of Grid-Connected Capability of Distributed PV Based on Multi-Data Source Fusion

Changhong Hu, Jingliao Sun, Yeyun Xiang, Jinyuan Liu, Zhihui Dong and Daqian Zhang

July 30, 2023

Analysis Method of Grid-connected Capability of Distributed PV based on Multi-data Source Fusion

Changhong Hu
Wenzhou Power Supply Company State Grid Zhejiang Electric Power Co., Ltd. Wenzhou Power Supply Company
Wenzhou, China
changhhu@126.com

Jingliao Sun
Wenzhou Power Supply Company State Grid Zhejiang Electric Power Co., Ltd. Wenzhou Power Supply Company
Wenzhou, China
sunjingliao@163.com

Yeyun Xiang
Wenzhou Power Supply Company State Grid Zhejiang Electric Power Co., Ltd. Wenzhou Power Supply Company
Wenzhou, China
17914554@qq.com

Jinyuan Liu
Wenzhou Power Supply Company State Grid Zhejiang Electric Power Co., Ltd. Wenzhou Power Supply Company
Wenzhou, China
373139269@qq.com

Zhihui Dong
Wenzhou Power Supply Company State Grid Zhejiang Electric Power Co., Ltd. Wenzhou Power Supply Company
Wenzhou, China
867245716@qq.com

Daqian Zhang
Jilin Northeast Electric Power University Science and Technology Development Co., Ltd
Jilin, China
271195539@qq.com

***Abstract*—This paper investigates and analyzes the conditions that restrict the acceptance capacity of distributed PV at home and abroad, and summarizes the factors that affect the acceptance capacity of distributed PV. An index system of distributed PV grid-connected acceptance capability is established, which takes into account grid reliability, quality and security. According to the integration of multi-source heterogeneous data such as distributed PV access information, grid production management information and user load information, the distribution network model containing distributed PV is completed, so as to carry out the acceptance capacity analysis. The example analysis shows that: access to high voltage levels can improve the distributed PV absorption capacity of the distribution network in the same distribution area. In addtion, demand response can improve the distributed PV absorption capability of distribution network.**

Keywords—distributed PV, influencing factors, evaluation index, data fusion, consumption analysis

I. INTRODUCTION

In order to build a new type of power system that adapts to the increasing proportion of new energy and promote clean and low-carbon energy transformation, new policies and models (collectively referred to as the "large-scale grid connection" model) have emerged, guided by large-scale distributed PV flexible access and nearby consumption, such as "rooftop PV development", "PV+" comprehensive utilization ", and" thousands of households bathe in sunlight action ". PV power generation will shift from centralized to both centralized and distributed, gradually becoming one of the main power sources in China along with wind power generation. Conventional power sources will gradually shift from power generation to basic and systematic regulatory resources [1].

With the large-scale distribution of distributed PV into the regional distribution network, the ability of distribution network to accept distributed PV has gradually become a research hotspot at home and abroad [2-3]. In the process of evaluating the ability of distribution network to accept distributed PV, voltage, load fluctuation and reverse power flow are mainly included as the limiting factors affecting the safe and stable operation of distribution network. The National Renewable Energy Laboratory (NREL) has published two reports on acceptance capacity, suggesting that distributed PV penetration of 10%-20% typically has a significant impact on the grid. Difficulty meeting the IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems (IEEE 1547) [4-5]. Natural Resources Canada CanmetENERGY Technology Centre research report pointed out that distributed PV penetration should not exceed 20% [6]. Literature [7] evaluated the ability of the traditional power system to accept PV, and took line voltage as the assessment index to exceed the limit. The simulation concluded that when a large number of distributed PV is connected to the low-voltage side of the transformer of the distribution network or the reactive power compensation device is used, its permeability can reach 50%. Literature [8-9] analyzed the application of technologies such as improving system flexibility, load transfer and increasing energy storage to improve the system's ability to accept PV, and pointed out that energy storage is a fundamental solution to break the boundary between PV power generation and conventional power generation. The results show that a distributed energy storage system with a storage capacity less than maintaining an average daily load can increase PV penetration to 50% of the total power of the power system.

II. ANALYSIS OF INFLUENCING FACTORS OF DISTRIBUTED PV ACCEPTANCE CAPACITY

Distributed PV high permeability access will have adverse effects on the distribution network, such as node voltage over the limit, branch load current over the limit, short circuit current over the limit, power quality reduction, reliability reduction, protection errors, and off-grid impact on the power grid and equipment, the following are the factors restricting the acceptance of distributed PV capacity of the distribution network are analyzed [10-11].

- Node voltage. Appropriate distributed PV access is beneficial for maintaining voltage stability, but when the penetration rate of distributed PV is too high, significant fluctuations in its output may cause the voltage of the distribution network to exceed the limit.
- Branch road carrying capacity. High permeability distributed PV will cause power backflow, and excessive branch current carrying capacity will lead to a series of problems such as overheating of distribution network wires and overload of transformers. At the same time, it will also limit the further access of distributed PV.
- Grid structure. If the type, capacity, installation location, energy storage capacity, and ratio of distributed PV access are not matched with the grid structure, it not only fails to leverage the advantages of distributed PV, but may also have negative impacts on the operation of the distribution system, such as increasing system operation risk, increasing energy consumption, and reducing system voltage stability.
- Load characteristics. The load characteristics have a significant positive correlation with the acceptance capacity of distributed PV. In order to improve the penetration rate of distributed PV, scholars have proposed concepts such as flexible load and demand side management, which use advanced communication technology to intelligently manage and flexibly adjust the demand on the load side.
- Short circuit current. Due to the impact of the integration of distributed PV on the protection of the existing distribution network, it is easy to cause protection rejection or misoperation. By analyzing the short-circuit current of distributed PV distribution networks, corresponding protection can be improved.
- Power quality. As the extreme end of the power system, the integration of high penetration distributed PV in the distribution network will pose significant challenges to the power quality of the distribution network, such as voltage drop, flicker, three-phase imbalance, and harmonics.
- Reliability. When distributed PV are connected to the distribution network, the power supply mode of the distribution network will shift from traditional radiation power supply mode to dual or multi terminal power supply mode. Due to the intermittent and random nature of distributed PV, this may have an impact on the reliability of system operation to a certain extent. A reasonable island strategy can help improve the reliability of the distribution network.
- Protection configuration. The integration of a large number of new energy distributed PV into the distribution network will have a profound impact on the structure of the distribution network, as well as the size and direction of short-circuit current in the distribution network, bringing many adverse effects to the relay protection of the distribution network. Adaptive protection provides a reference for solving such problems.
- Coordinated control. Generally, distributed PV are controlled in the form of microgrids, which are combined with energy storage devices to study coordinated control methods and improve the penetration rate of distributed PV.
- Energy optimization. Through the design and implementation of various energy optimization algorithms, while improving various indicators of the distribution network (such as minimum network loss, optimal economy, and best power quality), the access capacity of distributed PV is improved.

III. COMPREHENSIVE EVALUATION SYSTEM FOR THE ACCEPTANCE CAPACITY OF DISTRIBUTED PV

In order to proactively address the challenges brought by the large-scale grid connection of distributed PV to system operation, the factors affecting grid enterprises by the aforementioned distributed PV grid connection are classified into three dimensions: reliability, quality, and safety. A comprehensive evaluation index system for the acceptance capacity of distributed PV grid connection is constructed, as shown in Fig.1. in order to improve weak links and enhance the acceptance capacity of distributed PV grid connection.

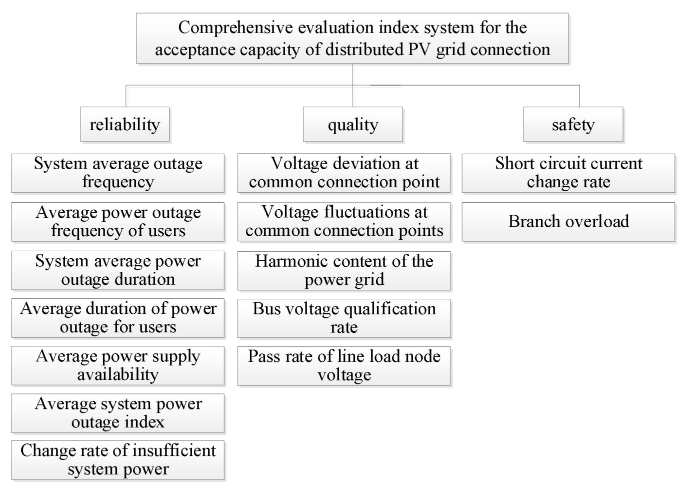

Fig. 1. Comprehensive evaluation index system for the acceptance capacity of distributed PV grid connection

(1) System average outage frequency

Use F_{xttd} to represent the average power outage frequency of the system, and the calculation formula is:

$$F_{xttd} = N_{upo} / N_{all} \times 100\% \quad (1)$$

N_{upo} represents the number of power outages for users and N_{all} represents the total number of users.

(2) Average power outage frequency of users

Use F_{yhtd} to represent the average power outage frequency of the user, and the calculation formula is:

$$F_{yhtd} = N_{upo} / N_{uapo} \times 100\% \quad (2)$$

N_{uapo} represents the number of users affected by power outages.

(3) System average power outage duration

Use *Txttd* to represent the average power outage duration of the system, and the calculation formula is:

$$Txttd = \sum (T_{epo} \times N_{uaepu}) / N_{all} \times 100\% \quad (3)$$

T_{epo} represents the time of each power outage, and N_{uaepu} represents the number of users affected by each power outage.

(4) Average duration of power outage for users

Using T_{yhtd} to represent the average duration of power outages for users, the calculation formula is:

$$T_{yhtd} = \sum (T_{epo} \times N_{uaepu}) / N_{uapo} \times 100\% \quad (4)$$

(5) Average power supply availability

Using K_{pjgd} to represent the average power supply availability, the calculation formula is:

$$K_{pjgd} = T_{upsh} / T_{tpsh} \times 100\% \quad (5)$$

T_{upsh} represents the user's power supply hours, and T_{tpsh} requests the total power supply hours.

(6) Average system power outage index

Use E_{xtqd} to represent the average system power outage index, and the calculation formula is:

$$E_{xtqd} = E_{tes} / N_{all} \times 100\% \quad (6)$$

E_{tes} represents the total electricity shortage.

(7) Change rate of insufficient system power

Using K_{xtdl} to represent the rate of change in system power shortage, the calculation formula is:

$$K_{xtdl} = (E_{tes1} - E_{tes2}) / E_{tes1} \times 100\% \quad (7)$$

E_{tes1} and E_{tes1} respectively represent the power shortage before and after the installation of distributed PV.

(8) Voltage deviation at common connection point

Distributed PV access has led to changes in the traditional distribution network structure, resulting in a certain degree of impact on voltage deviation. Among them, the voltage deviation at the public connection point has the greatest impact. Therefore, the voltage deviation at the public connection point is selected as the measurement indicator, and the calculation formula is:

$$\Delta U = (U - U_N) / U_N \times 100\% \quad (8)$$

ΔU represents the voltage deviation value, U and U_N respectively represent actual voltage and rated voltage.

(9) Voltage fluctuations at common connection points

When the supplied load changes rapidly and frequently, or when the supplied load changes rapidly but not frequently, it can cause significant voltage changes in the enterprise's power supply and distribution system. The difference between two adjacent extreme values during a sudden change in voltage is called voltage variation, usually expressed as a relative value (ratio to rated voltage) or its percentage.

$$V_t = (U_{max} - U_{min}) / U_N \times 100\% \quad (9)$$

V_t represents the voltage variation, U_{max} and U_{min} respectively represent maximum voltage and minimum voltage.

(10) Harmonic content of the power grid

The integration of distributed PV power into the distribution network requires the connection of a large number of power electronic devices, which can easily cause harmonic pollution to the power grid. The size of harmonic components is related to the capacity and connection location of PV power sources. The calculation formula for harmonic content index is:

$$HR = U_h / U_l \quad (10)$$

HR represents the harmonic content, U_h and U_l respectively represent the voltage harmonic value the basic voltage.

(11) Bus voltage qualification rate

Using R_{mxdy} to represent the qualification rate of bus voltage, the calculation formula is:

$$R_{mxdy} = (1 - T_{vol} / T_{vd}) \times 100\% \quad (11)$$

T_{vol} and T_{vd} respectively represent the voltage over limit time and voltage detection time.

(12) Pass rate of line load node voltage

Use R_{xlfh} to represent the qualification rate of line load node voltage, and the calculation formula is:

$$R_{xlfh} = N_{qvp} / N_{tlln} \times 100\% \quad (12)$$

N_{qvp} and N_{tlln} respectively represent the number of qualified voltage points for line load nodes and total number of line load nodes.

(13) Short circuit current change rate

Using dI_f to represent the rate of change of short-circuit current, the calculation formula is:

$$dI_f = (I_1 - I_2) / I_1 \times 100\% \quad (13)$$

I_1 and I_2 respectively represent the short circuit current before and after installation of distributed PV.

(14) Branch overload

Using I_o to represent the overload of branch current, the calculation formula is:

$$I_o = I_{max1} - I_{max2} \quad (14)$$

I_{max1} and I_{max2} respectively represent the maximum current before and after installation of distributed PV.

IV. Calculation of Distributed PV Grid Connection Acceptance Capacity

This article takes the limit values of voltage fluctuations and deviations in the distribution network as quantitative calculations, short-circuit current and equipment overload as constraints, and reliability indicators with calculation conditions as verification. At the same time, considering the demand side response of the load side and the reactive power regulation ability of distributed PV, the regional distribution network adopts the distributed PV simulation analysis method shown in Fig.2.

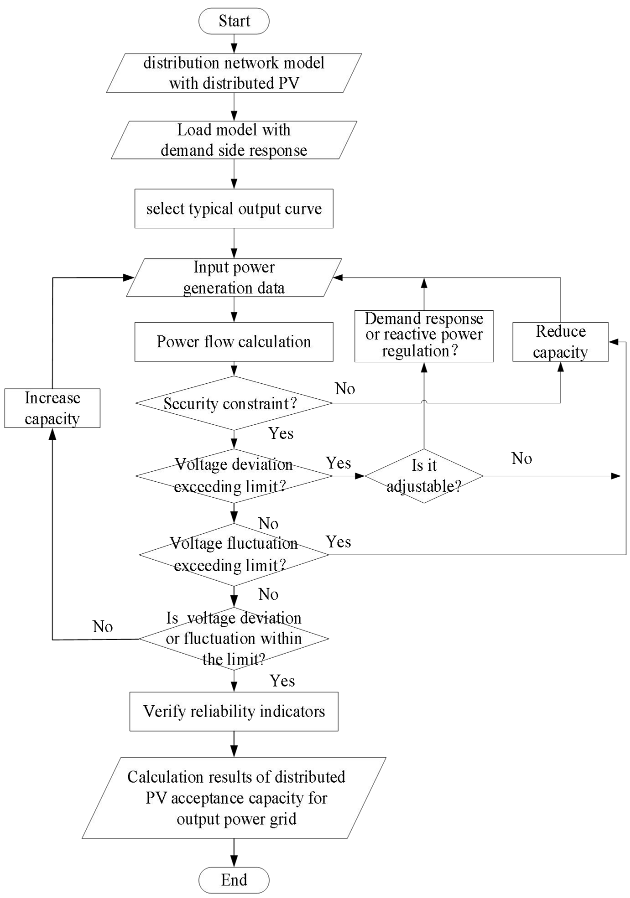

Fig. 2. Flow chart of distributed PV analysis and evaluation method for distribution network acceptance

The calculation cycle is one natural day, and the temporal characteristics are taken into account during the calculation. The specific analysis steps are as follows:

1) Distribution network modeling based on multi data source fusion technology.

2) Analysis of distribution network load characteristics and distributed PV output characteristics in different scenarios.

3) Power flow calculation and acceptance capacity calculation for distributed PV connected to distribution network.

4) Reliability evaluation of distributed PV integration into the distribution network.

V. Case Study

In this example, acceptance capacity analysis is conducted for both 380V and 10kV access scenarios, and the impact of demand side response on acceptance capacity is analyzed. When calculating, U_{min} = 0.93, U_{max} = 1.07, V_t = 2.95% (referring to the requirements of the national standard [9] for voltage fluctuations, the voltage fluctuation limit is 3%. Considering a certain safety margin, it is taken as 2.95%). The results are shown in Table I.

TABLE I. Analysis of Calculation Cases in Different Scenarios

Voltage Level	Scene analysis	
	Demand response	***Absorptive capacity***
380V	No	2.35MW
	Yes	3.15MW
10kV	No	3.2MW
	Yes	4.3MW

For the multi-point 380V connected PV power generation system, the maximum PV penetration rate is limited by the maximum change value of the system feeder terminal voltage. On the basis of not changing the grid structure, the total PV installed capacity should not be greater than 2.35MW. Considering the demand response, the total PV installed capacity can be increased to 3.15MW. For multi-point 10kV connected PV power generation systems, the above two indicators correspond to 3.2MW and 4.3MW respectively.

Through the comparative analysis of the above cases, it can be concluded that:

1) Within the same distribution area, connecting to a high voltage level can improve the distributed PV absorption capacity of the distribution network. Connecting to 10kV for distributed PV can increase absorption by 36% compared to connecting to 380V.

2) Demand side response can improve the distributed PV consumption capacity of the distribution network. In this example, the demand side response regulation capacity accounts for about 24% of the maximum load in the region, and the distributed PV consumption capacity can be increased by 34%, resulting in a significant increase in PV sales revenue.

VI. Conclusion and Outlook

This article proposes a method for analyzing the acceptance capacity of distributed PV grid connection based on the fusion of multiple data sources. A comprehensive evaluation index system for the acceptance capacity of distributed PV grid connection is constructed from three dimensions: reliability, power quality, and safety, providing reference and risk warning for the large-scale grid connection and operation consumption of distributed PV. In the future, when distributed PV participate in system regulation and friendly support on a large scale, further exploration is needed to comprehensively balance the regulation performance, power generation utilization rate, and economic benefits (marketization) of distributed PV.

REFERENCES

[1] Li Feng, Ding Jie, Zhou Caiqi, ect. Discussion on key technologies of large-scale grid-connected operation of distributed photovoltaic under the new-type power system[J/OL].Power System Technology:1-16[2023-07-18].DOI:10.13335/j.1000-3673.pst.2023.0771.

[2] Zhang Zhigang， Kang Chongqing． Challenges and prospects for constructing the new-type power system towards a carbon neutrality future[J]. Proceedings of the CSEE, 2022, 42(8)：2806-2819

[3] Liu Wenlong，Lv Zhipeng，Liu Haitao．An overview of morphological development and operation control technology of power electronics dominated distribution area[J/OL]. Proceedings of the CSEE:1-25[2023-03-28]. DOI:10.13334/j.0258-8013.pcsee.220890.

[4] Wang Yifeng, Tang Wei, Liu Ludeng, etc Construction and application of risk assessment and grading system for power grid operation [J] Power System Automation, 2015, 39 (08): 141-148

[5] Ni M, Mccalley J D, Vittal V, et al. Online risk-based security assessment[J]. IEEE Transactions on Power Systems, 2003, 18(1):258-265.18(1):258-265

[6] Wei Yuanhang, Liu Sige, Su Jian Risk assessment of urban power grid based on enumeration sampling method [J] Grid Technology, 2008, 32 (18): 62-66

[7] Qiu Wei, Zhang Jianhua, Liu Nian, et al Multi-objective generation optimization scheduling considering operational risks [J] Chinese Journal of Electrical Engineering, 2012, (22): 64-72

[8] Xiao Jun, He Qibo, Su Buyun. Safe and Efficient Operation Mode of Intelligent Distribution Network Based on Security Domain. Power System Automation, 2014, 38 (19): 52-60

[9] Xiao Jun, Su Buyun, Gong Xiaoxu, Wang Chengshan. Distribution Network Security Domain Model Based on Feeder Interconnection. Power System Protection and Control, 2015, 43 (20): 36-44

[10] Sheng Wanxing，Wu Ming，Ji Yu，et al．Key techniques and engineering practice of distributed renewable generation clusters integration[J]. Proceedings of the CSEE, 2019, 39(8)：2175-2186

[11] IMPRAM S，NESE S V，ORAL B．Challenges of renewable energy penetration on power system flexibility: A survey[J]. Energy Strategy Reviews, 2020, 31：100539.

Authors' background

Your Name	Title*	Research Field	Personal website
Changhong Hu	Senior Engineer	Power system automation	Inexistence
Jingliao Sun	Senior Engineer	Power system automation	Inexistence
Yeyun Xiang	Senior Engineer	Power system automation	Inexistence
Jinyuan Liu	Senior Engineer	Power system automation	Inexistence
Zhihui Dong	Engineer	Power system automation	Inexistence
Daqian Zhang	Master	Power system automation	Inexistence