

An Assessment Method of Substation Credible Capacity of Microgrids Considering the High Voltage Connection Mode

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Abstract. The microgrid accessing to active distribution network can improve the reliability of the system, meanwhile supply partial load in place of high voltage distribution network. An assessment method of substation capacity credit of microgrid is proposed to evaluate the capacity value of grid-connected microgrid based on the principle of equal reliability. The secant method and the sequential Monte Carlo method for state transition are used to solve the model. To verify the effectiveness of the method proposed in this paper, the credible capacities of different microgrid types in various typical connection modes of a high voltage distribution network are quantitatively analyzed in the case study, which can provide a reference for the capacity planning of an active distribution network substation and grid structure selection.

1. Introduction

Microgrid (MG) is a small hybrid generation and distribution system, characterized with self-control, management and protection, composed of distributed generations (DGs), energy storage devices, energy conversion devices, loads, monitoring and protection devices [1]. There are two kinds of distributed energy sources in MGs, one is the uncontrollable power supplies, which are mainly renewable energy power generation units such as solar photovoltaic cells; the other is the controllable power supplies, including diesel generators, fuel cells, and energy storage cells, which will serve as the power supply supplement and backup of the uncontrollable. A significant portion of loads can be supplied by MG, and in the scenario that many grid-connected distributed generations, both the capacity and reliability of distribution system are enhanced by introducing the energy storage integration and changing the power factor.

MGs could supply a part of loads as the backup sources of HV distribution network, thus, the assessment of the MGs capacity replacement value to HV distribution network not only supports to substation planning, but also assists to evaluate the contribution generalized energy source do to power system, benefiting the planning of market mechanism and power price policy.

There are generally two equivalent models for the impact of DGs on location and capacity of substation in traditional planning. In one of the models, DG is regarded as a kind of special load whose power consumption is negative, and its output multiplied by a certain factor for calculating the total installed capacity [2]. The planning substation capacity is reduced effectively depends on DG output is considered in this method, but the fluctuation of output and randomness of fault are not considered. The



other is based on the minimum output of DG without considering its total capacity value[3], which is a relatively conservative method. In [4], a substation planning method considering the capacity value of DG is proposed. The expected power loss of load is considered as the index within the power supply scope of a substation. The credible capacity is defined as the load capacity that can be increased after the connection of DG under the same reliability level. The final substation capacity is the value got by deducting the credible capacity from the original value.

There is a great deal of research about the application of credible capacity in the evaluation of DGs contribution for system capacity reliability [5]. In [6], it is pointed out that the credible capacity of wind power is defined as the capacity which wind turbines could replace under the premise of equal reliability, and the main calculation method is summarized. In [7], a wind power credible capacity calculation method based on sequence operations is proposed. In [8], a credible capacity calculation method for wind and solar power generation system combined with storage is proposed. The above studies are all based on the effective capacity of intermittent energy alternative to conventional generators at the level of the transmission networks. In the studies, the same reliability means that the adequacy of the power generation system remains unchanged. In [4,9], the concept of credible capacity is extended to the level of distribution networks for the first time. And the capacity that DGs can replace within the substation power supply scope be calculated. Currently, the load density and HV connection modes in the region are generally known in the planning model of HV distribution networks, and the contribution of unit capacity to reliability is different in different HV connection modes. For this reason, the substation capacity that MG can replace is not only related to the distribution of users under substation scope, but also to the grid structure of HV distribution networks.

In this paper, the definition of the credible capacity of MG in the distribution network is introduced firstly with a specific distribution area is taken as the research object. Under the premise of forecasting certain values of MG penetration and MG scattered distribution in the planning level year, considering the uncertainties and control strategies of MG, the calculation method of the credible capacity of high-voltage distribution network is studied, laying a foundation for substation locations and capacity under certain high-voltage connection modes.

2. The definition of the credible capacity of MG in the distribution network

To evaluate the capacity value of MG in the distribution network, the substation credible capacity of MG is defined as the equivalent transformer capacity of MG accessed in the distribution network based on the principle of equal reliability. The definition is at the level of high-voltage distribution networks, considering the components failure such as the main transformer, 110 kV lines and circuit breakers [10]. It can be applied to the overall planning of substation capacity and evaluating the contribution of intermittent energy sources to system capacity adequacy.

According to the definition, substation credible capacity is an alternative part of substation capacity with MG access under equal reliability. In this section, the effective load carrying capability (ELCC) indicator is used at a certain load level to evaluate the substation credible capacity of MG. The reliability refers to the power supply reliability of the high-voltage distribution network for 10kV network considering random failures of 110kV lines and transformers here. Due to the open-loop operation of high-voltage distribution network, the topological structure changes and line overload must be considered in the reliability calculation. The base loads of the substation are set to the safe maximum value to eliminate the contribution of the higher-level power supply to the new loads in this section. The maximum safety load of distribution network is the load supplying capability that the distribution network can meet the N-1 safety criteria under actual network operation conditions in a certain power supply area. When there are no MGs connected to network and the load increases further, the substation load rate will exceed the safe value. On this occasion, the upper level power grid will no longer provide support for the new loads allowance. From this point, the new loads are supplied by MGs under the premise of ensuring reliability. A 10kV distribution network with one transformer can be taken as an example. All loads and power supplies are equivalent to the 10kV bus of the transformer. Figure 1 is a

partial schematic diagram of a substation within the power supply zone, showing the distribution locations of the MG power and load equivalent access stations.

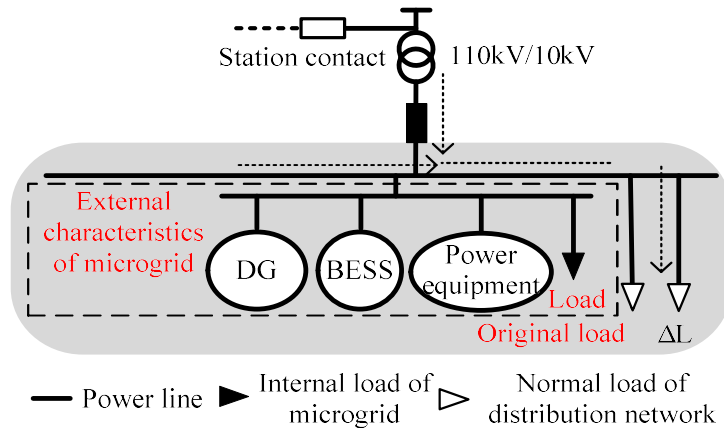


Figure 1. Substation partial schematic diagram

The expression of substation credible capacity of MGs in distribution network is as follow:

$$R(C_T, L_0) = R(C_T, C_{MG}, L_0 + \Delta L) \quad (1)$$

Where, $R(\bullet)$ is the estimation function of reliability in high-voltage distribution network, and system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI) or expected energy not supplied (EENS) can be selected by the reliability index. C_T and C_{MG} are the substation capacity and MG capacity under a certain connection mode respectively. L_0 and ΔL are the sum of the original loads and the new loads of the 10kV substations within each power supply zone respectively. When (1) is workable, the ΔL is the substation credible capacity of MG in the power supply zone.

3. The connection mode and power transfer mode of high-voltage distribution network

According to the Guidelines for Urban Power Network Planning and Design of the State Grid Corporation of China (SGCC), the power supply load under a single transformer belongs to the same power supply zone, when the failure of the HV distribution network causes the loss of load, the load is powered by the transfer HV distribution network firstly; and if the power transfer lines fail or the transfer load reach the limit, then the load is powered by connection of the station in MV side. The reliability level of the power system is determined by load transfer of both HV and MV.

HV distribution network mainly has the following wiring modes: direct power supply connection, single-sided power T-type connection, dual-power T-type connection, and dual-power π -type connection. As shown in Figure 2, single-sided power T-type connection is used to explain the operation mode after failure as an example [12]. Each transformer is responsible for the supply of a load zone.

In practice, the HV side connection modes in substation mainly include line transformer connection mode, bridge-shaped connection mode and T-type connection mode. In addition, the LV side connection modes mainly include loop-in and loop-out and single bus with subsection connection and so on. In this paper, the HV side connection mode between inlet and main transformers in substation line transformer connection mode with the bus ignored, and sectionalized single-bus configuration connection mode is used in LV side. Since the limit capacity of transmission lines is generally greater than the sum of the maximum safety loads in the substation zone, the limitation of lines' capacity on transfer load is not considered.

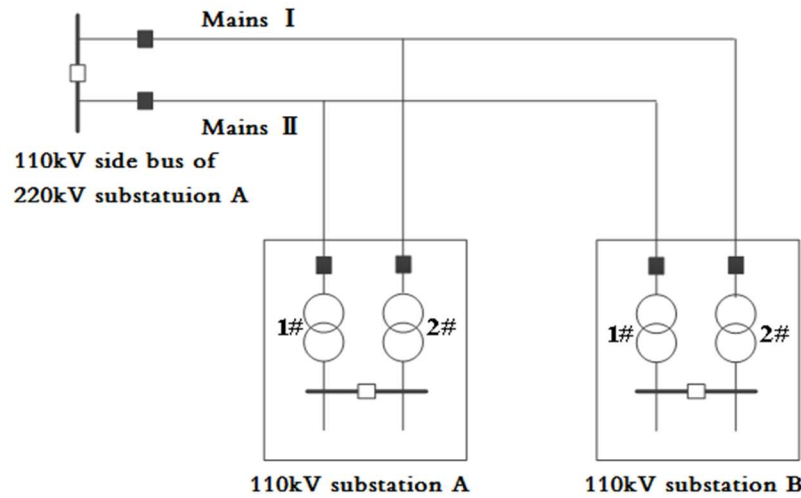


Figure 2. The single-sided power T-type connection

In the above figure, if the 110kV breaker on Mains I fails, the load zone connected to the 2# transformers of 110kV substations A and B will be outage, and they cannot be powered by the HV line side. So two load transfer modes are described: in-station load transfer mode and MV side station load transfer. In this paper, only the internal connection between the unit wiring methods is considered, that is, the connection between the A and the B station, which is limited by the capacity of transformers. When loss capacity of load is 50MW, 30MW of the load can be powered through the low voltage side of another transformer which is in normal operation in the substation, and the power outage time is the load-transfer time. Moreover, the remaining 20 MW load can be powered through medium voltage side. Since the reliability of the HV distribution network is studied in this paper, it is considered that the HV side stops supplying power to the 10kV load at its time, and the power outage time is regarded as the failure time.

From the above analysis, the load transfer after components failure is different in different connection modes, which results in different reliability.

4. The reliability evaluation algorithm of distribution network with MG based on Monte Carlo simulation

At present, there are two kinds of methods for reliability assessment of distribution networks: analytical method and simulation method. Regardless of aging failures, most outages in the power system are repairable, and the MG power status changes can be simulated through the cycle of "Run-Stop-Run". Therefore, a two-state model is used to characterize the state of the power supply. Considering the time-series of distributed energy output and load, sequential Monte Carlo simulation is adopted for the reliability evaluation of MG to reflect its status time sequence and the correlation between DG and load. This paper comprehensively considers the expected energy not supplied and loss of energy expectation as the evaluation indicators [13], which can be expressed as:

$$R_G = \frac{1}{N} \sum_{n=1}^p E_{ns,n} \quad (2)$$

Where, N is the total simulation year; Ens is the loss of energy and energy not supplied in one fault condition; p is the simulation times of component fault conditions.

The specific calculation steps are as follows: Step 1: Generate sequential change sequences. The time-sequence change of microgrid output is generated according to the type of microgrid in the simulated total length T. And based on the load characteristic and the operation strategy under the

normal operation of ESS, the state of charge(SOC) sequential change of the ESS is generated. Also, the output sequences of other power components are generated according to the price and cost level. Step 2: Generate the fault state sequences. Sequential simulation of the components in the system is carried out without considering the fault of double or above. When the fault state occurs, the fault evaluation of Step 3 is carried out, then $p+1$. Step 3: Fault assessment: According to the fault condition of the non-power supply components, the failure mode analysis table database is queried to determine the load loss area. Then, according to the output sequence of MG obtained in Step 1, the output of MG in the load-loss area during the system failure is determined. Confirm the load size and transfer route. When the transfer is unable to complete, the energy storage in the load loss area can implement the failure operation strategy and supply part of the load. When it still can't satisfy all the loads, the controllable load needed to be reduced could be determined. After all the above measures, the loss of load is the part that is still unable to be supplied, and the loss of energy and energy not supplied is recorded as $Ens.n$.

Step 4: The evaluation indicator. The component fault status indicators calculation is shown as Formula (1). The reliability index of the system is obtained based on it.

5. Method for evaluating the substation credible capacity of MG

At present, the main methods of credible capacity evaluation are the bisection method, the Newton method and the secant method. In [7], the bisection method is used to adjust the capacity of wind turbines, making the difference between the reliability of the actual system and that of the equivalent system within a certain error range. Then, the capacity of wind turbines is considered as the credible capacity. However, this method is less efficient because that the lack of a specific function formula for derivation makes the Newton iteration method not applicable.

The secant method is used in this paper. As a variation of the Newton iteration method, the secant method is a numerical calculation method to find roots, which has a fast computing speed.

Take two load values, namely L_1 and L_2 with the corresponding reliability values R_1 and R_2 . If R_1 and R_2 are both greater than or less than R_0 , re-select load values until the criterion is met that one of R_1 and R_2 is greater than R_0 , with the other one less than R_0 . A straight line connecting the points (L_1, R_1) and (L_2, R_2) , intersect the line whose ordinate is R_0 and parallels to the abscissa axis at a point L . Obtain the corresponding reliability level R . If R is greater than R_0 , turn L into the new L_1 . Following this, connect the new (L_1, R_1) and (L_2, R_2) before creating a loop. The concrete steps of solving the substation credible capacity of micro-grid in the active distribution network are as follows: Step 1: Input the grid connection structure of the HV distribution network and the inter-station contact constraint of the substation. Calculate the maximum safety load of the system under the wiring structure with the distribution network data in the previous planning scheme. Through the automatic traversing of the computer, a failure impact analytical table of all circuit components is established and the modes of transferring are determined. Step 2: Calculate the reliability level R_0 in the primal system when the micro-grid is not integrated. Step 3: Calculate the distribution network reliability level R_G with micro-grid integration using the Monte Carlo simulation method described in Section 3. Step 4: Using the secant method to adjust load (primal load is the maximum safety load L_0), make the system reliability R_G after the micro-grid integration equal to the primal system reliability R_0 . Obtain the corresponding maximum safety load L_p at this time. The difference between L_p and L_0 is the increment of the load, ΔL , which is exactly the substation credible capacity of the accessed MG.

6. Case studies

6.1. Transformer capacity selection

The IEEE 29-node power distribution system is used to validate the effectiveness of the model in a 10kV distribution network under a transformer.

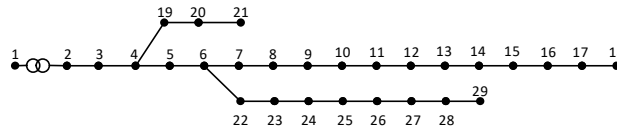


Figure 3. The IEEE 29-node power distribution system

The power distribution system includes 29 nodes. Node 1 is root node, connected to the 10kV side of the transformer and the infinite system. First, the transformer capacity is selected based on the calculated load of all the equipment and types and characteristics of the load. Calculation load is the basic basis of power supply design calculation. The maximum load of the 10kV line is $2.975+j1.345\text{MVA}$, and the system structure is shown in Figure 3. The ratio of OLTC is $1\pm 8\times 1.25\%$, and the low voltage side is equipped with a fixed compensation capacitor bank. The number and capacity of capacitor bank is $4\times 0.1\text{MVar}$. $P=2.975\text{ MW}$, $Q=1.345-0.1\times 4=0.945\text{ MVar}$, $S_c=\sqrt{2.975^2+0.945^2}=3.121\text{MVA}$. The load rate of the transformer is generally 70%~85% for it can transfer between stations to meet the load under the condition of main transformer failure. In this paper, the load rate is 70%. Transformer capacity $S_{N.T}\geq S_c / 0.7=3.121 / 0.7=4.459\text{ MVA}$. In the power substation, two transformers usually have the same capacity. Each transformer capacity should meet the following two conditions at the same time: (1) $S_{N.T}\approx 0.7S_c$; (2) Meet the needs of all the first level and second level load. From the above, each substation has two equal capacity transformers, each transformer capacity is set to 5 MVA.

6.2. The data analysis of results

The four modes correspond to four network frame structures. Mode 1: Direct power supply connection; Mode 2: Single-sided power T-type connection; Mode 3: Dual-power T-type connection; Mode 4: Dual-power π -type connection. The selected 3 nodes of the feeder are connected to 3 MGs. The four combination types of multi MGs are all the business MGs(Type.a), all the residential MGs(Type.b) all the industrial MGs(Type.c), and all types of MGs respectively. The connection position is the node 7,18,29. The generalized power distribution diagrams of residential, business and industrial MGs are as follows:

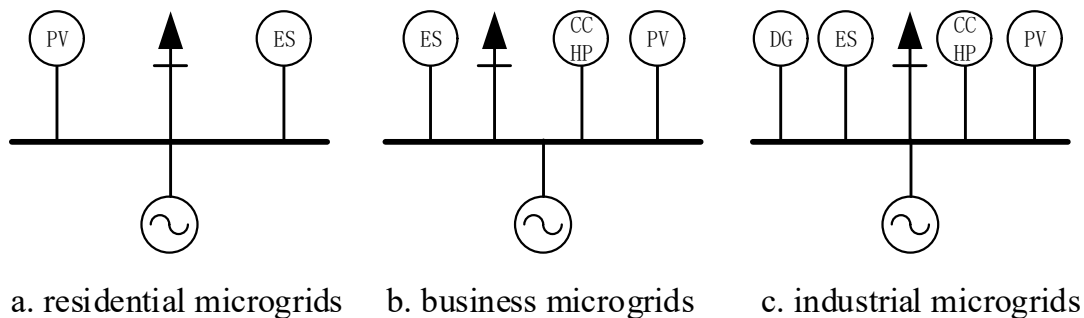


Figure 4. Multi type generalized power of MG distribution schematic diagram

(1) The impact of weather and seasonal factors on credible capacity.

First, under the same connection mode of the HV distribution network, the impact of weather and season on the credible capacity is analyzed.

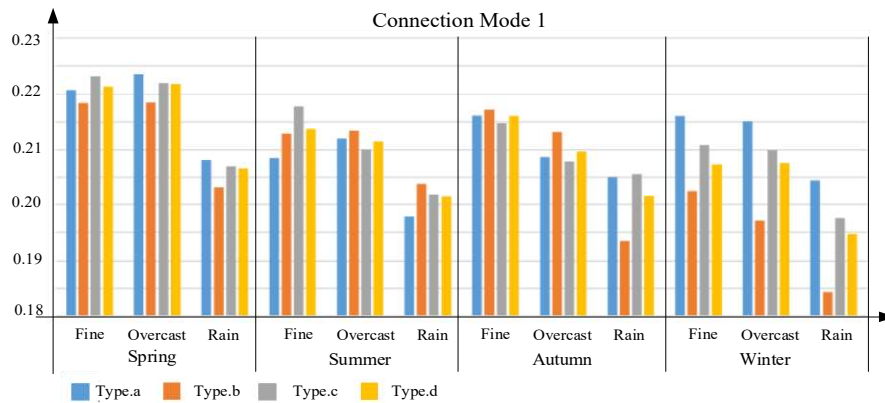


Figure 5. Comparison of credible capacity in different weather and seasons under Mode 1

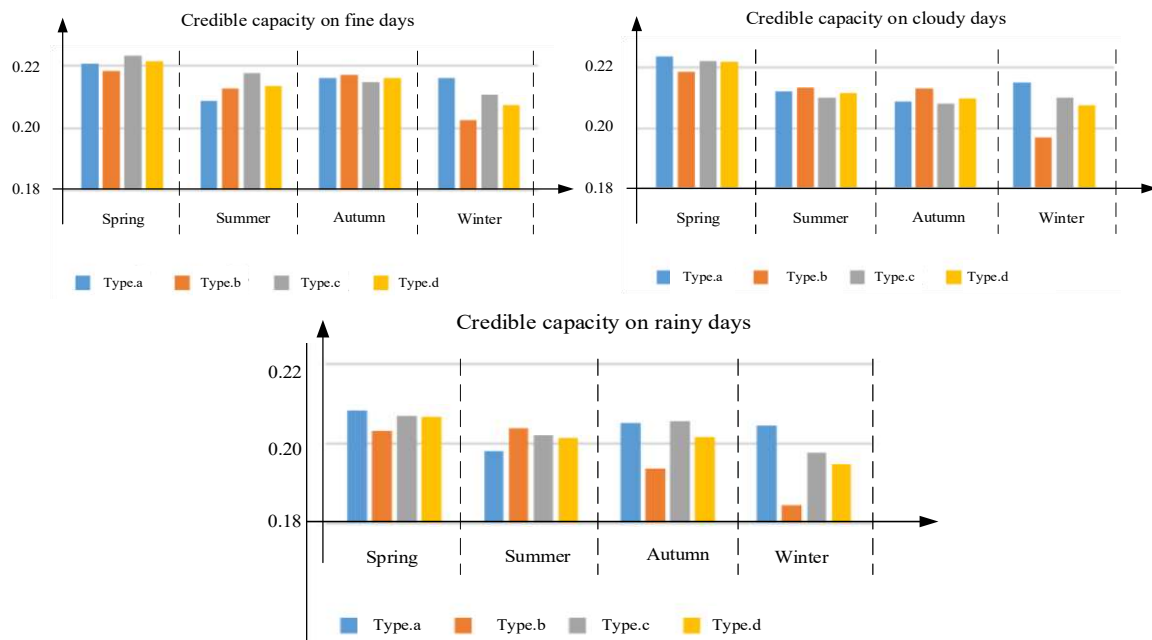


Figure 6. Comparison of credible capacity under three weather types.

Taking Mode 1 as an example, combined with photovoltaic power generation, it is observed that:

No matter what season, the creditable capacity in rainy days is relatively minimum. The cloudy day is the next small, sunny days are the greatest.

From the view of season, the fine days in spring is the greatest. While on the sunniest of days in summer, the creditable capacity is not the greatest. Combined with the load data, it can be seen that this is mainly due to the heavy load in summer, and the alternative transfer capacity of MG is smaller. On cloudy days, the creditable capacity in summer and autumn is similar. It indicates that a strong cloudy day in summer the light conditions offset the high load demand. On rainy days, the four seasons have little difference, and the reliable capacity in winter is slightly lower.

(2) Comparison of reliable capacity of different combinations of multi MGs

There are four types of multi MGs. The three MGs accessed are set as Type.a, Type.b, Type.c, and Type.b. The results of the creditable capacity are as follows:

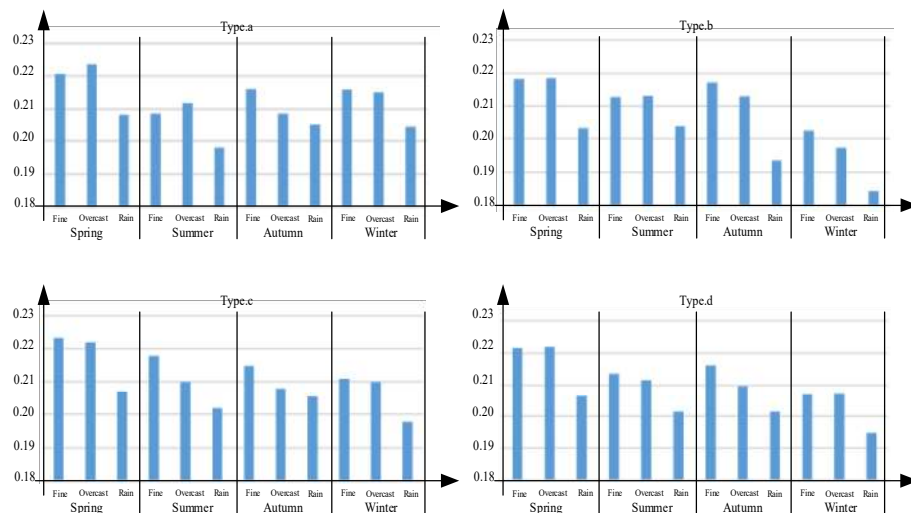


Figure 7. Comparison of credible capacity of various weather under different micro-grid types

Based on the above results, it can see that the total capacity of the whole commercial MG decreases greatly on the rainy days in summer, while the whole residential MG decreases significantly in winter. In contrast, the whole industrial MGs and hybrid MGs are more stable, which is related to the more stable load. According to the comparison of the above data, it can find that the reliable capacity of the MGs in winter rainy days is relatively low, while in sunny and rainy days in spring it is relatively high.

Next, the highest spring sunny days and winter rainy days were selected to compare the differences of the credible capacities between the four different connection modes.

(2) Comparison of the credible capacity in four connection modes.

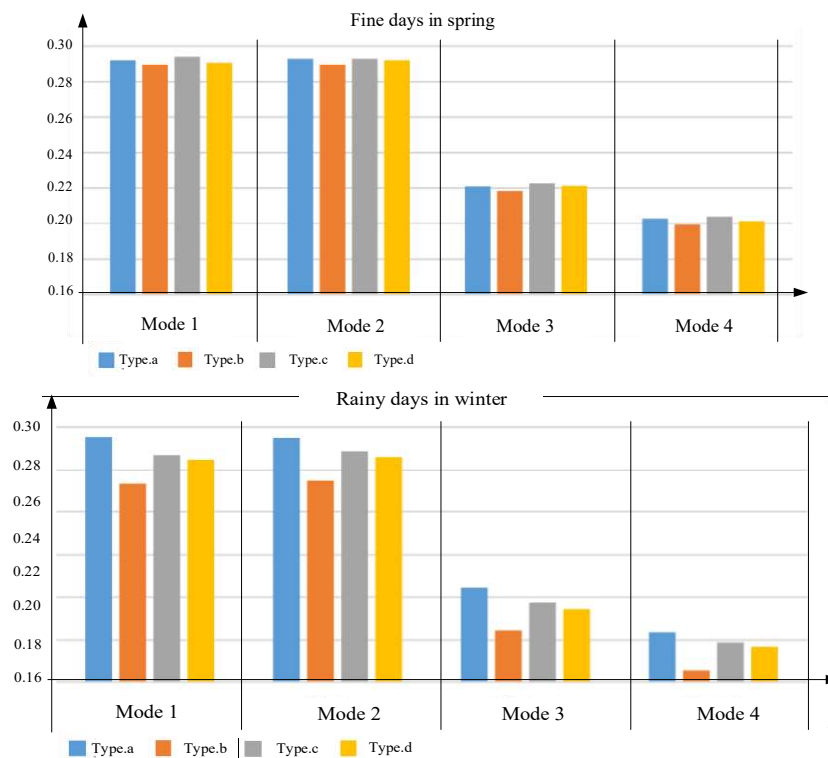


Figure 8. Comparison of the credible capacity in four connection modes

On fine days in spring, it can be seen that the credible capacity is minimal in Mode 2, slightly higher in Mode 1, while much higher in Mode 3 and 4 on fine days in spring when MGs with the same type of capacity are settled. In the same mode, the impact of different MGs types are not obvious. The main difference of the leading credible capacity is because of the connection mode of the high voltage distribution network. On rainy days in winter, the difference between different MGs modes is more obvious than in spring. The credible capacity in Mode 1 and 2 are greater than in Mode 3 and 4. It shows that the credible capacity of high voltage distribution network can be affected by different weather conditions. The lower the base credible capacity in a certain weather, the more obvious the difference in the credible capacity of the different connection modes.

7. Conclusion

An assessment method of substation credible capacity of MG considering the high voltage connection mode is proposed in this paper. The following conclusions are obtained by simulation analysis:

(1) The grid-connected MG can reduce the energy not supplied, meanwhile improve the reliability of the system and equipment utilization rate. MG in the distribution network can replace a certain amount of substation capacity.

(2) Under different high-voltage connection modes, the replacement capacity of the same microgrid is different. The grid with poor high-voltage transfer capability is more dependent on MG supply.

(3) The contribution of different types of multiple micro-grids to credible capacity is different. The credible capacity of whole industrial MGs and hybrid MGs are more stable when the seasons and weather change.

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