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Substation planning method in an active distribution network under low-carbon economy

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Abstract A substation planning method that accounts for the widespread introduction of distributed generators (DGs) in a low-carbon economy is proposed. With the proliferation of DGs, the capacity that DGs contribute to the distribution network has become increasingly important. The capacity of a DG is expressed as a capacity credit (CC) that can be evaluated according to the principle that the reliability index is unchanged before and after the introduction of the DG. A method that employs a weighted Voronoi diagram is proposed for substation planning considering CC. A low-carbon evaluation objective function is added to the substation planning model to evaluate the contribution of DGs to a low-carbon economy. A case study is analyzed to demonstrate the practicality of the proposed method.

Keywords Substation planning, Capacity credit (CC), Active power distribution network

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1 Introduction

The development of a low-carbon economy has worldwide consensus and has been accepted by many countries as an important part of their future development strategy. The power-generation industry, which is the main sector of energy consumption and an important source of CO_2 emissions, will therefore operate the following low-carbon policy [1–7].

To cope with the requirements of a low-carbon economy, and to help provide a reliable and cost-effective power supply, an increasing number of distributed generators (DGs) have been connected to distribution networks around the world. The most common new DG systems are solar photovoltaic (PV) arrays which are seen as means of exploiting climate-friendly renewable energy sources and supporting efficient use of electricity. With the growing penetration of DGs into distribution networks, the power capacity contributed by DGs to networks has noticeably increased.

Traditional substation planning is entirely based on load forecasting, and establishing a balance between substations and loads [8]. However, the power output by DGs can partially supply loads, and therefore the power capacity contributed by DGs to the distribution network cannot be ignored and will affect the planning of substation capacity.

To assess the effect of this capacity substitution on the substation, the concept of the capacity credit (CC) of a DG is proposed. CC is the power capacity that is equivalent to the substation capacity at the same level of reliability, and it can quantify the contribution that DGs make to the power system [9]. The main part of CC assessment is reliability assessment. There are two types of methods of evaluating the reliability of a system having DGs: analytical and simulation methods. An analytical method usually regards a DG as a multi-state conventional generator. Its shortcoming

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is its failure to describe the temporal characteristics of distributed generation, resulting in inaccurate estimation of the power output. The main simulation method is the sequential Monte Carlo method [10]. This method not only describes the temporal output of the distributed power generation but also calculates reliability indices of frequency and duration, and is thus extensively applied.

This paper proposes a CC assessment method employing the sequential Monte Carlo method and considering power failure and DG output. Furthermore, a planning method for a substation in an active distribution network is proposed. In the process of planning optimization, the CC of a DG is included in the substation capacity. This allows a reduction in the capacity of and investment in traditional substations. This train of thought is in line with the principles of a low-carbon economy.

2 Substation planning model for an active distribution network

The traditional substation planning problem can be described as follows. After load forecasting for the target year, the number, capacities, locations and power supply ranges of substations can be optimized using the objective function of the minimum cost of substations, network investment and annual operating costs. This problem is stated mathematically as:

$$\begin{cases} \min C = C_1 + C_2 + C_3 \\ C_1 = \sum_{i=1}^{n} \left[f(s) \dfrac{r_0(1+r_0)m_s}{(1+r_0)m_s - 1} + u(S_i) \right] \\ C_2 = \alpha \left[\dfrac{r_0(1+r_0)m_s}{(1+r_0)m_s - 1} \right] \sum_{i=1}^{n} \sum_{k \in J_i} l_{ik} \\ C_3 = \beta \sum_{i=1}^{n} \sum_{k \in J_i} P_{ik}^2 l_{ik} \\ \text{s.t.} \quad \sum_{k \in J_i} P_{ik} \le S_i \gamma_i \cos\ \varphi, \quad i = 1,\ 2, \cdots,\ N \\ \qquad J_1 \cup J_2 \cup \cdots \cup J_N = J \\ \qquad l_{ik} \le R_i \end{cases} \tag{1}$$

where C_1 is the construction and operation costs of the substations; C_2 the construction cost of the lines; C_3 the network loss cost; N the total number of existing and newly constructed substations; n the number of newly constructed substations; $f(S_i)$ the construction cost of substation i; $u(S_i)$ the operation cost of newly constructed substation i; S_i the capacity of substation i; γ_i the load rate of substation i; J_i the load collection carried by substation i; J the collection of all load points; l_{ik} the length of feeder k added from substation i; P_{ik} the load (active power) carried by feeder k of substation i; m_s the depreciation years of the substations; m_1 the depreciation years of the low-voltage sides of substations; r_0 the discount rate; $\cos\ \varphi$ the power factor; R_i the limit of the power supply radius of substation i; and α the investment cost per unit length of the feeder. Additionally, β is the feeder loss conversion factor expressed as:

$$\beta = \frac{\beta_1 \beta_2 \beta_3}{U^2 \cos\ \varphi}$$

where β_1 is the line resistance per unit length; β_2 the unit energy consumption discount factor; β_3 the line loss hours per year; and U the line voltage on the low-voltage side of a substation.

After DGs are connected to the grid, the costs of the lines and network loss between substations and DGs are added to the objective function:

$$C_2 = \alpha \left[\frac{r_0(1+r_0)m^1}{(1+r_0)m^1 - 1} \right] \sum_{i=1}^{N} \left(\sum_{k \in J_i} l_{ik} + \sum_{d \in D_i} l_{id} \right) \tag{2}$$

$$C_3 = \sum_{i=1}^{N} \left(\beta \sum_{k \in J_i} P_{ik}^2 l_{ik} + \beta_d \sum_{d \in D_i} P_{id}^2 l_{id} \right) \tag{3}$$

where $\beta_d = \beta_{1d}\beta_{2d}\beta_{3d} / U^2 \cos\ \varphi$ is the loss conversion factor of the contact line between a substation and DG; β_{1d} the line resistance per unit length; β_{2d} the unit energy consumption discount factor; β_{3d} the line loss hours per year; D_i the set of DGs in the i^{th} substation's power supply range; and l_{id} the length of contact line d from substation i to the d^{th} DG.

Two constraint conditions are added:

$$rel_{fol}(i) \ge rel_{pre}(i), \quad i = 1,\ 2, \cdots,\ N \tag{4}$$

$$\sum_{j \in J_i} P_j \le S_i' \cos\ \varphi + CC_{PV}(i) + CC_{WTG}(i) \quad i = 1,\ 2, \cdots,\ N \tag{5}$$

where $rel_{fol}(i)$ is the reliability index after DGs are introduced in the power supply range of the i^{th} substation; $rel_{pre}(i)$ the reliability index after DGs are introduced in the power supply range of the i^{th} substation; $CC_{PV}(i)$ the CC of PV power in the power supply range of the i^{th} substation; $CC_{WTG}(i)$ the CC of wind power in the power supply range of the i^{th} substation; and S_i' the optimized capacity of the i^{th} substation.

The optimization model for substation planning in a low-carbon economy takes the overall cost in the planning period as the objective function to minimize. To evaluate the effect on the low-carbon economy, two components are added to the objective function: ① C_4 is the annual variable operation fee, or the increased cost of fossil fuel and CO_2 emissions resulting from transmission loss, and ② C_5 is the cost of water and wind spillage due to transmission capacity deficiency, which is measured through the increased indirect cost of fossil fuel and CO_2 emissions [11–13]. The objective function can be formulated as:

$$\min C = C_1 + C_2 + C_3 + C_4 + C_5 \tag{6}$$

$$C_4 = \sum_{i=1}^{N_L} P_{loss.i} T_{ave} \left(\sigma_F^{ave} K_F + \sigma_C^{ave} K_C \right) \tag{7}$$

$$C_5 = (P_{Awi} + P_{Awa}) T_{ave} \left(\sigma_F^{ave} K_F + \sigma_C^{ave} K_C \right) \tag{8}$$

where $P_{loss.i}$ (MW) is the transmission power loss of candidate line i; T_{ave} the annual average of the number of utilization hours; σ_F^{ave} (tce/MWh) the average fuel consumption intensity of units in the planning system; σ_C^{ave}(t CO_2/MWh) the average CO_2 emission intensity of units in the planning system; K_F (¥/tce) the fuel price in the planning system; K_C (¥/tCO_2) the unit cost of CO_2 emission mitigation using low-carbon technology, CDM or ET transaction price or the penalty for exceeding an emission allowance; and P_{Awi}, P_{Awa} (MW) the wind and hydro power spillage due to transmission capacity deficiency.

3 Capacity credit

3.1 Definition of the CC of a DG

The reliability of a power system refers to the ability to continuously provide customers electric power of high quality. This ability is usually expressed as probability, and the high quality refers to the frequency and voltage being in certain ranges. The reliability of power systems has often been measured using reliability indices [14]. Reliability improves with the addition of new generating units but reduces when the electric power load increases. The concept of the effective load carrying capability (ELCC) of new additional generating units refers to the extra load that can be served by these generating units while maintaining the system reliability at a designated level [15–17]. This designated level is usually the loss of load expectation (LOLE) of the power system before the new additional generating units are integrated. The concept of the ELCC can be expressed as [18]:

$$F(C, L) = F(C + \Delta C, L + \Delta L) \tag{9}$$

where ΔL is the extra load that can be served by the generating units providing additional capacity ΔC, and F is calculation function of ELCC. Under general conditions, $\Delta C \neq \Delta L$ owing to possible system outages caused by failures of generating units and transmission lines.

The same ΔL served by different types of generating units such as traditional thermal power plants and DGs at the same designated reliability level results in different installed capacities. For example an extra load of $\Delta L = 100$ MW could be served by a 300 MW DG or a 120 MW traditional thermal power plant, according to their different levels of availability. If the integration of a 300 MW DG and the integration of a 120-MW traditional thermal power plant provide the same reliability in meeting the load demand of $L + \Delta L$, then (1) can rewritten as:

$$F(C, L) = F(C + \Delta C_1, L + \Delta L) = F(C + \Delta C_2, L + \Delta L) \tag{10}$$

where ΔC_1 and ΔC_2 are the capacities of different generating units.

Figure 1 shows a curve of the relationship between the reliability level, measured as the probability of an outage, and the typical load demand. The system load is presumed to have the same overall variability regardless of the load level. Changes in system load are represented by increments of a percentage of the typical peak load and can be calculated according to:

$$L_{ci} = L \pm i \cdot c \cdot L_{pk} \; (i = 0, 1, 2, \cdots, n) \tag{11}$$

As shown in Fig. 1, the curve for the original system (before the addition of generating units) is modified in different was by the addition of thermal power plants or the addition of DGs. The dashed line R indicates the reliability of the original system and intersects with the curves for the original system and the curves for the system modified by the addition of thermal power plants or DGs; the distance between the points of intersection is ΔL which is the increase in ELCC at reliability level R.

The CC of a DG can be defined according to the concept of the ELCC as follows. Under the condition of maintaining a designated reliability level, the extra load demand that can be served by the addition of a DG could also be

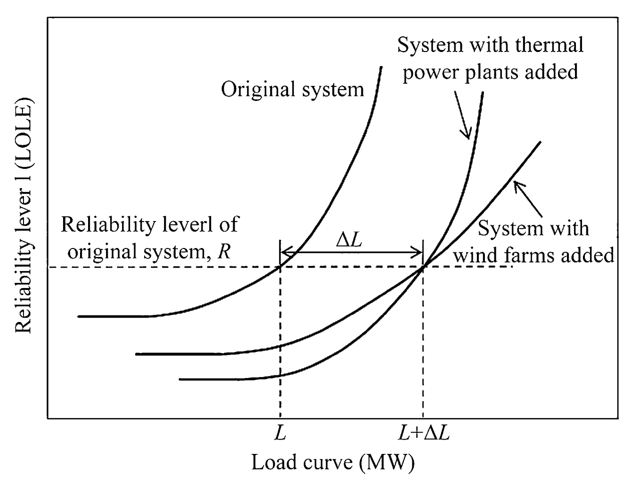

Fig. 1 Relationship between the reliability level and load

served by the installation of a thermal power plant with a certain capacity. The ratio of the extra load demand ΔL capacity to the capacity of the newly installed DG is the CC of the DG. This is expressed as:

$$C_C = \frac{\Delta L}{C_D} \times 100\% \tag{12}$$

where C_C is the installed capacity of an ideal thermal power plant that can serve the same ΔL as a DG with capacity C_D.

3.2 Calculations of the CC of DGs

According to the concept of the CC of DGs, ΔL is the unknown variable that we should calculate. If the installed capacity of newly added DGs is C_D, then theoretically, the maximum ΔL is C_D. According to Fig. 1, ΔL is the load demand of the power system after the addition of new DGs minus the typical load demand, and the result should be in the interval $[L, L + \Delta L]$. Non-sequential Monte-Carlo simulation can easily compute reliability indices from different load curves, but the reverse calculation is very difficult. Because the relationship between the reliability level and load demand increases monotonically, the reverse calculation can be made by employing secants [19], as shown in Fig. 2.

The calculation steps are as follows.

Step 1: If the peak load of a typical load curve is L_{pk0} and the deviation is ε, compute the reliability index of the original system with load L, the reliability index of the system having added DGs of capacity C_D with load L, and the reliability index of the system having added DGs of capacity C_D with load $L + C_D$ to obtain R, R_1 and R_2 respectively.

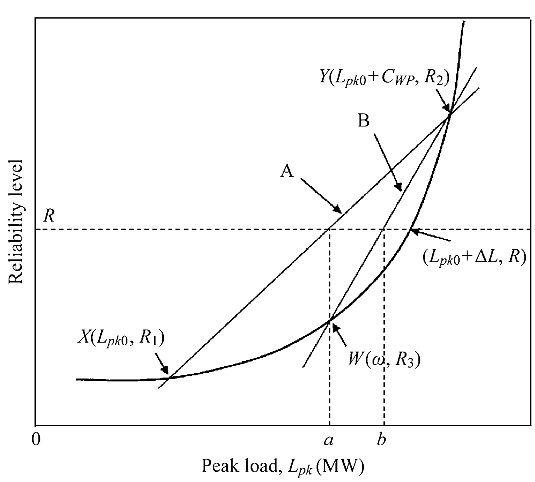

Fig. 2 Relationship between the reliability level and peak load showing how the secant approach is used

Step 2: Compute the abscissa a of the intersection point of line A, which passes through points X (L_{pk0}, R) and Y $(L_{pk0} + C_D, R_2)$, and line R, and conduct a non-sequential Monte-Carlo simulation with new load curve $L_{ci1} = L + a - L_{pk0}$ to calculate the reliability index R_3.

Step 3: If $|R_3 - R| > \varepsilon$, compute the abscissa b of the intersection point of line B, which passes through points W (a, R_3) and Y $(L_{pk0} + C_D, R_2)$, and line R, and conduct a non-sequential Monte-Carlo simulation with new load curve $L_{ci2} = L + b - L_{pk0}$ to calculate the reliability index R_4.

Step 4: Continue iteratively until $|R_4 - R| < \varepsilon$, and then find ΔL, which is equal to the CC of the DG.

4 Substation planning method for an active power distribution network

Traditional planning of a substation takes the substation siting to meet "$N - 1$" load rate criteria as the main constraint. However, the large-scale implementation of DGs provides not only power for local use but also, at times of low load, surplus power that can be fed to the distribution network. Thus, in the planning of a substation site, if the power of DGs in the area is not taken into account, there will be an inevitable and unreasonable waste of the substation capacity, leading a poor return on investment. Therefore, from the viewpoint of reliability, this article

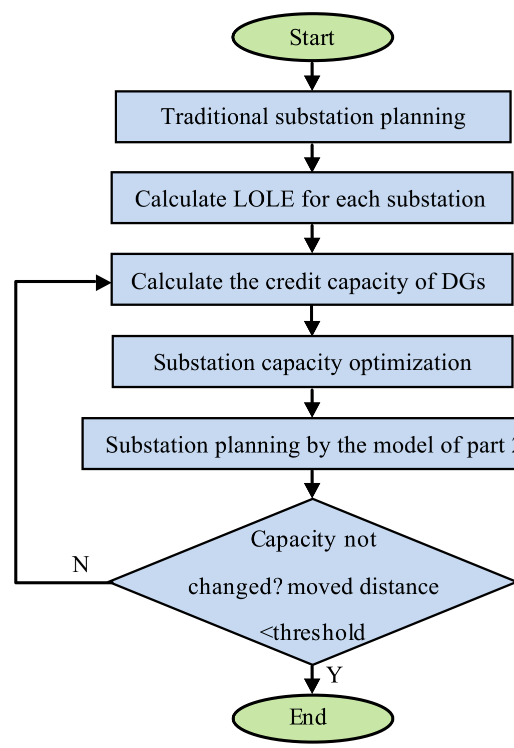

Fig. 3 Flowchart of the proposed method of substation planning

Table 1 Fault parameters

	Average failure rate (times/year)	Average fault time (hours/time)
Turbine	4.600	15
Solar	3.000	20
One transformer fault	0.100	6
Two transformers fault	0.030	10
Three transformers fault	0.001	30

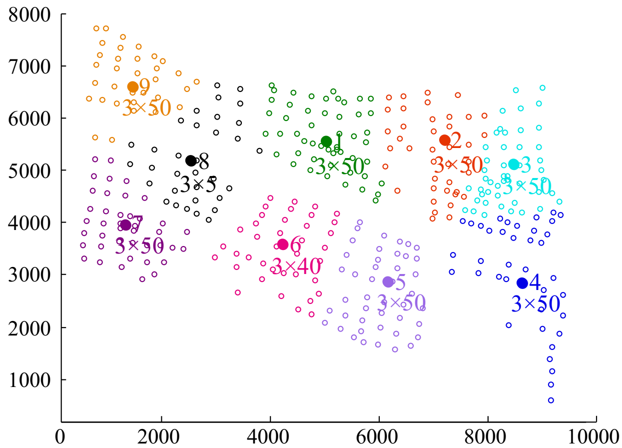

Fig. 4 Substation planning using the traditional method

Table 2 Planning result obtained using the traditional method without consideration of DGs

No.	Capacity (MW)	Loads (MW)	LOLE (MW)
1#	3 × 50	88.800	31.088
2#	3 × 50	82.730	28.963
3#	3 × 50	87.709	30.706
4#	3 × 50	81.896	28.671
5#	3 × 50	105.322	36.872
6#	3 × 40	75.777	26.529
7#	3 × 50	77.496	27.131
8#	3 × 50	73.106	25.594
9#	3 × 50	71.612	25.071

considers substation failure and DG power, and analyzes the timing characteristics and fault conditions of DG power. According to the theory of the CC of a DG within the scope of a substation described in the previous section, and using a substation locating and sizing algorithm that employs a weighted Voronoi diagram, a method is established for the planning of a substation site in the presence of DGs. In this paper, we choose the LOLE as the

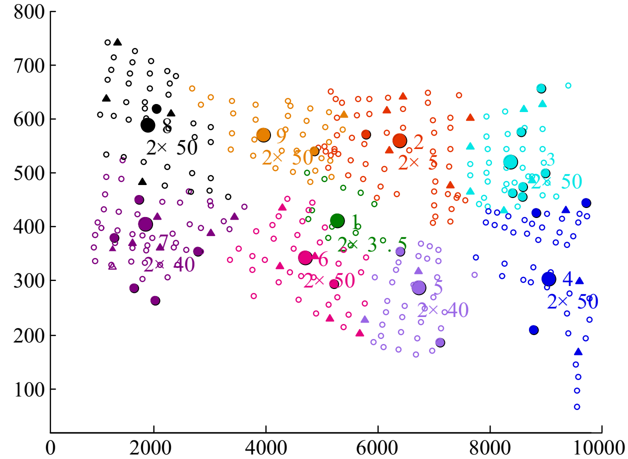

Fig. 5 Substation planning with consideration of DGs

reliability parameter. The specific steps of the proposed method are as follows.

Step 1: Without considering the operation of the DG and by employing the weighted Voronoi diagram algorithm for traditional substation planning in an area, obtain the capacity and power range for each substation.

Step 2: Calculate the reliability index LOLE accounting for the power supply range of each substation.

Step 3: Calculate the reliability index LOLE after the introduction of the DGs, and then calculate the CC of the DGs for the power supply range of each substation.

Step 4: Optimize the substation capacity. If a new substation satisfies the condition $S_i \cos\varphi \le S_{dXi} \cos\varphi + CC_D(i)$, then it is treated as a substation with capacity S_{dXi}, where S_i is the capacity of the i^{th} substation, $\cos\varphi$ is the power factor, $CC_D(i)$ is the sum of CCs of all DGs, and S_{dXi} is the optional capacity at the next level.

Step 5: Update the capacity of each substation. Sum the active power and CC of the DGs as the actual active power. Carry out substation planning using the model in section 2.

Step 6: If the sum of the distances moved by all substations is less than the threshold value and the substation capacity does not change, then go to step 7; otherwise go to step 3.

Step 7: Output the result comprising each substation's location, capacity, power supply range and cost.

The flow chart is as Fig. 3.

5 Case study

The proposed method of substation planning is applied to a case study in which a district covers an area of 63.08 km^2. This area is divided into 368 blocks for load

Table 3 Planning result obtained using the proposed method

No.	Capacity (MW)	Loads (MW)	Solar (MW)	Wind turbine	LOLE	Credit capacity (MW)	Capacity credit (%)
1#	2 × 40	55.275	0	13	19.351	1.360	31.23
2#	3 × 40	83.072	105.0	60	28.083	36.634	29.28
3#	2 × 50	95.521	128.0	15	30.738	9.674	7.27
4#	2 × 50	109.594	102.0	52	27.425	17.131	14.34
5#	2 × 50	90.048	57.0	68	31.525	11.702	14.66
6#	2 × 50	85.802	140.0	13	26.102	14.907	10.33
7#	2 × 50	76.271	72.5	128	26.702	25.555	22.15
8#	2 × 50	80.266	65.0	33	25.100	18.753	24.65
9#	2 × 50	68.602	65.0	33	24.017	24.361	32.03

forecasting. The target planning year is 20 years from the present. The total load in the target year is 744.5 MW. The area is a new planning area with no existing substations. There are four options for the substation capacity: 2 × 31.5 MVA, 2 × 40 MVA, 2 × 50 MVA, 3 × 40 MVA, and 3 × 50 MVA. The high-voltage side of the substation is 110 kV and the power factor is assumed to be 0.9.

The forecast installed capacity of solar power in the target planning year is 734.5 MW. The forecast number of wind turbines is 415, and the installed capacity of each turbine is 335 kW. The starting, rated, and cut-out wind speeds of a turbine are 2.5, 12.5 and 25 m/s, respectively. The number of years simulated for Monte Carlo analysis is 100000 to ensure that enough contingency events are encountered. The fault parameters of components are given in Table 1.

The result of substation planning using the traditional method without consideration of DGs is shown in Fig. 4. Hollow dots represent loads, solid dots represent substations, and numbers are the serial numbers and capacities (MW) of the substations. The planning result is presented in Table 2.

The result of substation planning obtained using the proposed method with consideration of DGs is shown in Fig. 5. Triangles represent solar power and small solid dots represent wind turbines. The planning result is presented in Table 3.

It is seen that the total capacity of all substations reduces, but the LOLE of each substation does not increase. The total costs of the substations planned using the traditional method and proposed method are 11.012 and 7.352 billion RMB, respectively. It can thus be concluded that ① the DGs clearly contributed power capacity to the substations and ② in traditional substation planning, the margin of a substation's capacity is too large, leading to a poor return on investment.

6 Conclusion

A substation planning method that accounts for the introduction of large-scale DGs was proposed on the basis of the assessment of the CC of DGs. the LOLE reliability parameter was used to determine whether the substation capacity is reasonable, and the capacity was reduced as much as possible while maintaining the same reliability, in an effort to meet the targets of low carbon emissions and low cost. The main contributions of the paper are as follows.

1) Starting from the viewpoint of reliability and considering substation faults and a distributed power supply, an integrated substation planning method with an objective function that strives for a low-carbon economy was proposed.
2) In accordance with the principle of invariant reliability, a method of evaluating the CC of a DG was proposed to measure the effective load carrying capacity that the DG contributes to the distribution network.
3) The method was verified by comparison with the traditional method for planning substations.

This research is only a preliminary exploration and much follow-up work is required; e.g., studies that consider energy storage and studies that classify load types.

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