A novel model of load supply capability evaluation in active distribution network

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Abstract. The output of the controllable distributed generation (DG) is determined by the economic dispatch strategy of the active distribution network (ADN). When we calculate the load supply capability (LSC) of ADN, the influence of the economic dispatch results must be taken into account. This paper proposes a bi-level optimization model for maximum power supply capacity of ADN based on chance constrained programming. The upper level model is used to calculate the LSC, and the lower level considers the economic dispatch of controllable DGs. Based on the improved IEEE-33 distribution system, the results show that the model can get the maximum power supply capacity that meets the economic operation requirements of ADN.

Key words: active distribution network; load supply capability; economic dispatch; bi-level optimization; chance-constrained programming

1. Introduction

The active distribution network (ADN) is derived from the distributed energy application and development [1]. It has the characteristics of active control and active management of distributed power compared with traditional power distribution network (DN), and has attracted wide attention and developed rapidly [2]. The output of ADN is influenced by many factors. The output of controllable distributed generation (DG) such as the diesel generator and the micro gas turbine is determined by the scheduling strategy with source-network coordination. While the output of uncontrollable DG such as the wind power and the photovoltaic power, is uncertain because it is affected by natural factors [3]. The load supply capability (LSC) is an important index to reflect the security and reliability of DN, and it is determined by the operation mode [4]. However, the factors that affect the output of DG are bound to affect the analysis of the LSC. Thus when LSC is studied, the operation characteristics of ADN must be considered.

The concept of the LSC of the DN is used for reference to that of the transmission network [5]. In view of this problem, some scholars make an economic distribution on the initial operating points according to the economic cost of power generation, without considering other operating points [6]. On this basis, some scholars coordinate the relationship between the LSC and the optimal scheduling considering the contradictions of power system security and economy [7]. For ADN, the analysis of the LSC when DGs connected to DN has achieved fruitful results. For example, the utilization of different methods to represent the uncertainty of wind power, photovoltaic power and other uncontrollable DGs can strengthen accuracy and credibility of the LSC calculation [8]. The installation
of energy storage power station can not only enhance the LSC of the network, but also increase the flexibility of DN [9]. It can adjust the output and reduce the uncertainty of the uncontrollable DGs by using complementary scheduling rules based on the prediction results [10].

In ADN, some of the DGs are controllable and they participate in the economic operation. Therefore, when establishing the LSC model of ADN, the active management of controllable DGs and the uncertainty of uncontrollable DGs should be considered.

A bi-level optimization model for the LSC of ADN is proposed in this paper, of which the upper level model is used to calculate the LSC and the lower level model make a dispatch considering the economic operation of the ADN. The opportunity constrained programming is utilized in this model to deal with the uncertainty of uncontrollable DGs.

2. Influence factors of the LSC
When studying the LSC of ADN, the main factors that affect the accuracy and rationality should be firstly considered, and the model should be built based on them.

2.1. The influence of the economic dispatch of the ADN
Compared with traditional DN, ADN has the ability to make an active management and scheduling, which will affect not only the output of DGs but also the distribution of voltage and power flow. Thus the economic dispatch is necessary for each operating point in the process of calculating the LSC. The coordination of economy and the maximization of LSC need to be considered as they have a game relationship.

2.2. The influence of uncontrollable DGs' uncertainty
The output of the uncontrollable DGs such as wind power generation and photovoltaic power generation is uncertain, which will cause the uncertainty of the power flow of ADN is uncertain. That will complicate the solution process. In this paper, random variables are utilized to express the output of uncontrollable DGs. And a model with opportunity constrained programming is built.

2.3. Logical architecture of the Double layer model
As is stated above, economic dispatch needs to be considered when the LSC is calculated. The bi-level double optimization model is suitable for this problem, which is as figure 1 shows. The upper level model is designed to calculate the LSC of ADN, while the lower level model makes the economic dispatch. Meanwhile, the chance constrained programming theory is used in the model to deal with the uncertainty of uncontrollable DGs. The LSC considering the operation of ADN can be obtained, and the contradiction between the safety and economy of operation can be solved effectively.

![Figure 1 The frame diagram of bi-level model](image-url)

3. Model establishing and solving

3.1. The upper level model
3.1.1. The objective function. According to the definition, the LSC refers to the maximum load power supply, which is determined by the mode of operation and the load growth, when all the operation constraints are satisfied. In this paper, the load is supposed to grow by equal proportions. The growth mode of the controllable DGs and the load can be expressed as follows:

\[
\begin{align*}
    P_{di} &= P^0_{di} (1 + \lambda K_{di}) \\
    Q_{di} &= Q^0_{di} (1 + \lambda K_{di}) \\
    P_{DGi} &= P^0_{DGi} (1 + \lambda K_{DGi})
\end{align*}
\]

(1)

where \(P_{di}\) and \(P_{DGi}\) are respectively the load demand and the active power output of the controllable DGs at node \(i\), while \(P^0_{di}\) and \(P^0_{DGi}\) are the initial state. \(\lambda\) is the load growth factor. \(K_{di}\) represents the load growth mode and \(K_{DGi}\) is the growth mode of active power output of controllable DGs.

Thus the objective function of the upper level is to maximize the load supplying in the ADN:

\[
\max P_{\text{max}} = \sum_{i=1}^{N} P^0_{di} (1 + \lambda K_{di})
\]

(2)

3.1.2. Constraint condition. In order to ensure the safe and stable operation of the ADN, the constraints of the upper model are as follows:

1) The constraint of power flow balance

\[
P_{Gi} + P^0_{DGi} (1 + \lambda K_{DGi}) + P_{\text{RESi}} - P^0_{di} (1 + \lambda K_{di}) - U \sum_{j=1}^{N} U_j \left( G_{ij} \cos \theta_j + B_{ij} \sin \theta_j \right) = 0
\]

(3)

\[
Q_{Gi} + Q^0_{DGi} (1 + \lambda K_{DGi}) - U \sum_{j=1}^{N} U_j \left( G_{ij} \sin \theta_j - B_{ij} \cos \theta_j \right) = 0
\]

(4)

2) The constraint of node voltage

\[
\Pr \left\{ U_{i,\text{min}} \leq U_i \leq U_{i,\text{max}} \right\} \geq \beta
\]

(5)

3) The constraint of line capacity

\[
\Pr \left\{ \left| P_i \right| \leq P_{i,\text{max}} \right\} \geq \beta
\]

(6)

4) The constraint of transformer

\[
S_T \leq S_{T,\text{max}}
\]

(7)

5) The constraint of distributed generation supply

\[
P_{DGi,\text{min}} \leq P_{DGi} (1 + \lambda K_{DGi}) \leq P_{DGi,\text{max}}
\]

(8)

\[
Q_{DGi,\text{min}} \leq Q_{DGi} \leq Q_{DGi,\text{max}}
\]

(9)

where \(P_{\text{RESi}}\) is the active power output of uncontrollable DG at node \(i\). \(U_i\) and \(\theta_i\) are voltage amplitude and phase angle of node, respectively. \(P_{ij}\) is the transmission power for line \(ij\). \(S_T\) is the power flow out from the transformer \(T\). Parameters with the subscript max and min represent the maximum and minimum of the corresponding variables.

3.2. The lower level model

3.2.1. The objective function. The objective function of the lower level model is to minimize the operation cost of the ADN system.

\[
\min F = \sum_{i=1}^{N} C_{DGi} \left( P_{DGi} \right) + C_p \cdot P_{\text{grid}}
\]

(10)

where \(N_i\) is the number of the controllable DGs and \(C_{DGi}\) is the operation cost of them. \(P_{\text{grid}}\) is the power purchased from the higher level grid and \(C_p\) is the electricity price.
The operation cost function of a diesel generator is as formula (11) shows and that of a gas turbine is as formula (12) shows.

\[ C_{DE} = aP_{DE}^2 + bP_{DE} + c \]  
\[ C_{MT} = \left( C_{ng} / LHV_{ng} \right) \frac{P_{MT}}{\eta(P_{MT})} \]  

3.2.2. Constraint condition
1) The constraint of power flow balance
\[ P_{DG} + P_{RES} + P_{grid} - P_d - P_{Loss} = 0 \]  
2) The constraint of distributed generation supply
\[ P_{DG,min} \leq P_{DG} \leq (1 + \lambda K_{DG}) \leq P_{DG,max} \]  
3) The constraint of the power interaction with the large power grid
\[ P_{grid,min} \leq P_{grid} \leq P_{grid,max} \]  

3.3. The solution of the model
Alternative and iterative algorithm is utilized to solve the bi-level optimization problem in this paper. As there are random variables in the upper level model, the particle swarm optimization (PSO) algorithm based on Monte Carlo simulation is utilized. The lower level model is solved by interior point method. The solution procedure is as follow:

1) Initialize the related parameters. In this part, the parameters of the DN are obtained and the basic parameters of PSO are given.
2) Solve the upper level model. The LSC of ADN is obtained and the load growth factor is determined.
3) Information transfer. The load growth factor is transferred to the lower level optimization model.
4) Solve the lower level model. According to the transmission load growth factor, the economic dispatch and the growth mode of the controllable DGs can be achieved.
5) If the difference between the two adjacent optimization results is within the range of precision requirements, the optimal results can be obtained. Otherwise, update the growth mode of controllable DGs and return to step 2.

4. Case analysis
In this paper, the improved IEEE-33 distribution system with wind, photovoltaic and diesel generators is presented for calculation. Parameters of the DN is shown in [11]. An uncontrollable 200kw photovoltaic generator is connected to node 30. Two uncontrollable 300kw wind power generators are connected to node 7 and node 24, respectively. The light intensity and the local error of wind power prediction are both satisfies Beta distribution. Two 600kw diesel generators are respectively connected to node 14 and node 32, and a gas turbine is connected to node 25. The confidence level of the opportunity constraints is set to 0.95. The learning factors of PSO \( c_1 \) and \( c_2 \) are both 2. The population size is 40. The parameters \( r_1 \) and \( r_2 \) representing the random number within 0 to 1. The maximum iteration number is 1000, and the initial value of inertia weight is 0.9. \( C_{ng} \) is set to 2.5 yuan/m³ and \( LHV_{ng} \) is set to 9.7 kWh/m³.

Table 1 shows the results contrast of LSC and the cost between the paper’s mode and the conventional mode.

| model                  | cost/yuan | LSC/kW |
|------------------------|-----------|--------|
| the paper’s mode       | 3098.1    | 4746   |
| the conventional mode  | 3187.3    | 4769   |
The LSC and operation cost of ADN are reduced when the economic dispatch is considered in the model. Thus, the LSC that meets the requirements of economic operation can be obtained in this model. And the coordination of safety and economy of ADN can be achieved.

**Figure 2** Active outputs of controllable DGs

Figure 2 shows the output of the controllable DGs in the two modes. The outputs of controllable DGs are allocated economically considering the influence of the economic dispatch in the model. When load reaches a certain level, more power will be purchased from the higher level grid to replace that supplied by the controllable DGs, because the operation cost of the controllable DGs become much higher. The model in this paper can enable the resources of the ADN to be economically and rationally utilized. And the operation cost is saved under the premise of ensuring safety.

The line flow distribution in two modes is as figure 3 shows. The main factor to restrict the increase of the LSC is the power flow of line 14 and 17 without considering the economic dispatch. The power flow constraints of line 14 and 17 do not reach the upper limits because of the economic operation restriction in the bi-level model.

**Figure 3** Comparison of line load rate under two modes

**Figure 4** Comparison of LSC under different confidence level

Figure 4 lists the LSC under different confidence levels. As the figure shows, chance constrained programming model can realize the safety constraint of DN under a certain probability. But a certain expense of objective will be suffered because of the uncertainty. The higher the confidence level is, the stricter the security constraints are and the greater the expense of the objective will be.

5. Conclusion

In this paper, a model for calculating the LSC of ADN considering the influence of uncontrollable DGs with uncertainty is built. Through the analysis of the improved IEEE33 distribution system, we obtain the following conclusion.

1) A bi-level model for calculating the LSC considering the economic operation of the ADN is
established. The economic dispatch of the ADN will reduce the LSC of the ADN to a certain extent, but the economy of operation can be ensured and the rationality of the resource utilization can be improved.

2) The chance constrained programming is utilized to deal with the uncertainty of uncontrollable DGs in this model flexibly. The calculation results show that the higher the confidence level is, the more stringent the security constraint is and the smaller the LSC will be.

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