Overview of distributed generation planning in electric distribution networks

Xiaomeng Wu¹,², Zheng Shi¹, Guo Feng¹, Qianyu, Wang¹

¹School of Electric Engineering, Xi’an Shiyou University
²Key Laboratory of Measurement and Control Technique of Oil and Gas Wells of Shaanxi Province Xi’an, China
xmwudz@xsyu.edu.cn, 2023699198@qq.com, 13336365406@qq.com, 1316766946@qq.com

Abstract. As the proportion of distributed generation (DG) in the electric distribution network continues to increase, the intermittent characteristic of DG and uncertain load have many effects on electric distribution network planning and operation. Reasonable planning of DG in the electric distribution network can reduce network losses, improve power quality, reduce line transmission power, and improve system reliability. Unreasonable DG planning will cause problems such as waste of facilities, harmonic pollution and voltage fluctuations. Therefore, reasonable planning of DG has important practical significance. In this paper, the modeling of uncertain factors, the models of DG planning and optimization algorithms for solving planning models are introduced. The advantages and disadvantages of various algorithms are analyzed, and DG planning in electric distribution networks is more comprehensively reflected.

1. Introduction

DG usually refers to a small generator set that supports the economical and reliable operation of electric distribution networks and microgrids, is installed close to the user’s side, and has a generated power of several kilowatts to tens of megawatts. DG mainly includes: solar power generation, wind power generation, micro gas turbine and biomass power generation. According to the different output characteristics, DG can be divided into two types: stable output type and intermittent output type. Stable output type DG mainly includes: micro gas turbine, diesel generator and energy storage battery. Intermittent output type DG mainly includes: distributed wind power generation and photovoltaic power generation [1-3]. The intermittent DG output power is highly uncertain due to weather conditions and temperature and other environmental factors.

| S.No. | Class                      | Size            |
|-------|----------------------------|-----------------|
| 1.    | Small distributed generation | 1W-<5KW         |
| 2.    | Medium distributed generation | 5KW-<5MW       |
| 3.    | Large distributed generation | 5MW-<50MW      |

DG planning refers to the installation type and installation location in the electric distribution network according to the relevant objective functions under the premise that the load forecast results and the basic status of the distribution network and the requirements of the electric distribution...
network operation and control constraints are met within a known planning period, make the economic and reliability of the distribution network optimal during the entire planning period.

2. Uncertainty modeling

The uncertain factors in the DG planning in the electric distribution network mainly include the uncertain output of the intermittent DG (wind and photovoltaic power generation), the uncertainty of the load, the uncertainty of the electricity price and the uncertainty of the fuel cost. The adequate planning of DG necessitates the computationally accurate and efficient modelling of these uncertain input parameters [4].

Figure 1. The uncertainty modelling techniques.

2.1. Uncertainty of wind power generation

The factors that affect the output of wind power generation include surface characteristic parameters, wind speed, and fan parameters. Among them, wind speed is one of the most important factors that affect the output of wind power generation. At present, the main models describing uncertain wind speed are: probability model, interval model and fuzzy model. Probability models are the most widely used. The main probability models describing the uncertainty of wind speed are: Weibull model, Rayleigh model and Inverse Gaussian model. The most commonly used probability distribution model for describing wind speed is the Weibull model [5].

The probability density function of the Weibull distribution model is:

\[
f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right]
\]

\[k = \left(\frac{\sigma_v}{\mu_v}\right)^{-0.1086} \quad (2)\]

\[c = \mu_v / \Gamma(1 + 1/k) \quad (3)\]
k is the shape factor; c is the scale parameter; $\Gamma(.)$ is the gamma function; $\mu_s$ is the average value of the wind speed series; $\delta_s$ is the standard deviation of the wind speed series. The shape factor k has a great influence on the distribution of wind speed.

The relationship between the active output power of the wind turbine and the wind speed can be approximated by equation (4).

$$
P_w(v) = \begin{cases} 
0, & v \leq v_i \text{ or } v > v_{out} \\
p_r \frac{v - v_i}{v_r - v_i}, & v_i \leq v \leq v_r \\
p_r, & v_r \leq v \leq v_{out}
\end{cases}
$$

(4)

$P_w$ is the active power output of the wind turbine; $v_i$ is the cut-in wind speed of the wind turbine; $v_r$ is the rated wind speed of the wind turbine; $v_{out}$ is the cut-out wind speed of the wind turbine.

2.2. Uncertainty of photovoltaic power generation

Aiming at the uncertainty of light intensity, there are mainly probability models and interval models to describe them. The probability models of light intensity mainly include Weibull distribution and Beta distribution, among which Beta distribution is the most widely used. The parameters of the Beta distribution can be obtained by statistics on historical data. Common methods include mean and variance estimation methods. The interval model of light intensity uses the interval number to describe its uncertainty. It is suitable for occasions where intensive reading is not required, and has the obvious characteristics of simple model [6-8].

When using the Beta distribution, the probability density function of light intensity is as follows:

$$
\dot{f}(s) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \Gamma(\beta)} \left( \frac{s}{s_{max}} \right)^{\alpha-1} \left( \frac{1 - s}{s_{max}} \right)^{\beta-1}
$$

(5)

$$
\begin{cases}
\alpha = \mu \left[ \frac{\mu (1 - \mu)}{\sigma^2} - 1 \right] \\
\beta = (1 - \mu) \left[ \frac{\mu (1 - \mu)}{\sigma^2} - 1 \right]
\end{cases}
$$

(6)

$s$ is the light intensity; $s_{max}$ is the maximum light intensity; $\alpha$ and $\beta$ is the two shape parameters of the Bate distribution; $\Gamma(.)$ is the gamma function; $\mu$ is the average value of the light intensity; $\sigma$ is the standard deviation of the light intensity.

The relationship between the output power of the photovoltaic generator and the light intensity is approximately expressed by equation (7).

$$
p = \begin{cases} 
p_r \frac{s}{s_r}, & s \leq s_r \\
p_r, & s > s_r
\end{cases}
$$

(7)
\( P \) is the active power output of the photovoltaic generator; \( P_r \) is the rated active power output of the photovoltaic generator; \( S_f \) is the rated light intensity.

2.3. Uncertain model of load
The actual power load is affected by socio-economic development, policy changes, climatic conditions, energy policies, etc. There are great uncertainties, and it is difficult to use deterministic mathematical methods to express and consider. The uncertainty model of load mainly includes probability model, interval model and fuzzy model. The most common load probability model is the normal distribution, and its parameters can be estimated by the probability density estimation method. The fuzzy model uses fuzzy numbers to characterize its uncertainty. The interval model uses interval numbers to characterize its uncertainty. The interval model has the characteristics of a simple model, and is suitable for situations where the requirements for intensive reading are not high [9].

3. DG planning model
The purpose of DG planning in the electric distribution network is to obtain the optimal access location and access capacity of DG. In essence, it is a complex multi-objective and multi-constrained nonlinear programming problem to analyze distributed power planning [10]. With the reform of the electricity market and the complexity of the actual environment after DG access to the electric distribution network, uncertainties are increasing [11].

3.1. The objective function of DG planning
The following introduces some common DG planning objective functions.

3.1.1. Consider the objective function of minimizing network loss.

\[
\min F = \sum_{n=1}^{Ns} \sum_{k=1}^{Nl} G_{k(i,j)} [U_i^2 + U_j^2 - 2U_iU_j \cos(\delta_i - \delta_j)]
\]

\( N_s \) is the number of scenes; \( N_l \) is the number of network branches; \( G_{k(i,j)} \) is the conductance of the branch connecting the two nodes; \( U_i, U_j \) is the voltage of the node i and j; \( \delta_i, \delta_j \) is the voltage phase angle of the node i and j.

3.1.2. The objective function considering the investment cost of DG installation.

\[
C_{TZ} = \frac{r (1+r)^n}{(1+r)^n - 1} \sum_{i=1}^{N_{DG}} Z_{DG,i} \times C_{TZ,i}
\]

\( r \) is the annual cost factor; \( n \) is the economic life of DG; \( N_{DG} \) is the number of nodes to be installed in DG; \( Z_{DG,i} \) is the capacity of DG installed at node i; \( C_{TZ,i} \) is the installation investment cost of unit capacity DG of node i.

3.1.3. The objective function considering DG operation and maintenance costs.

\[
C_{yx} = \sum_{n=1}^{N_i} D_n \left( \sum_{i=1}^{24} \sum_{r=1}^{N_{DG}} C_{yx,i} P_{DG,i,r,n} \right)
\]
\( D_n \) is the number of days for scene \( n \) in a year. \( C_{xy,i} \) is the operation and maintenance cost of unit power is issued for the DG of node \( i \).

### 3.2. The general mathematical model of DG planning

The general mathematical model of DG planning in the electric distribution network can be described as follows:

\[
\begin{align*}
\min & \quad f(u, x) \\
\text{s.t.} & \quad h(u, x) \leq 0 \\
& \quad g(u, x) = 0
\end{align*}
\]  

\( u \) is a control variable, that is, DG's investment decision variables include the installation type, location and capacity; \( x \) is a state variable, that is, the node voltage amplitude and phase angle, branch power, etc.; \( f(u, x) \) is the objective function, generally aim at the smallest network loss, the least power loss, and the smallest technical risk; \( h(u, x) \leq 0 \) is inequality constraints, there are mainly voltage amplitude constraints, reliability constraints, branch power constraints, DG permeability constraints, etc.; \( g(u, x) = 0 \) is equality constraints, there are mainly active power balance and reactive power balance equations for each node.

### 3.3. The common methods of DG planning considering uncertainty

The common methods of DG planning considering uncertainty are: planning methods based on multi-scenario technology, planning methods based on fuzzy mathematical theory and planning methods based on chance constraint theory [12].

The planning method based on multi-scenario technology selects the typical scenarios of DG and load uncertainty through specific rules, and analyzes the typical scenarios to complete the DG planning. It is difficult to select effective scenes through scene reduction. The DG planning model is often solved by intelligent algorithms.

The planning method based on the chance constraint theory is based on the chance constraint theory to describe and simulate a large number of uncertain factors with corresponding random variables, allowing the DG planning scheme to not meet the constraint conditions with a certain probability. The DG planning model established by this method is a mixed integer nonlinear chance constrained planning model, which is often solved by intelligent algorithm combined with probabilistic power flow [13].

The planning method based on fuzzy mathematics theory is based on the fuzzy theory to characterize the uncertain factors with fuzzy numbers, without the need to know the probability distribution function of related factors. The accuracy of the fuzzy programming method is relatively low.

### 4. Solution method of DG planning model

The mathematical model of the DG planning problem in the electric distribution network has the characteristics of non-linearity, multiple constraints, discrete variables and continuous variables. At present, optimization methods for solving uncertain DG planning problems in electric distribution networks include classical mathematical methods, modern intelligent algorithms and numerical calculation methods [13].

Classical mathematical methods mainly include quadratic programming methods, linear programming and nonlinear programming methods. However, these methods have a large amount of calculation, insufficient flexibility, and require the preconditions of continuous objective function. It is difficult to apply in practical problem.
Intelligent algorithms such as genetic algorithm, particle swarm optimization algorithm, ant colony algorithm and differential evolution algorithm have remarkable characteristics such as high self-adaptive, strong general-purpose and parallel computing. However, the intelligent algorithm also has some obvious defects, such as poor model robustness and easy to fall into local optimality.

Because the intelligent algorithm has the above-mentioned defects, a numerical calculation method is proposed to improve the calculation efficiency and obtain the global optimal calculation result. There are two main types: convex optimization methods and model linearization methods. Common convex optimization methods are: semi-definite programming method, quadratic programming method and convex relaxation method (second-order cone programming, sequential convex programming, etc.). Most convex optimization algorithms can calculate the results in polynomial time, but usually ignore or simplify certain constraints, which will affect the actual application of the model [14]. Common model linearization methods include DC power flow model and successive linearization model. The successive linearization model uses the Taylor series to expand the linearized power flow, which greatly reduces the number of iterations, but it is difficult to ensure that the solution area is feasible [15].

5. Conclusion
With the increase in the types of DG, the increase in DG penetration capacity and the application of new technologies, electric distribution network planning problems in the new environment face more and more complex uncertainties than traditional planning problems. The DG planning model in the electric distribution network is becoming more and more complex, how to simplify it, and propose a more efficient solution algorithm is also a future research direction.

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References
[1] Du E, Zhang N, Kang C, et al. (2016) Managing wind power uncertainty through strategic reserve purchasing. J. IEEE Transactions on Power Systems, Commun., 32(4): 2547-2559.
[2] Wang Y, Zhou Z, Botterud A, et al. (2017) Optimal wind power uncertainty intervals for electricity market operation. J. IEEE Transactions on Sustainable Energy, Commun., 9(1): 199-210.
[3] Jia L, Qian X, Hao C, et al. (2017) Multi-objective coordinated and optimized configuration of distributed power supply considering N-1 safety. J. Power Automation Equipment, Commun., 37(07): 84-92(in Chinese).
[4] Li Z, Wu W, Shahidehpour M, et al. (2015) Adaptive robust tie-line scheduling considering wind power uncertainty for interconnected power systems. J. IEEE transactions on power systems, Commun., 31(4): 2701-2713.
[5] Zhang S, Cheng H, Zhang L, et al. (2013) Probabilistic evaluation of available load supply capability for distribution system. J. IEEE Transactions on Power Systems, Commun., 28(3): 3215-3225.
[6] Yang Z, Zhong H, Xia Q, et al. (2016) Optimal power flow based on successive linear approximation of power flow equations. J. IET Generation, Transmission & Distribution, Commun., 10(14): 3654-3662.
[7] Yang Z, Bose A, Zhong H, et al. (2016) Optimal reactive power dispatch with accurately modeled discrete control devices: A successive linear approximation approach. J. IEEE Transactions on Power Systems, Commun., 32(3): 2435-2444.
[8] Liu Z, Wen F, Ledwich G. (2011) Optimal siting and sizing of distributed generators in distribution systems considering uncertainties. J. IEEE Transactions on power delivery, Commun., 26(4): 2541-2551.

[9] Zangeneh A, Jadid S, Rahimi-Kian A. (2011) A fuzzy environmental-technical-economic model for distributed generation planning. J. Energy, Commun., 36(5):3437-3445.

[10] Zhang S, Cheng H, Li K. (2014) Multi-stage site selection and capacity planning of wind turbines considering correlation. J. Grid Technology, Commun., 38(01):53-59.

[11] Zhang S, Li K, Cheng H, et al. (2015) Location planning of distributed wind power in active management mode. J.Power System Automation, Commun., 39(09):208-214.

[12] Wang J, Lin X, Xin J, et al. (2019) Multi-objective optimal configuration of distributed wind power considering reliability. J. Power Capacitors and Reactive Power Compensation, Commun., 40(02):160-165+177.

[13] Ren Z, Guo M, Gong H. (2019) Active power distribution network distributed power planning under power-user interaction mode. J. Renewable Energy, Commun., 37(11):1643-1649.

[14] Xiao P, Fang S, Ming Z, et al. (2019) Distributed power source planning method for active distribution network based on demand correlation group prediction. J. Renewable Energy, Commun., 37(04):582- 587.