Optimal Allocation of Distributed Generation in Distributed Network

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Abstract—**The paper proposes a multi-objective optimization model of distributed generation optimal allocation in distributed network, comprehensively considering system operating cost and environmental benefit. The active network loss sensitivity analysis and voltage analysis is adopted to determine the location of distributed generation. A multi-objective particle swarm optimization algorithm is presented to obtain the capacity of distributed generation. The algorithm incorporates non-dominated sorting and crowding distance to improve the diversity of the Pareto solutions The results in the IEEE-33 bus system application show that the method proposed can get reasonable site and size of distributed generation, greatly improving the economics and environmental protection of the power system.**

Keywords-distributed generation; environmental benefits; multi-objective optimization; particle swarm algorithm

I. INTRODUCTION

Network-connected distributed generation brings great impacts on voltage distribution, network losses, system protection and reliability of distribution network [1-3]. Therefore, reasonable site and size of distributed generation is important to ensure the environmental protection, safety, reliability, economy of the system. Furthermore, as the construction and development of smart grid, more attention should be paid to the research on distributed generation. One important feature of smart grid is that it has good compatibility for both large power resources and distributed generation, which meet the requirement of electric power and nature environment, social harmonic development [4].

In [5], bilevel programming plan optimization model is proposed, considering multiple load level and energy saving dispatch. The upper optimization model determines the location and capacity of distributed generation and energy storage battery. The lower optimization model determines the distributed generation output. Reference [6] analyzes the advantage of distributed generation in remote and rural areas, and points out the rationality of using distributed generation as main power supply in power planning for users that have special requirements of power supply reliability. In [7], aimed to minimize the total investment cost of distributed generation and the cost of purchasing power from the main grid, the paper proposes a heuristic approach to determine optimal distributed generation capacity investment for a rural distribution system under typical transmission system scenarios, including normal operation with fixed electricity price, consideration of the outage state circumstance as well as real-time price under the competitive electric power market condition. However, all these research ignored the environmental benefit of distributed generation. This will lead to imbalance development of clean energy and non-clean energy. Conventional power plants excessively develop, while clean energy and renewable energy is restricted. So it is very necessary to take environmental value as an optimization index in distributed generation planning.

The paper proposes the improvement index of environment of distributed generation on the base of analyzing the good environmental performance of distributed generation. Taking the position and capacity of distributed generation as unknown variables, a multi aim optimization model is established, considering system operating cost and environmental benefit. The optimization algorithm is adopted to find the solution to the model. The results in actual application show the correctness and effectiveness of the proposed method.

II. OPTIMAL ALLOCATION MODEL

Distributed generation is generally close to the load center, so assume that Distributed generation is connected to load node. Take an *n*-node system for example, set the V_i , θ_i as the voltage magnitude and phase angle respectively, then

$$P_i(V,\theta) = V_i \sum_{j=1}^{N} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \quad i = 1,2,...,n \,. \tag{1}$$

$$Q_i(V,\theta) = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \quad i = 1,2,...,n \,. \tag{2}$$

Assume that load condition is given. The ratio of reactive power to active power of distributed generation at node i is set as f_{Gi} . Distributed generation allocation optimization model is proposed that takes account into minimizing the system operation cost and maximizing the environmental benefits.

A. Objective Function

1) lowest system operation cost

System operation costs contain investment costs, maintenance costs of distributed generation and purchase cost from large power grid. System operation costs function is:

$$\min F = C_{SN} + C_{DG} = (\sum_{i=1}^{n} P_{Di} + P_{Loss} - \sum_{i=1}^{n} P_{Gi}) \; C_S + \sum_{i=1}^{n_{DG}} P_{Gi} C_{Gi} \tag{3}$$

where, C_{SN} is purchase cost from large power grid, P_{Di} is the active load power at node i, P_{Loss} is the active network loss, P_{Gi} is the active power of distributed generation connected to node i, C_S is the conventional energy generation cost, n_{DG} is the total number of distributed generation, C_{Gi} is the unit generation cost of distributed generation installing on node i.

2) best environment benefits

The reduction of pollutant emission that is due to the installation of distributed generation consists of two parts. One part is due to the distributed power generating capacity, another is due to the reduction of network loss.

Environmental improvement index $EIRI_i$ is defined as the ratio of quantity of the *i*-th pollutant gas (CO_2, SO_2, NO_x) before interconnecting distributed generation to after interconnecting distributed generation [8]. The smaller the value is, the better the system's environmental benefits.

$$EIRI_i = \frac{PE_{iw}}{PE_{iwo}} . \tag{4}$$

where, PE_{iw} is the quantity of the *i*-th pollutant gas emission after interconnecting distributed generation, PE_{iwo} is quantity of the *i*-th pollutant gas emission before interconnecting distributed generation. The values can be obtained by the following equations respectively.

$$PE_{i\omega} = \sum_{j=1}^{B} (EG)_{Aj}(AE)_{ij} + \sum_{k=1}^{H} (EDG)_k(AE)_{ik} . \tag{5}$$

$$PE_{i\omega o} = \sum_{j=1}^{B} (EG)_j(AE)_{ij} . \tag{6}$$

where, $(EG)_{Aj}$ is the *j*-th traditional generator output after interconnecting distributed generation while $(EG)_j$ is the value before interconnecting distributed generation. $(AE)_{ij}$ is the quantity of the *i*-th pollutant gas emission of the *j*-th traditional generator per unit output. $(AE)_{ik}$ is the quantity of the *i*-th pollutant gas emission of the *k*-th distributed generator per unit output. $(EDG)_k$ is the *k*-th distributed generator active power output. B is the number of traditional generators. H is the number of distributed generators.

The comprehensive index contains all pollutant gases can be defined as

$$EIRI = \sum_{i=1}^{NP} (EI)_i(EIRI)_i . \tag{7}$$

where, $(EI)_i$ is the weighting factor of the *i*-th pollutant gas. NP is the number of all pollutant gases. $(EI)_i$ is subjected to $0 \le (EI)_i \le 1$ and $\sum_{i=1}^{NP} (EI)_i = 1$.

The objective function considering environment benefits is

$$\min F_3 = \min(EIRI) . \tag{8}$$

B. Constraints

Equality constraints are the power flow equations. Inequality constraints include node voltage constraint, the proportional controller factor constraint between reactive and active power of distributed generation, single distributed generation capacity constraint and the total output constraint of distributed generation.

$$P_{Gi} - P_{Di} - P_i(V,\theta) = 0 \quad i = 1,2,...,n . \tag{9-a}$$

$$Q_{Gi} - Q_{Di} - Q_i(V,\theta) = 0 \quad i = 1,2,...,n . \tag{9-b}$$

$$Q_{Gi} = f_{Gi}P_{Gi} \qquad i = 1,2,...,n . \tag{9-c}$$

$$V_{i\min} \le V_i \le V_{i\max} \qquad i = 1,2,...,n . \tag{9-d}$$

$$P_{Gi\min} \le P_{Gi} \le P_{Gi\max} \qquad i = 1,2,...,n . \tag{9-e}$$

$$\sum_{i=1}^{n} P_{Gi} \le \rho \sum_{i=1}^{n} P_{Di} \qquad i = 1,2,...,n . \tag{9-f}$$

where, P_{Gi}, Q_{Gi}, $P_{Gi\min}$, $P_{Gi\max}$ are the active power, reactive power, active power lower limit and active power upper limit of distributed generation connected to node i. P_{Di}, Q_{Di} are the active and reactive load power at node i. $V_{i\min}$, $V_{i\max}$ are the voltage lower and upper limit of node i.

III. The Location of DG

Nodes active power and reactive power loss sensitivity is [9]

$$\begin{cases} \dfrac{\partial P_{Loss}}{\partial P} = \dfrac{\partial P_{Loss}}{\partial V}\dfrac{\partial V}{\partial P} + \dfrac{\partial P_{Loss}}{\partial \theta}\dfrac{\partial \theta}{\partial P} \\ \dfrac{\partial P_{Loss}}{\partial Q} = \dfrac{\partial P_{Loss}}{\partial V}\dfrac{\partial V}{\partial Q} + \dfrac{\partial P_{Loss}}{\partial \theta}\dfrac{\partial \theta}{\partial Q} \end{cases} . \tag{10}$$

By changing the style, the sensitivity value of *i*-th node can be obtained by the following equation

$$\begin{cases} \partial P_{Loss}/\partial V_i = 2\sum_{j=1}^{n} V_j G_{ij} \cos\theta_{ij} \\ \partial P_{Loss}/\partial \theta_i = -2V_i \sum_{j=1}^{n} V_j G_{ij} \cos\theta_{ij} \end{cases} . \tag{11}$$

Then, when node active and reactive power respectively changes dP and dQ, the change of the active power loss is

$$dP_{Loss} = \frac{\partial P_{Loss}}{\partial P}dP + \frac{\partial P_{Loss}}{\partial Q}dQ . \tag{12}$$

In the case of constant load power, the node power change is caused by the output change of distributed generation. Assume that load condition is given. The ratio of reactive power to active power of distributed generation at node i is set as f_{Gi}.

$$dP_{Loss} = \frac{\partial P_{Loss}}{\partial P}dP + f_G\frac{\partial P_{Loss}}{\partial Q}dP = (\frac{\partial P_{Loss}}{\partial P} + f_G\frac{\partial P_{Loss}}{\partial Q})dP . \tag{13}$$

In order to measure the change of network active power loss caused by node active and reactive power changes, comprehensive sensitivity can be defined as

$$S=\frac{\partial P_{\rm Loss}}{\partial P}+f_{\rm G}\frac{\partial P_{\rm Loss}}{\partial Q}\,. \tag{14}$$

Comprehensive sensitivity coefficient reflects the node active and reactive power change's contribution to the active power loss.

For the node voltage, the same capacity of distributed generation interconnecting in different location brings different effects to the voltage profile. When the access points are close to the end of the feeder line, the effect to the voltage change is significant. On the contrary, distributed generation has little effect on voltage change when the access points are close to bus. Furthermore, distributed generation only affect the voltage of the nodes in front of the access points. While, the voltage change of the nodes behind the access points passively follow the voltage change of the access points [10]. Therefore, the low-voltage nodes can be selected as the candidate to install distributed generation.

The location of distributed generation interconnecting to the distributed network can be chose by the following two steps, considering system network structure, geographical conditions, distributed generation resource constraints, the practical requirements of the planning system and other factors. First obtain the comprehensive sensitivity coefficient of each node and choosing some high sensitivity nodes. Then, choose low-voltage nodes. And then, the intersection of the nodes can be selected to install distributed generation.

IV. MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION ALGORITHM

A. *Particle Swarm Optimization*

Particle swarm optimization is a population-based optimization tool, which is used to solve the non-linear optimization problem, combinatorial optimization problem, mixed-integer nonlinear programming problem [11]. The advantage of particle swarm optimization algorithm is simple and easy to implement, not many parameters need to be adjusted, and not require gradient information.

The flight velocity and position of particle is adjusted by the following formula:

$$v_i(t)=wv_i(t-1)+c_1r_1(p_i-x_i(t-1))+c_2r_2(p_g-x_i(t-1)) \tag{15}$$

$$x_i(t)=v_i(t)+x_i(t-1) \tag{16}$$

where, w is inertia weight. c_1 , c_2 are acceleration coefficient. r_1 , r_2 are random number in the rage $[0,1]$. p_i , p_g are the individual particles optimal location and global optimal particle position.

w adopts self-adaptive adjustment methods according to (17) to enhance the algorithm's global search capability. Minor c_1 is used to enhance the local search capability in initial stage [12]. While, lager c_2 is used to enhance the global search capability in later stage. c_1 , c_2 are determined by (18) and (19).

$$w=w_0+r(w_1-w_0) \tag{17}$$

$$c_1=(c_{1f}-c_{1i})\ iter/MAXITER+c_{1i} \tag{18}$$

$$c_2=(c_{2f}-c_{2i})\ iter/MAXITER+c_{2i} \tag{19}$$

where, $w_0\in[0,1]$, $w_1>w_0$,both constant, w_0 is in the range $[0,0.5]$. r is random number in the rage $[0,1]$. c_{1f} , c_{1i} , c_{2f} , c_{2i} are constants. *iter* , *MAXITER* are the current iteration number and total iteration number.

B. *Selction of Guide Particle*

Guide particle directs the flight of particles. Optimal particle is the optimal frontier. [13] The guide particle is selected following (20).

$$fitness=1/\sum_{i=1}^{M}w_i f_i(x) \tag{20}$$

The fitness of each particle is calculated according to (20). The particle of most current fitness is the global optimal particle. w_i is random number and M is the number of optimal particles.

C. *Mutation Operation*

Mutation operation can enhance the global search capability of particles, increasing the diversity of solutions. When the mutation produces an excellent particle, the particle can attract the attention of other solutions, in order to avoid falling into local optimum. Mutation operation follows (21) and (22).

$$v_m=2(r_3-1)\cdot\beta\cdot V_{max} \tag{21}$$

$$x_i^d(t)=x_i^d(t)+v_m \tag{22}$$

where, v_m is mutation value. $\beta\in[0,1]$ is to adjust mutation degree. r_3 is random number in the rage $[0,1]$. x_i^d is the d-dimensional of i-th particle that selected randomly.

V. EXAMPLE ANALYSIS

Take the IEEE-33 bus system for example [14]. The system reference voltage is 12.66 kV, the total active power load 5084.26kW and total reactive power load 2547.32kvar. The network configuration show as Fig. 1.

Without lost of generality, assuming that due to the geographical location and generation resource restriction, distributed generation is allowed connected only at node 2, 4, 10, 14, 17, 20 and 27.

According to the optimization model proposed above, the active power network loss comprehensive sensitivity of node 14, 10, 17, 25 is higher than the others'. The voltage of node 17, 14, 10, 27 is lower than the others'. So node 14, 17, 27 can be chose to install distributed generation, comprehensively considering the above factors. Tab I shows the optimal location and capacity of distributed generation, using the proposed optimization model and algorithm.

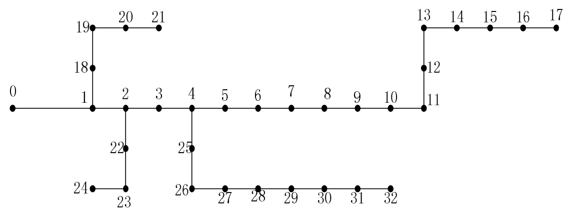

Figure 1. IEEE-33 bus system

TABLE I. OPTIMAL LOCATION AND CAPACITY OF DG

Node	10	14	17
Capacity (kW)	14	17	27

Before distributed generation interconnecting, the emission quantity of SO2, NOx, CO2 is 34.94 kg/h, 15.53 kg/h, 3359.04 kg/h. While the emission quantity of them is 27.15 kg/h, 12.81 kg/h, 2919.02 kg/h, decreasing respectively by 22.3%, 17.5%, and 13.1. As it is can be seen, due to the good environmental performance of distributed generation, the interconnecting of distributed generation makes the system significantly reduce the quantity of pollutant emission.

Fig.2 shows the system voltage profile before and after interconnecting distributed generation. We can see I that system node voltage is low, the voltage of some nodes are out of limit before installing distributed generation. The interconnecting of distributed generation gives strong support to the system node voltage. Such as the voltage of node 17 raise from 0.91 pu to 1.00 pu. The voltage distribution is rational, which will be good to the steady of system.

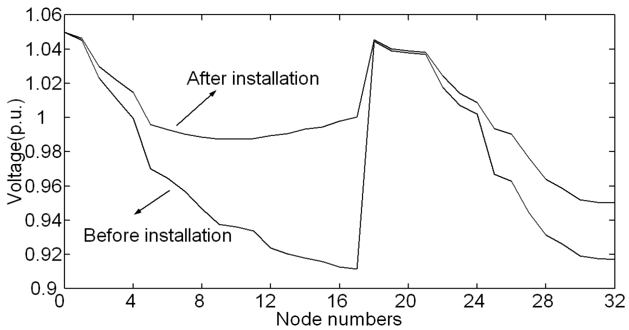

Figure 2. Voltage profile

VI. CONCLUSION

The rise of distributed generation and development of smart grid require the deep research on distributed generation interconnection. A multi-objective optimization model of distributed generation optimal allocation in distributed network is proposed, comprehensively considering system operating cost and environmental benefit, reflecting the requirements of sustainable development. The multi-objective particle swarm optimization is used to solve the optimization model. The results in IEEE-33 bus system show the correctness and effectiveness of the proposed method.

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