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Two-Layer Optimal Dispatching Strategy of Distribution Network Considering Demand Side Load

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Abstract. The traditional optimal dispatching of distribution network usually takes the demand load measurement as the rigid load. However, as the demand for electricity continues to rise, a large amount of distributed renewable energy generation is incorporated into the power grid. It is difficult to ensure the safe and reliable operation of the electrical system if only the optimal dispatching of the generating side is carried out. This paper proposes a two-layer optimal distribution network scheduling strategy that considers the demand side load. The upper layer model chooses controllable load output as the objective and aims to achieve the lowest overall operation cost of the distribution network, as well as the lowest comprehensive load fluctuation to reflect the power supply reliability of the distribution network. The adaptive particle swarm optimization algorithm based on genetic algorithms is implemented to solve the model based on its characteristics. Simulation verification is performed on the IEEE33-node distribution system, and the results depict that the proposed two-layer optimization method reduces the operating cost of the distribution network, effectively stabilizes the peak valley difference of load, and improves the overall stability of the distribution network.

Keywords. Distribution network, Two-layer optimization, load fluctuation, particle swarm optimization, load peak valley

1. Introduction

The distribution network is a very important part of electric system, which is directly connected to the end users. However, as the proportion of Renewable Distributed Generation connected to the distribution network, the economy and stability of the distribution network are particularly important [1-4]. With the large-scale access of DG, the traditional centralized management mode of distribution network is not applicable, and a new load scheduling method for demand side load is needed [5-9].

With the wind power, photovoltaic, micro gas turbine and other distributed equipment access to the distribution network, through the demand side load management and regulation, to achieve the load curve 'peak shaving' and 'valley filling'[10-11]. In References [12-13], aiming at the minimum total operation cost and network loss of wind power, a wind farm model is established to study the optimization of distribution network scheduling. In References [14], a multi-category DG planning

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model is created to explore the economy and stability of the distribution network from the intermittence and timing of DG output. In References [15], aiming at the problems of voltage deviation, network loss and comprehensive operation cost of power generation in distribution network, a two-layer optimization model based on DG is established. Reference[14] proposed a three-tier model of distribution network considering the interests of distribution companies, DG operators and users to optimize the distribution network scheduling problem. In Reference [16], aiming at distribution network cost problem, the goal is to reduce the overall operation cost. Meanwhile, the capacitor bank is installed in the appropriate position, and the control and scheduling strategy is adopted to reduce the network loss. In Reference [17], in order to improve the absorptive capacity of DG and reduce the load fluctuation, the regional model is established to improve the stability of the distribution network.

This paper proposes a two-layer optimal dispatching strategy of demand side load. The upper layer takes the controllable DG as the object, and aims at the lowest overall operating cost of the distribution network, focusing on the economy of the distribution network. The lower layer focuses on the stability of the distribution network through the demand management of DG, the optimal configuration of DG, and the minimum fluctuation range and fluctuation rate of the comprehensive load of the distribution network.

2. The framework of Two-layer optimal model

Demand side load regulation in distribution network is a multi-objective problem, involving multiple variables, multiple constraints and other optimization problems [18-19]. This paper focuses on the operation cost and the stability of distribution network operation, and builds a two-layer model. The upper aims to reduce the overall operating cost of the distribution network, and the lower layer aims to minimize the load fluctuation. The upper and lower targets achieve the optimization effect through mutual cooperation. This paper considers the scheduling of wind power, photovoltaic, micro gas turbine, EV cluster and generalized flexible load. The two-layer optimization model is shown in Figure 1.

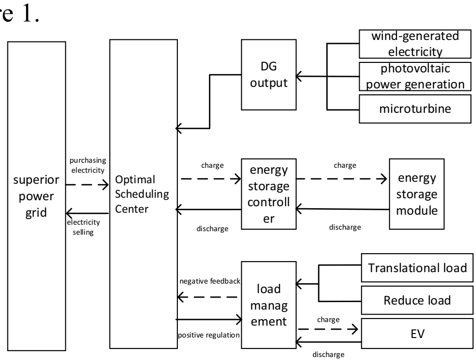

Fig 1 Distribution network two-layer optimal scheduling model

3. Establishment of two-layer scheduling model

3.1 The upper optimization model

（1） Upper function

The aim of the upper model is to reduce the operating cost, including the upper-level power cost, DG power generation cost, and energy storage operation and maintenance cost. The economic optimization scheduling function can be transformed into a single objective function by normalized addition. The specific expression is as follows:

$$\min F_1 = \sum_{t=1}^{T}(\alpha_1 F_G + \alpha_2 F_{DG} + \alpha_3 F_{OD}) \tag{1}$$

Among them, F_G is the cost of power from the superior power grid, F_{DG} is the power generation cost of controllable DG, and F_{OD} is the cost of energy storage. α_1, α_2 and α_3 are weight coefficients, which are 0.3,0.4 and 0.3 respectively.

The expression of electricity cost is:

$$F_G = P(t)\cdot C(t) \tag{2}$$

Among them, $P(t)$ represents the interaction power between the distribution network and the upper electrical system during the t period. $C(t)$ indicates the unit price of electricity from the superior power grid during the t period.

The cost expression of controllable DG is as follows:

$$F_{DG} = F_{MT}(t) + F_{HD}(t) \tag{3}$$

$$F_{MT}(t) = \sum_{i\in v_{MT}}(c_f \frac{P_{mt,i}(t)}{\eta_i} + c_{op}P_{mt,i}(t)) \tag{4}$$

$$F_{HD}(t) = \sum_{i=1}^{v_{hd}} c_{hd}\cdot P_{hd,i}(t) \tag{5}$$

Among them, $F_{MT}(t)$ and $F_{HD}(t)$ represent the operation cost function of micro gas turbine and small hydropower respectively. c_f and c_{op} represent unit fuel cost and maintenance cost respectively, $P_{mt,i}(t)$ represents the power generation of the i th gas turbine, and η_i represents the conversion efficiency of the i th gas turbine. c_{hd} represents the operating cost of small hydropower, and $P_{hd,t}(t)$ represents the output power of the ith small hydropower in period t.

The energy storage operation cost expression is as follows:

$$F_{OD}(t) = \sum_{i=1}^{n}(c_{op}\cdot P_{op,i}(t)) \tag{6}$$

Among them, c_{op} represents cost of the maintenance, and $P_{op,i}(t)$ represents the operating power of the i th energy storage device.

(2) Constraint conditions

1.System power balance constraints

$$\begin{Bmatrix} P_{pci}(t) + P_{DGi}(t) - P_{Li}(t) = U_i(t)\sum_{k\in i} U_k(t)(G_{ij}\cos\theta_{ik}(t) + B_{ik}\sin\theta_{ik}(t)) \\ Q_{pci}(t) + Q_{DGi}(t) - Q_{Li}(t) = U_i(t)\sum_{k\in i} U_k(t)(G_{ij}\sin\theta_{ik}(t) - B_{ik}\cos\theta_{ik}(t)) \end{Bmatrix} \tag{7}$$

Here $P_{pci}(t)$ and $Q_{pci}(t)$ denote the active and reactive power injected by node i at time t; $P_{DGi}(t)$ and $Q_{DGi}(t)$ respectively represent the active power and reactive power injected by DG or energy storage at node i at time t; $P_{Li}(t)$ and $Q_{Li}(t)$

respectively represent the active and reactive power demand of node i load at time t; $U_i(t)$ and $U_k(t)$ respectively represent the voltage of nodes i and k at time t; G_{ij} and B_{ik} are branch conductance and susceptance; θ_{ik} is the voltage phase angle difference of nodes i and j.

2. Node voltage constraints:

$$U_{i\_\min} \le U_i(t) \le U_{i\_\max} \tag{8}$$

Here $U_{i\_\min}$ and $U_{i\_\max}$ denote the upper and lower limits on node i respectively.

3. Branch current constraint

$$I_j \le I_{j\max} \tag{9}$$

Here $I_{j\max}$ is the maximum current on the branch j.

4. Controllable DG output power constraints:

$$P_{DG,\min} \le P_{DG}(t) \le P_{DG,\max} \tag{10}$$

Among them, $P_{\mathrm{DG,min}}$ and $P_{\mathrm{DG,max}}$ represent the minimum and maximum values of the controllable DG output connected to the distribution network respectively.

3.2 The lower level optimization model

(1) Objective function

The objective of the lower level optimization is to minimize the load variation, which is determined by the fluctuation amplitude and fluctuation rate of the comprehensive load of the distribution network. The specific expression is as follows:

$$\min F_2 = \eta_1 F_T + \eta_2 F_\lambda \tag{11}$$

$$F_T = \frac{P_{k,\max} - P_{k,\min}}{\overline{P_k}} \tag{12}$$

$$F_\lambda = \max\left[\frac{|P_k(t+1) - P_k(t)|}{\overline{P_k}}\right] \tag{13}$$

Among them, function F_T represents the load fluctuation amplitude function, and function F_λ represents the load fluctuation rate function. η_1, η_2 represents the weight coefficient. Since the load fluctuation rate has a greater impact on the reliability of the distribution network than the load fluctuation range, this paper takes $\eta_1 = 0.3, \eta_2 = 0.7$. P_k represents the daily load power of the distribution network, $P_{k,\max}$ and $P_{k,\min}$ represent the maximum and minimum daily load power of the distribution network respectively, $\overline{P_k}$ represents the daily average load power of the distribution network, $P(t)$ and $P(t+1)$ represent the load power of the distribution network at time t and time t+1 respectively.

(2) Constraint conditions

1.DG output active power constraint

$$\begin{Bmatrix} P_{\mathrm{DG}}(t) = (1+\mu_f) P_{DG,f}(t) \\ 0 \le |\mu_f| \le \mu_{f,\max} \end{Bmatrix} \tag{14}$$

Among them, $P_{DG}(t)$ represents the DG output active power function, $P_{DG,\ f}(t)$ represents the predicted value of DG output active power at time t, μ_f represents the prediction error coefficient of DG output, and the closer the μ_f value is to 0, the higher the prediction accuracy is.

2.Power interaction constraints between distribution network and controllable DG:

$$P_{pc,\min} \le P_{pc}(t) \le P_{pc,\max} \tag{15}$$

Here, $P_{pc,\min}$ and $P_{pc,\max}$ denote the minimum and maximum interactive power at time t, respectively.

3. Voltage stability index constraint:

$$P_{pc,\min} \le P_{pc}(t) \le P_{pc,\max} \tag{16}$$

Here $U_{SI,\max}$ is the upper limit of the voltage stability index, $U_{SI}(t)$ should be less than 1, otherwise the system will collapse.

4. Method to solve model

The genetic algorithm is a derivative stochastic optimization algorithm. The core of the genetic algorithm is to use the chromosome to characterize the population [20-21]. Genetic algorithm can greatly improve the local search ability of the algorithm through crossover operation, and can quickly find the global optimal solution through mutation [22-23].

In this paper, the adaptive particle swarm algorithm based on genetic algorithm is used. The upper goal includes the minimum value of the normalized target value of the power purchase cost, DG power generation cost and energy storage operation and maintenance cost of the distribution network to the upper level, in which the variables are controllable DG load output and energy storage output. The lower target is the minimum fluctuation of the comprehensive load of the distribution network, which is determined by the fluctuation range and fluctuation rate of the power supply load, and the variable is the daily load power of the distribution network.

5. Example analysis

In this paper, the IEEE33 node distribution system is used to construct a distribution network model with controllable DG and energy storage for simulation verification, shows in the figure 2. There are 33 nodes and 32 branches in the system. The distributed photovoltaic power supply with capacity of 1WM and 0.8WM is connected at nodes 3 and 29, respectively. The distributed wind power supply with capacity of 1.5WM and 1WM is connected at nodes 16 and 31, respectively. The energy storage system is connected at node 15. The reference voltage U=12.66 kV and the total active load of the network is 5216 kVA. The simulation step is set to 15 min, and a scheduling cycle is 24 hours.

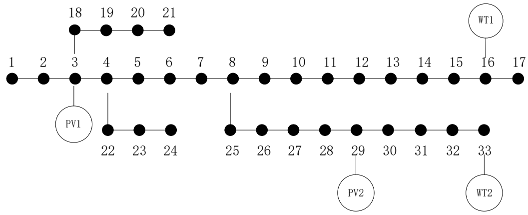

Fig.2 IEEE 33 Node distribution system structure diagram

Set the distribution network energy storage related parameters as shown in Table 1; the time-of-use electricity price table for purchasing and selling electricity in the distribution network is shown in table 2, and the relevant parameters of photovoltaic and wind turbines are shown in table 3.

Table 1 Related parameters of the energy storage system

Type	Parameter	Type	Parameter
Installed capacit（MWh）	2.5	Conversion efficiency (%)	0.9
Active power（MW）	0.4115	State of charge（SOC）	0.1~0.9
Call cost（Yuan/MWh）	255	Discharge subsidy（Yuan/kWh）	0.15
Unit capacity cost（Yuan /kWh）	856	Maintenance cost（Yuan /kWh）	60

Table 2 Time-of-use tariff

Time period type	Valley period	Usual period	Peak period
Time frame	22:00-5:00	5:00-8:00 12:00-17:00	8:00-12:00 17:00-22:00
Electricity sales price /Yuan·kWh^{-1}	0.35	0.55	0.75
Electricity purchase price/ Yuan·kWh^{-1}	0.38	0.58	0.79

Table 3 Controllable DG related parameters

Category	Photovoltaic	Wind power
Design life (years)	20	20
Installation cost (ten thousand yuan /kW)	4.5	2
Operation and maintenance costs (yuan/kWh)	0.12	0.03
Annual cost coefficient (%)	8	8

In the scheduling process, the controllable DG output and the maximum charge and discharge of the energy storage system have a certain error range, and the setting error is 10 %. In the real-time distribution network scheduling, photovoltaic output, wind power output and basic load output are the main concerns.

Aiming at the bi-level optimal scheduling strategy of distribution network considering demand side load proposed in this paper, two different scenarios are set up for simulation analysis:

(1) Only considering the generation side controllable, traditional reactive power compensation device scheduling scheme;

(2) Considering controllable DG, energy storage device, reactive power compensation device, but do not have distributed energy and energy storage scheduling scheme;

(3) Considering the controllable DG, energy storage device, demand side load, reactive power compensation device of distribution network bi-level optimal scheduling scheme;

The annual operating costs of the distribution network in three cases are shown in Table 4.

Table 4 Annual operating cost of distribution network

Scene	Investment cost (ten thousand yuan)	Operation and maintenance costs (ten thousand yuan)	Electricity purchase cost (ten thousand yuan)	Total cost (ten thousand yuan)
1	0	0	2388.9	2388.9
2	69.2	138.6	1869.2	2014
3	80.4	167.3	1477.4	1725.1

The electricity purchase cost in scenario 1 is the sum of the total load consumption and network loss in the distribution network system, and the electricity price is set to 0.61 yuan/kWh. In Scenario 2, the equipment investment and equipment operation and maintenance costs are increased, but the power purchase cost of the distribution network to the superior power grid is greatly reduced. In Scenario 3, the demand measurement load is considered, and the controllable DG and energy storage load are regulated. Although the equipment investment and operation and maintenance costs are increased, the power purchase of the distribution network is 6.638 million yuan less than that of Scenario 1,2.889 million yuan less than that of Scenario 2, and the economy is better.

Taking the voltage amplitude of 33 nodes between 11:00-12:00 during the peak period, the amplitude fluctuations in the three scenarios are compared as shown in Fig.3.Scenario 2 and Scenario 3 have obvious voltage amplitude changes compared with the traditional distribution network dispatching mode. Considering the demand side load, and coordinating the controllable DG and energy storage output, Scenario 3 intersects with Scenario 2, and the voltage amplitude fluctuation is reduced by 5%, which ensures that the distribution network has a higher voltage level and promotes the stable and reliable operation of the distribution network.

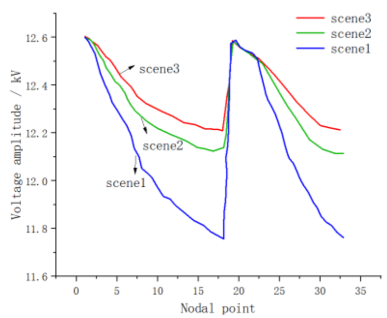

Fig.3 Voltage amplitude curve of each node during 11:00-12:00

In this paper,17 nodes and 17 nodes are selected as the research object of single node voltage. The 17 node voltage pairs in the traditional distribution network scene 1, scene 2 and scene 3 modes are shown in figure 4. The reactive load is large in the peak load period, and the voltage level in the three scenes is relatively high. However, the voltage curve of scene 2 and scene 3 is more gentle than that of scene 1, which further improves the level of node voltage. Compared with scene 2, in the peak load period, the voltage curve is more gentle, and the average extreme value fluctuation amplitude is reduced by 10%.

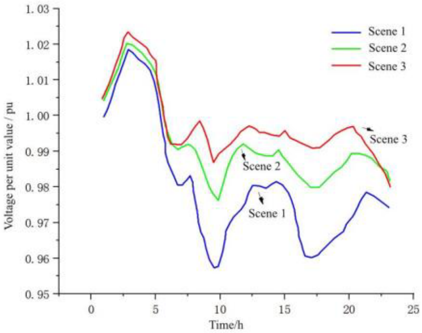

Fig.4 Voltage comparison curves of 17 nodes in the distribution network in different scenarios

6. Conclusion

This paper establishes a two-layer optimization scheduling strategy for the traditional distribution network, which considers demand side load. The upper layer focuses on controllable DG and aims to achieve the lowest overall operation cost of the distribution network, concentrating on its economy and applicability. Meanwhile, the lower layer emphasizes the stability and security of the distribution network through the demand management and optimal configuration of DG, with the goal of achieving the minimum fluctuation range and fluctuation rate of the comprehensive load of the distribution network. To address the proposed model, the adaptive particle swarm optimization algorithm based on genetic algorithms is utilized to solve the model. The IEEE33 node distribution system is then employed as an example to verify the simulation comparison. Results indicate that the proposed bi-level optimization method can reduce the distribution network's operation cost, effectively stabilize the load peak-valley difference, and improve the network's overall stability.

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