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Optimal Allocation method on Distributed Energy Storage System in Active Distribution Network

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Abstract

With distributed generations (DG) including the wind and photovoltaic power generations continually connected to the distribution network, reasonable allocation of energy storage system is extremely important to active distribution network (ADN). In this paper, a method to optimize the location and capacity of the embedded distributed energy storage system (DESS) is proposed to meet the needs of ADN and DGs. Firstly, the model of DGs is built according to the natural characteristics of wind and solar energy. Secondly, the model of allocating the DESS is established to achieve the best economical investment results with the constraints of ADN, DG and DESS themselves. Finally, a test ADN with wind and photovoltaic power generations is used to verify the efficiency of the method proposed in this paper.

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Keywords: Active Distribution Network; Distributed energy storage; Annual income of distribution network; Capacity optimization

1. Introduction

The distributed generations (DGs) including wind power (WG) and photovoltaic power (PV) can improve energy efficiency and reduce CO_2 emissions. However, the fluctuation and unpredictable characteristics of DGs may greatly

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affect the reliability and security of power system [1-3]. Active distributed network (ADN) is an intelligent distributed network which can automatically control and actively manage the abundant controllable resources within the network [4-5].

Energy storage system (ESS) can quickly adjust power flow. It can store energy when DG generation is sufficient, and output power to alleviate the shortcomings of intermittent DG generation, which is the key of AND's flexibility to adjust grid-connected DG and network's operation state [6-7]. But configuration and operation of ESS will directly affect AND's management of DGs and the economy of grid's operation. [8] proposed an optimized charging/discharging model of ESS unit in which the minimum fluctuation of active power is taken as objective function. [9] managed to plan the ESS's capacity aiming at achieving the best profits with tracking the estimation results and peak load shifting technology. [10] established a nonlinear constrained optimization model to formulate the optimal control strategy for the distributed energy storage system of intermittent grid-connected distributed power. But this model is computationally large, so it is not suitable for large-scale distribution network. [11] used a multi-objective algorithm to optimize the energy storage capacity. [12] proposed a multi-period mixed-integer nonlinear optimization model with the objective of minimum total investment and operation cost of DESS. Improved genetic algorithm (GA) is used to optimize the DESS allocation scheme, but the energy interval of ESS is slightly different from the actual situation. [13] proposed a novel bi-level optimization method for locating and sizing of DESS. Due to the time sequence matching of grid, load and ESS, the calculation period become longer.

This paper proposes a practical model of allocating distributed energy storage system (DESS) corresponding to DGs in the AND. The objective of the model is to achieve the best economical investment results with the constraints of ADN, DGs and DESS. The GA is used to solve the algorithm, and the power flow calculation is based on the former push back method.

2. Modeling of distributed generations and energy storage system in active distribution network

2.1. The advantage of distributed energy storage system

In AND with DGs, energy storage devices generally have two kinds of architectures: centralized architecture and distributed architecture [14]. The centralized architecture means that energy storage device will be installed in the same location, which can be used to balance the unstable output of all the DGs in ADN. While in the distributed architecture, every ESS is designed for each DG and it will only cooperate with the DG at the same location.

This paper chooses the DESS configuration method as the main research goal. The advantages of distributed configuration are not only that the storage capacity is less than the centralized, but also that it is cost-effective and can be flexibly installed. DESS can effectively solve the problems of planning and running of power generation.

2.2. The model of wind power

The number of wind power is closely related to the wind speed of the wind turbine. In this paper, Weibull Distribution is used to simulate the random fluctuations of wind [15-16]. The probability density function is

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

Where, k and c are the shape parameters and scale parameters in the Weibull distribution.

2.3. The model of photovoltaic power

The amount of PV generation is closely related to light intensity. According to the relevant statistics, the change of light intensity is basically consistent with the Beta distribution [17]. The probability density function is:

$$f(r)=\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\cdot\left(\frac{r}{r_{\max}}\right)^{\alpha-1}\cdot\left(1-\frac{r}{r_{\max}}\right)^{\beta-1} \tag{2}$$

Where, Γ denotes the Gamma function. r is the current light intensity. $r_{\max}$ is the maximum light intensity. α and β are the shape parameters of the Beta distribution.

2.4. The model of distributed energy storage system

The state of charge (SOC) represents the ratio of the remaining capacity of the energy storage device to the fully charged state capacity. The SOC of the energy storage device at time *t+1* is determined by the power supply and demand at the time *t* and the charge/discharge state of the energy storage device. The model is as follows:

$$SOC_{t+1}=SOC_t-(\alpha_{c,t}\frac{P_{ESS,t}\eta}{E_{ESS}}+\alpha_{d,t}\frac{P_{ESS,t}}{E_{ESS}\eta})\Delta t \tag{3}$$

SOC_t is the state of energy storage at time t. $\alpha_{c,t}$, $\alpha_{d,t}$ is the charge and discharge of variable energy. When charging, $\alpha_{c,t}=1, \alpha_{d,t}=0$. Otherwise, $\alpha_{c,t}=0, \alpha_{d,t}=1$. $P_{ESS,t}$ is the active output of the energy storage t period. η is the charge and discharge efficiency of energy storage. E_{ESS} is the rated capacity of the energy storage system. Δt is the time interval for energy storage and discharge.

The general strategy of the charge and discharge control of the energy storage device is that the energy storage is in the state of charge when the DGs output is greater than the load; when the DGs' output is less than the load, the energy storage is in the discharge state.

3. Optimal allocation model of distributed energy storage system

3.1. Objective function

This paper mainly focused on the economics of newly-allocated DEES in ADN. The allocation of DEES needs large investment on the construction and Maintenance. However, ADN will benefit from DEES through saved expansion investment and distribution network loss costs as well as increased electricity consumption of DG [18].

The objective function is as follows:

$$\max\ F=C_B+C_{loss}+C_{w,s}-C_{DESS} \tag{4}$$

Where, C_{B} is the saved expansion investment; C_{loss} is saved network loss; $C_{w,s}$ increased electricity consumption of DG; C_{DESS} is the total investment of DESS. These variables can be simulated through the allocation plan of DESS.

3.2. Constraints

- Power flow constrains: The state of AND should always satisfy the power flow formulas [19].

- The constrain of voltages: The newly-allocated DESS will change the voltages of ADN [20-21]. While the voltages should always follow the constrains as

$$U_N(1-\varepsilon_1) \leq U_\mathrm{i} \leq U_N(1+\varepsilon_2) \tag{5}$$

Where, U_x is the voltages of the nodes in the AND; ε_1 and ε_2 is the allowed deviation of voltages.

- The constrain of DGs: The output of DGs has its own maximum limits and is limited by the real-time weather condition [22].

$$\begin{cases} 0 \leq P_{DG} \leq P_{DG\max} \\ Q_{DG} \to 0 \end{cases} \tag{6}$$

Where, P_{DGmax} is the theoretical maximum output of DGs. Assume that DGs generate no inactive power.

- The constrain of DESS: All the DESS should meet the constrains about SOC, charging and discharging power.

$$\begin{cases} SOC_{\min} \leq SOC_t \leq SOC_{\max} \\ 0 \leq \left|P_{\mathrm{DESS},t}\right| \leq P_{\mathrm{DESS,max}} \end{cases} \tag{7}$$

Where, $SOC_{\max}$ and $SOC_{\min}$ is the upper and lower limits of the SOC of each distributed energy storage; $P_{\mathrm{DESS,max}}$ is the maximum power of each DESS; SOC_t and $P_{\mathrm{DESS},t}$ is SOC and power of each distributed energy storage at time *t*.

3.3. Solution and algorithm

This paper mainly studies the configuration of distributed storage system in AND. Unlike the transmission system, ADN has a radiation tree structure and the branch resistances cannot be ignored, so the forward push back method is used to solve the power flow problem.

GA algorithm is suitable for solving the mathematic problem in this paper. And the flow chart of the method is illustrated in Fig. 1.

4. Case study

4.1. Model and parameter settings

In this paper, a distribution network including 40 nodes and 39 branches is selected as the test system. The rated voltage of the system is 23kV, three-phase power base value is 15MVA and the total load in system is 13.599MW. Fig.2 shows the topology of the network's structure where node 15 and 38 are connected to WG, node 28 and 39 are connected to PV.

According to the historical data of a region's wind speed, the shape parameter *k* and scale parameter *c* of the Weibull distribution model are obtained as 9.82 and 2.04 respectively. In WG, the cut-in wind speed is 3m/s, the rated wind speed is 15m/s and the cut-out wind speed is 20m/s。According to the historical data of the same region's light intensity, the two parameters α and β of the Beta distribution model are 2.27 and 2.1. Because of the small scale of this system, it is assumed that each node shares the same wind speed and light intensity.

The distribution network's voltage amplitude are constraints between 0.95 to 1.05 based on the national standard of supply voltage deviation.

In GE, the maximum generation and the population size of each generation are both 100, the crossover probability and the mutation probability are 0.7 and 0.05 respectively. To prevent the program from falling into the dead loop when it is not converging, we set the maximum number of iterations to 100.

Capacity lithium-ion battery is used in DESS which has a 12 hours' continuous working time. The SOC is limited from 0.1 to 0.9 and the initial state of SOC is 0.4.

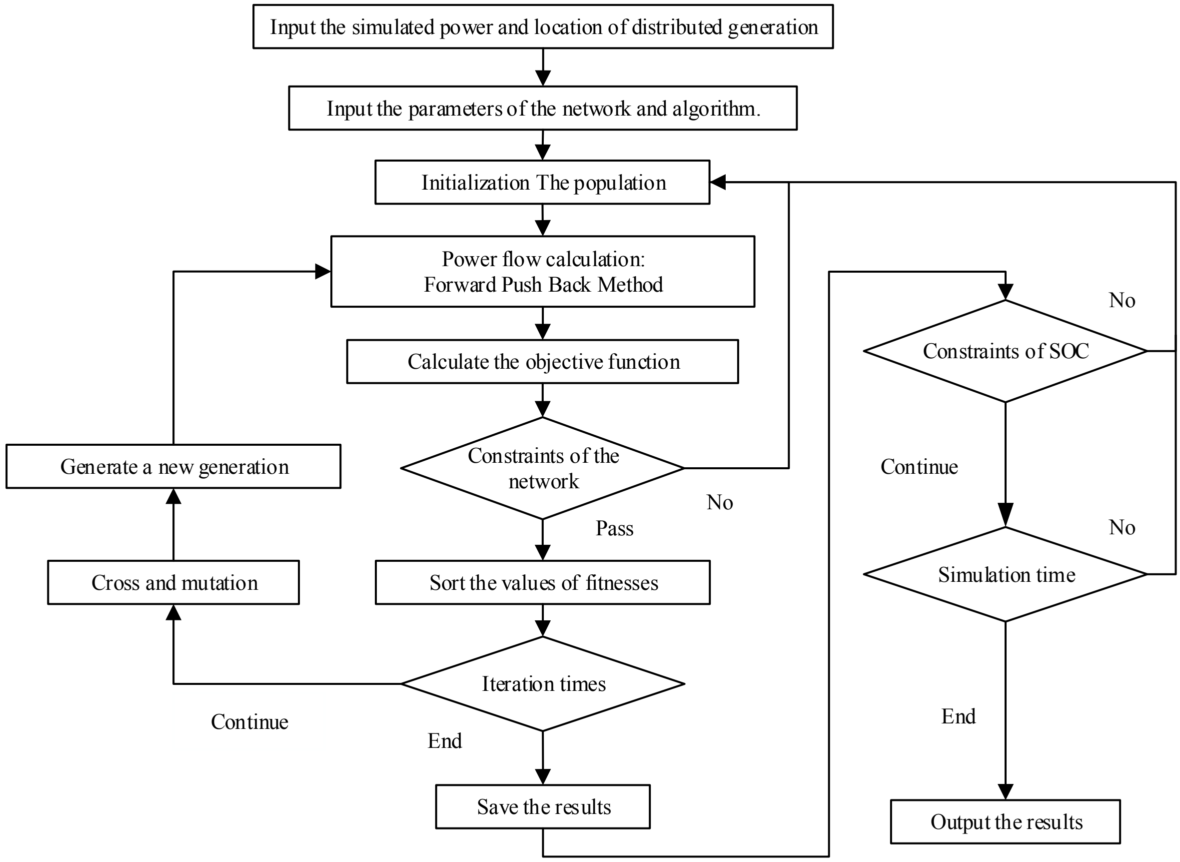

Fig. 1. The flow chart of the method

4.2. Results and analysis

- Scenario 1:

When the rated power of WG is 2.1 MW and the rated power of PV is 1.5MW, the optimal configuration scheme of the DESS capacity in each node is shown in Table 1. The change state of SOC of DESS in each node is shown in Fig. 4.(a). It can be seen that the constraints about SOC are all met during the working hours.

In order to verify the feasibility of the algorithm provided by this paper, each generation's optimal average value of the objective function obtained by GA in the continuous working time of DESS is shown in Fig. 3., which proves the accuracy from the qualitative point of view.

- Scenario 2:

When the rated power of WG is 2.4 MW and the rated power of PV is 1.5MW, the optimal configuration scheme of the DESS capacity in each node is shown in Table 1.

Scenario 2 keeps the rated power of PV constant but increases the access capacity of WG. Compared with scenario 1, it can be found that the power capacity of DESS in the nodes 15 and 38 which including WG is larger, but the energy capacity becomes smaller. Because with the increasing access capacity of WG, the power capacity of corresponding DESS should be proportional changed to ensure absorb more wind energy to prevent the voltage amplitude beyond the limitation. But the economy of the system should also be taken into account, so the energy capacity is reduced. In this scheme, the change rate of the SOC is bigger than that in scenario 1, which can be shown in Fig. 4.(b). Therefore, to protect the performance and service life of DESS from the affection caused by the situation of long time's high rate fluctuations, increasing the energy capacity appropriately should be considered in the actual allocation.

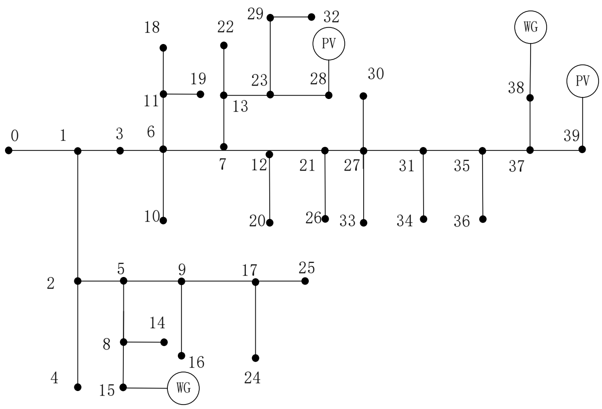

Fig. 2. The structure of 40-node network

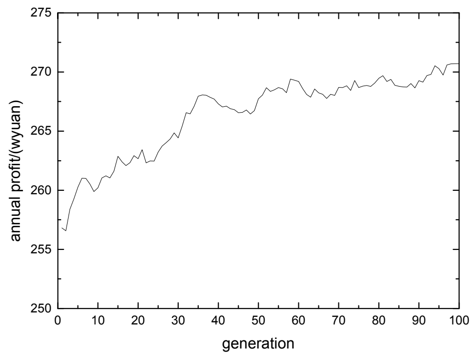

Fig.3. The change curve of objective function

Table 1. The optimal configuration scheme in different scenarios

Scenario 1			Scenario 2		
Node	Power (kW)	Capacity (MW·h)	Node	Power (kW)	Capacity (MW·h)
15	626.13	13.723	15	651.45	13.293
28	535.18	13.465	28	566.23	13.285
38	659.51	13.324	38	685.25	13.132

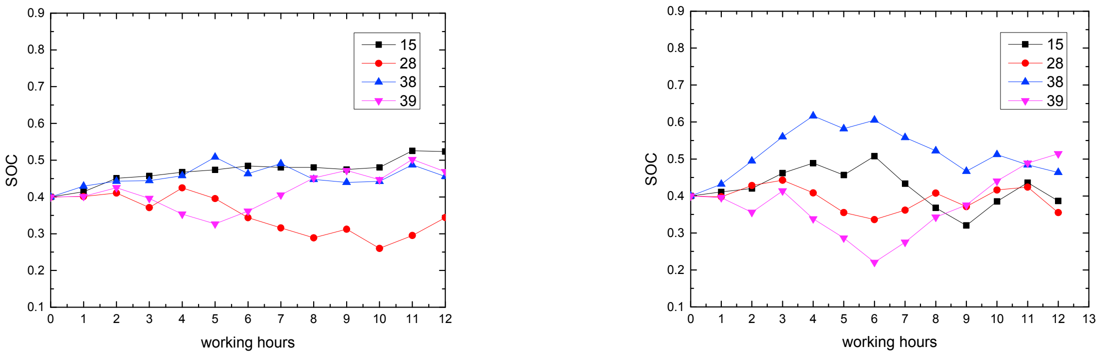

Fig. 4. (a) The change state of SOC in scenario 1; (b)The change state of SOC in scenario 2

5. Conclusions

The research object of this paper is the optimal allocation of ESS in ADN, and the feasibility and rationality of DESS scheme are verified as well, which provides a new way to solve these problems.

This paper stands the perspective of ESS's investors. It sets the maximum annual profit as objective function after ESS has being installed into the ADN, which considers the money saved by reducing the power grid expansion and transmission losses, additional income by increasing power from DG and DESS's joint work, and the cost of construction and maintenance of DESS. Meanwhile, the constraints are considered thoroughly from the network point, DG point and ESS point.

In this paper, the optimization model of ESS's capacity is solved by GA with good researching ability and convergence. The forward and backward substitution method is used in the algorithm, which is suitable for calculation of the power flow in the radial distribution network. The analysis of examples shows that the optimal allocation method and model on DESS in ADN based on GE can get the reasonable scheme considering the economy and safety. And the influence of different DG output cases on the optimal allocation of ESS are also obtained in this process.

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