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Multi-Objective Reactive Power Optimization of Distribution Network with Distributed Generation

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Abstract. Distributed generation (DG) is considered to be a very promising alternative of power generation because of its tremendous environmental, social, and economic benefits. But the randomness and intermittent of DGs brings new problems to the system. This paper analyzes the reactive power optimization problem of distribution network with correlative DGs based on scenario analysis method. A new scenario division rule according to the joint distribution function of wind-PV power outputs is proposed in the paper. Then a multi-objective reactive power optimization model whose objects include the minimum active power losses, the minimum voltage deviation and the maximum static voltage stability margin is established. Non-dominated sorting genetic algorithm-II is used to solve the model. At the last of the paper, the model and the algorithm proposed are verified with an improved IEEE 33-bus system. The results show that the model will be a reference to the reactive power optimization problem in distribution system.

1 Introduction

DG's advantages of being environmental friendly, low-cost and layout flexible have drawn considerable attention in recent years, making them be a very promising alternative of power generation.

But the randomness and intermittent of their outputs bring new problems to the safety and stability of power system, which means the traditional control methods of power system such as the reactive power optimization need some new research[1-4].

This paper studies the reactive power optimization problem of distribution network with correlative DGs. It is organized as follows. In section II, we establish the joint probability model of wind-PV outputs based on Copula theory. A new multi-scene division method based on the joint probability model is proposed in section III. In section IV, we put forward a multi-objective reactive power optimization model and in section V non-dominated sorting genetic algorithm-II is used to solve the model. The simulation results are presented in Section VI and concluded in Section VII.

2 Joint probability model of wind-PV outputs

2.1 Probability model of wind farm

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The output of wind power farm is closely related to the wind speed. It is studied that the wind speed of a certain area usually follows skew normal distribution. Its probability distribution can be described by Weibull distribution [5]:

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

where v is the wind speed, k and c are the shape parameter and scale parameter of Weibull distribution.

The relationship of wind farm's output and the wind speed can be expressed as follows:

$$p_w=\begin{cases} 0 & v\le v_{ci}, v\ge v_{co} \\ \dfrac{p_r}{(v_r-v_{ci})}v+\dfrac{p_r v_{ci}}{(v_r-v_{ci})} & v_{ci}\le v\le v_r \\ p_r & v_r\le v\le v_{co} \end{cases} \tag{2}$$

where P_{w} is the power output of wind farm, P_{r} is the rated power output, v_{ci} , v_{r} and v_{co} are the cut-in wind speed, rated wind speed and cut-out wind speed respectively.

The probability density function $f_{\mathrm{W}}(p_w)$ and the probability distribution function $F_{\mathrm{W}}(p_w)$ of wind farm output can be deducted with (1) and (2).

2.2 Probability model of photovoltaic

Similarly, the output of photovoltaic power plants is mainly affected by the light intensity. The light intensity in a certain period of time approximately obeys Beta distribution. So the output of photovoltaic power plants also obeys Beta distribution [6]. Its probability density function can be expressed as (3):

$$f_{\mathrm{S}}(p_s)=\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\cdot\Gamma(\beta)}\cdot\left(\frac{p_s}{p_{s\max}}\right)^{\alpha-1}\cdot\left(1-\frac{p_s}{p_{s\max}}\right)^{\beta-1} \tag{3}$$

where p_s is the photovoltaic power output, $p_{s\max}$ is the maximum power output; α and β is the shape parameter of Beta distribution.

The probability distribution function of photovoltaic power plants output $F_S(p_s)$ can be obtained by integrating (3).

2.3 Joint probability model of Wind-PV outputs

Under normal circumstances, the output powers of wind farm and photovoltaic power plant in the same area have certain correlation. This paper introduces Copula theory [7] to describe this correlation.

Sklar's theorem [7]: An N-dimensional joint distribution function can be formed by the marginal distributions of the N variables and a Copula function which describes the correlation between the variables. This theorem can be expressed in (4):

$$F(x_1,x_2,\cdots,x_n)=C\left(F_{X_1}(x_1),F_{X_2}(x_2),\cdots,F_{X_n}(x_n)\right) \tag{4}$$

where $F(\cdot)$ is the joint distribution function, is the Copula function, $F_{X_i}(x_i)$ is the marginal distributions of variables X_i .

The common used Copula functions include oval Copula functions and Archimedes Copula functions. In this paper we choose the normal Copula function of the oval Copula functions to form the joint probability distribution function of wind-PV outputs, which can be written as:

$$C(u,v;\rho)=\Phi_\rho\left[\Phi^{-1}(u),\Phi^{-1}(v)\right] \tag{5}$$

where $\Phi_\rho(\cdot)$ is the bi-normal probability distribution function with the correlation coefficient ρ , $\Phi^{-1}(\cdot)$ is the inverse function of normal function.

Applying Copula theory to what we are studying, we can obtain the joint probability distribution function of wind-PV outputs:

$$F(p_w, p_s) = \Phi_\rho\left[F_{\mathrm{W}}(p_w), F_{\mathrm{S}}(p_s)\right] \tag{6}$$

3 Multi-scene division method

Scenario analysis method has great advantage in dealing with uncertain problem which can turn the uncertainty into the combination of several deterministic scenarios. We try to adopt scenario analysis method to cope with the uncertainty caused by DGs. How to divide the scenarios is the key of the method. The traditional way is dividing according to the state transition points of wind turbines, as is the case in [4]. But this division method is relatively rough, and the DGs need to be independent from each other..Here in the paper a new multi-scene division method according the joint probability model in the previous section is given.

A. divide

Firstly, divide the wind DG's output interval into N subintervals and similarly the photovoltaic DG's output interval $[0, P_{s\max}]$ into M subintervals.

B. combine

There are N intervals of wind power DG's output and M intervals of photovoltaic DG's output, so in total there are $N \times M$ combinations of power intervals which we denote as $\{S_{11}, S_{12}, S_{13} \cdots S_{nm} \cdots S_{NM}\}$ where S_{nm} is the combination of the *nth* wind DG's output interval and the *mth* photovoltaic DG's output interval.

C. calculate the probability

We define the outputs of the scenario as the average output of the interval:

$$P_{\mathrm{W}}(S_{nm}) = \frac{(2n-1)\cdot P_r}{2N} \tag{7}$$

$$P_{\mathrm{S}}(S_{nm}) = \frac{(2m-1)\cdot P_{s\max}}{2M} \tag{8}$$

And the probability of the scenario is calculated as follows:

$$f(S_{nm}) = \iint_D f(p_w, p_s)\mathrm{d}p_w \mathrm{d}p_s \tag{9}$$

$$D = \{(p_w, p_s) \left| \frac{(n-1)P_r}{N} \le p_w \le \frac{n\cdot P_r}{N}, \frac{(m-1)P_{s\max}}{M} \le p_s \le \frac{m\cdot P_{s\max}}{M} \right.\} \tag{10}$$

4 Multi-objective reactive power optimization model

In the traditional reactive power optimization model, the object function is always the minimum active power losses and the voltage demand acts as the constraint of the model. In this case, the voltage may be close to the voltage limits. In the distribution network with DGs, the fluctuation of the DGs may cause the voltage to go over the limit. So in this paper, we include the voltage demand in the object function and establish a multi-objective reactive power optimization model.

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4.1 Objective function

a) minimum active power losses

$$\min f_1 = E\left(P_{loss}\right) = \sum_{n=1}^{N}\sum_{m=1}^{M} f\left(S_{nm}\right) P_{loss\_nm} \tag{11}$$

where $E\left(P_{loss}\right)$ is the expectation of active power losses, P_{loss_nm} is the system active power losses in scenario S_{nm} .

b) minimum voltage deviation

$$\min f_2 = E\left(\Delta u\right) = \sum_{n=1}^{N}\sum_{m=1}^{M} f\left(S_{nm}\right) \cdot \sum_{k=1}^{N_L} \frac{\left|U_k - U_k^{'}\right|}{U_{k\max} - U_{k\min}} \tag{12}$$

where N_L is the number of the load nodes, U_k is the actual voltage of node *k*, $U_k^{'}$ the reference value of voltage, $U_{k\min}$, $U_{k\max}$ is the upper limit and lower limit of voltage on node *k* respectively.

c) maximum static voltage stability margin

$$\min f_3 = E(\frac{1}{\delta}) = \sum_{n=1}^{N}\sum_{m=1}^{M} f\left(S_{nm}\right) \cdot \frac{1}{\delta_{nm}} \tag{13}$$

where δ_{nm} is the minimum singular value of the Jacobian matrix in scenario S_{nm} .

4.2 Constraints

$$\begin{cases} P_{Si} - P_{Li} = V_i \sum_{j\in i}^{N_L} V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) \\ Q_{Si} - Q_{Li} + Q_{Ci} = V_i \sum_{j\in i}^{N_L} V_j \left(G_{ij}\sin\delta_{ij} + B_{ij}\cos\delta_{ij}\right) \\ 0 \le Q_{ci} \le Q_{ci\max} \qquad i = 1,2,3\cdots p \\ V_{i\min} \le V_i \le V_{i\max} \qquad i \in N_L \end{cases} \tag{14}$$

where N_L is the node number, P_{Si} , P_{Li} are generator active power output and active power of load at node *i*. Q_{Si}, Q_{Li}, Q_{Ci} are generator reactive power input, load reactive power and capacity of capacitive reactive compensation device at node *i* respectively.

5 Non-dominated sorting genetic algorithm-II

The reactive power optimization problem of distribution network with DGs is multi-objective, non-linear, and multi-constraint. Traditional optimization methods are difficult to obtain global optimal solution. Non-dominated sorting genetic algorithm-II (NSGA-II) algorithm is good at dealing with multi-objective optimization problem.

The main features of the algorithm: 1) Fast non-dominated sorting method based on grading; 2) introducing the concept of crowding distance, which is used to measure the population density of the individuals in the same front after fast non-dominated sorting; 3) introducing elitist mechanism. Parent and offspring together compete for the next generation.

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6 Example

In order to validate the model and the algorithm proposed in this paper, a test is done with the improved IEEE33 bus system. The line parameters and the load information of the system is the same with [8]. A 500kW wind power DG and a 100kW photovoltaic DG whose correlation coefficient $\rho = -0.122$ are connected to bus 11 and bus 27 respectively. Both of the wind power and photovoltaic DG work with a constant power factor. The wind power DG's power factor is set to 0.95 and photovoltaic DG's is set to 0.9. Bus 2, 16, and 32 are the candidate places for reactive power compensation. There are 20 groups of parallel capacitors at each place and the compensation capacity of each group is 50kvar.

Fig.1 shows the comparison between the joint probability density function of wind-PV outputs and the probabilities of 120 scenarios calculated using the multi-scene division method given in this paper. From the figure, we can draw the conclusion that the multi-scene division method put forward in this paper has good effect in practice.

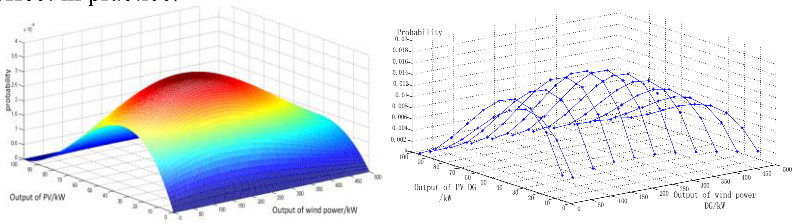

Figure 1. Joint probability density distribution of wind - PV power outputs

We choose 3 solutions from the Pareto and show them in table 1: the minimum power losses one, the minimum voltage deviation one and a comprehensive one.

Table 1. Schemes for reactive power optimization and results

scheme	Q_{c1} (kvar)	Q_{c2} (kvar)	Q_{c3}(kvar)	Q_{c4}(kvar)	**Power losses (kW)**	**voltage deviation**	**Voltage stability margin**
no	0	0	0	0	165.16	15.27	0.1471
scheme 1	550	800	300	700	95.04	9.73	0.1574
scheme 2	950	850	800	950	113.73	6.31	0.1615
scheme 3	550	750	650	1000	104.22	7.04	0.1600

From the table, we can see that compared to the system without optimization, all of the three schemes can reduce the system active power losses, the system voltage deviation and enhance the voltage stability margin tremendously. But scheme 1 reduces the most active power losses and scheme 2 reduces the most voltage deviation. Compared to scheme 1 and 2, none of the three objective functions of scheme 3 is the best, but it makes balance between the three objective functions and seems more moderate.

This is the advantage of multi-objective optimization which provides us more options to choose from, each option laying different emphasis on different objectives.

Fig. 2 shows the voltage expectation curve of the 33 nodes and figure 3 shows the voltage curve of node 18 under 120 scenarios.

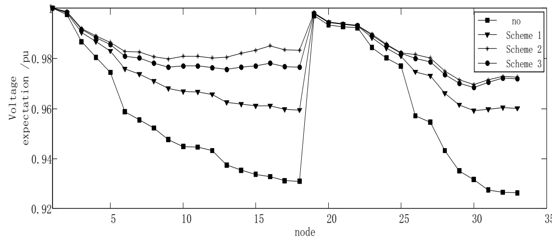

Figure 2. Voltage curves of load bus before and after reactive power optimization

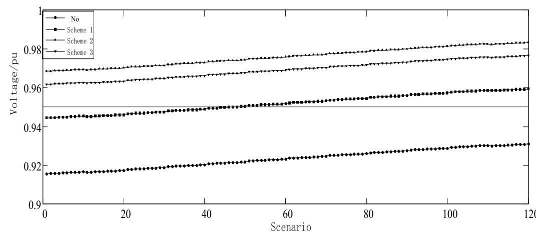

Figure 3. Optimal voltage curve of bus 18 at different scenarios

Once again we can find from the two figures that the three schemes can enormously improve the system voltage. One thing we should point out is that from fig.5,we find that under scheme 1, there are 54 scenarios in which the voltage of bus 18 will be lower than the lower limit 0.95pu.. This give us the lesson that if we are in obsession of reducing the active power losses, there may be threat to the voltage safety. That is just what we have said in the beginning of section IV .

7 Conclusion

In this paper we established a multi-objective reactive power optimization model based on the scenario analysis method and the multi-scene division method. Non-dominated sorting genetic algorithm-II is adopted to calculate Pareto. Simulation of IEEE 33-bus distribution systems shows that the proposed method and model is feasible and effective.

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