Planning for Micro-grid with Static Voltage Stability and Maximizing Renewable Energy Utilization

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Abstract. The access position and capacity of distribution generation (DG) affect the static voltage stability of micro-grid, thus affecting the renewable energy utilization. In the current reform of the energy supply side, a multi-objective optimization model is established, aiming at the abandoning wind and abandoning light problem. This model has three advantages, which are the largest renewable energy utilization, static voltage stability of micro-grid and the minimum cost of DG investment considering environmental benefits. It can effectively promote the use of wind power, photovoltaic power generation and other renewable energy sources. In this paper, the multi-objective optimization problem is transformed into a single objective programming problem by using the deviation method; the optimal solution of multi-objective function is solved by using particle swarm optimization algorithm, so as to establish the planning scheme of micro-grid. Simulation results prove the correctness and feasibility of the optimization method.

1. Introduction

In 2016, the national development and Reform Commission deeply discussed the abandoning wind, abandoning light problem in the current reform of the energy supply side. The installed capacity and location of DG in micro-grid seriously affect the process of renewable energy integration. However, at present, the study of micro-grid mainly concentrated in the modelling of micro power, control strategy, etc. Static voltage stability of micro-grid and micro-grid planning areas lack some recognized and mature theory. Therefore, the research of micro-grid planning with static voltage stability and maximizing renewable energy utilization is of great significance, it can effectively promote the grid connection process of wind power and photovoltaic power generation. Some scholars have made some achievements, they are studied from three angles which are operation cost, reliability and safety, energy saving and environmental protection, but these results are the optimization programs with a single indicator. A multi-objective optimization model of island micro-grid with seawater desalination load is established in reference [1], but the load is limited and the model is ideal. A multi-objective optimization model of composite energy storage is established in reference [2], this model has three advantages, which are the lowest cost of the device, the best power matching and renewable energy output power is smooth, but the object is stored energy rather than the micro-grid. A multi-objective optimization model to determine the system capacity and location of DG is established in reference
[3], this model has three advantages, which are the maximum DG active output, the minimum investment cost, and the minimum network loss, but its research object is the smart grid rather than the micro-grid.

This paper establishes a multi-objective model of DG planning, based on the reliability, economy and environmental protection. The objective function consists of three sub optimal targets, which are renewable energy utilization, static voltage stability of micro-grid and the DG investment cost considering environmental benefits. Deviation sorting method is used to convert the three dimensional different sub-goals into single objective programming, and then the particle swarm optimization algorithm is used to solve the optimal solution.

2. Multi-objective optimization model

In this paper, the typical micro-grid example [4] is shown in Figure 1, including wind power generation system, photovoltaic power generation system, battery, fuel cell and other DG. Among them, the photovoltaic arrays, wind turbines and batteries access the AC bus through the inverter. The load consists of uncontrollable load, transferring load and interruptible load.

![Example system of low voltage micro-grid](image)

**Figure 1.** Example system of low voltage micro-grid

2.1. Maximizing renewable energy utilization

At present, under double pressures of energy demand and the electric power development, renewable energy has become a new direction of the development of electric power. Taking into account the economic operation of micro-grid, it is important to accelerate the development of wind power and photovoltaic grid connected process. Maximizing renewable energy utilization is become a key target of micro-grid. Based on the above considerations, the objective function of maximizing the DG installed capacity is:

\[
\min f_1 = \min \left( \sum_{i=1}^{m} \lambda_i S_{DG_i} \right)
\]

Where \(\lambda_i\) is power factor of DG; \(m\) is the total number of the DG which had accessed to micro-grid; \(S_{DG_i}\) is the capacity of DG.

2.2. Maximizing static voltage stability margin

The access position and capacity of DG change the power flow of the micro-grid, increase flow of branch power flow when DG injection capacity is too large. Therefore, the different location and
capacity of DG accessing to micro-grid will affect the power flow. This article adopts the method based on existence of the power flow [5] to quantify the index of the micro-grid static voltage stability.

\[ L_{ij} = 4((P_jX_{ji} - Q_jR_j)^2 + (P_jR_j + Q_jX_{ji})U_i^2)/U_i^4 \]  

(2)

Where \( L_{ij} \) is the static voltage stability index of any one branch; \( P_j \) and \( Q_j \) respectively represent active power and reactive power of node \( j \); \( R_j \) and \( X_{ji} \) respectively represent the resistance and reactance; \( U_i \) is the first voltage amplitude.

For the micro-grid, the voltage stability index \( L \) is defined as the maximum value of all branch voltage stability indices,

\[ L = \max \{ L_{ij} \} \]

(3)

The largest branch \( L_{ij} \) is the branch with the weakest voltage stability. The static voltage stability of micro-grid requirements the value of \( L \) must be less than 1.0. Therefore, the voltage stability margin can be defined as the distance between the value of \( L \) and the critical value 1.0, to determine the stability of the system voltage. The objective function is

\[ \min f_2 = \min L \]

(4)

2.3. Minimum DG investment cost

Renewable energy power generation technology is aroused more and more attention, one of the most important reasons is that DG is environmental friendly. Therefore, besides the capital, the environmental benefits must be considered, when calculating the costs of electricity production. The cost of DG considering the environmental is [6]

\[ C_h = \sum_{i=1}^{n_{DG}} \alpha_i \{ (r(1 + r)^n) \left( \frac{C_{ac,i}}{87.6k} \right) + C_{OM,i} + C_f + C_e \} \]

(5)

Where \( \alpha_i \) is the ratio of DG in the total average energy. \( n_i \) is the payback period, generally equal to the life of the device; \( C_{ac,i} \) is the installation cost; \( C_{OM,i} \) is the operation and maintenance cost; \( r \) is a fixed annual rate; \( C_f \) is the cost of the unit power utilization, when the fuel does not need to buy, this is zero.

The function \( f_3 \) of DG investment costs is as follows:

\[ \min f_3 = \min \sum_{i=1}^{n_{DG}} C_h * P_{rati} \]

(6)

Where \( C_h \) takes into account the DG costs of the environmental, \( n_{DG} \) is the total number of nodes of DG, \( P_{rati} \) is the rated capacity of the DG.

2.4. Constraint conditions

Constraint conditions include equality constraints and inequality constraints. Equality constraints are power balance. Inequality constraints include node voltage and the maximum limit of branch power.

\[
\begin{align*}
V_{min} \leq V \leq V_{max} \\
P_{rati} \leq P_{lmax} \\
P_{PV,i} + P_{W,i} + P_{ac,i} = P_{L,i}
\end{align*}
\]

(7)

2.5. Processing of multi-objective function

The linear weighted method is used to aggregate multiple objective functions as a single objective function. In this paper, the objective function of complex multi-objective aggregation is:
\[
\min f(x) = \lambda_1 f_1 + \lambda_2 f_2 + \lambda_3 f_3 \\
\text{s.t. } x \in X
\]  

The weight coefficients \( \lambda_i \) of the formula (9) is determined according to the deviation sorting method. The deviation of a certain objective function is described by the difference between the function value of the DG with different capacities and the optimal value. Its expression is:

\[
\delta_{ij}^f = f_{ij}^f - f_{i,j} \quad i,j = 1,2,\ldots,m
\]

\( m \) is the number of targets; \( f_{ij}^f = f_i(x_j) \), is the objective function fitness value when DG takes different configuration.

3. Solving method

At present, the planning problem sets the least cost and system network loss as the goal, the artificial intelligence algorithm can improve computing speed and convergence of this planning problem. So the artificial intelligence algorithm is widely used in the power system planning problem. In this paper, particle swarm optimization algorithm is used to solve the multi-objective optimization problem. Particle updated their location \( x_{id} \) and speed \( v_{id} \) by formula (13).

\[
\begin{align*}
    v_{id} &= w v_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (P_{gd} - x_{id}) \\
    x_{id} &= x_{id} + v_{id}
\end{align*}
\]  

Where, \( c_1 \) and \( c_2 \) are constant acceleration. According to the method in reference [7], \( c_1 = 2.8, \ c_2 = 1.3 \). \( p_{id} \) is its own optimal position, \( P_{gd} \) is the global optimal position. \( r_1 \) and \( r_2 \) are uniformity random numbers in the \([0,1]\). \( w \) is the coefficient to maintain the original speed, takes 0.4.

4. Simulation results

This paper adopts the typical example system of low voltage micro-grid, system voltage is 400V, the main feeders are \( L_2-L_3, L_3-L_4, L_6-L_7, L_8-L_9 \ldots L_{111-L_{12}} \), each feeder is the LJ_95 type wire which length is 50m, wire parameters are shown in Table 2. \( L_2-L_{13}, L_3-L_{14}, L_5-L_{15}, L_7-L_{16}, L_8-L_{17}, L_{111-L_{18}}, L_{12-L_{19}} \), each feeder is the LJ_70 type wire, the specific lengths are shown in Figure 1, wire parameters are shown in Table 1. Types of DG in micro-grid, rated active power and power factor are shown in Table 2. DG installation node set is \{L_{14}, L_{16}, L_{17}, L_{18}, L_{19}\}. The amplitude of each node voltage \( V_{\min} \) is 0.94, \( V_{\max} \) is 1.06. The number of particle swarm is 500, and the iteration number is 100.

**Table 1.** Parameters of low voltage micro-grid.

| line type | R1  | X1  | R0  | X0  |
|-----------|-----|-----|-----|-----|
|           | Ω/km | Ω/km | Ω/km | Ω/km |
| LJ_95     | 0.340 | 0.311 | 0.544 | 0.498 |
| LJ_70     | 0.46  | 0.318 | 0.736 | 0.509 |

**Table 2.** DG’s configuration parameters

| DG            | Maximum capacity/kVA | Output active power/kW |
|---------------|-----------------------|------------------------|
| Photovoltaic cells | 30                    | 20.4                   |
| wind turbine  | 12                    | 10.0                   |
| fuel cell     | 10                    | 10.0                   |
| battery       | 30                    | Active power is not output when connected to the grid |
Table 3 shows the results of the single objective and multi-objective optimization. Among them, scheme 1 is the optimization result of DG investment cost with maximum renewable energy utilization; Scheme 2 is the optimization result of DG investment cost when micro-grid voltage is stable; scheme 3 is the optimization result of DG investment cost considering environmental benefits. Scheme 4 is the multi-objective optimization results combining three single targets.

**Table 3.** Single objective and multi-objective optimization results

| planning scheme | Planning results | DG’s capacity (MW) | Static voltage stability margin L | Investment cost (/yuan/kwh) |
|-----------------|------------------|--------------------|----------------------------------|-----------------------------|
| 1               | L14(30kW),L16(20.1kW),L17(28.3kW), L18(10kW),L19(9.2kW) | 0.08395            | 1.066                            | 1.37                        |
| 2               | L14(14.9kW),L17(7kW),L18(1.4kW), L19(4.3kW)          | 0.03318            | 0.551                            | 1.24                        |
| 3               | L14(30kW),L16(2kW),L17(20kW), L18(10kW),L19(7.1kW)  | 0.05996            | 0.873                            | 0.93                        |
| 4               | L14(28.4kW),L16(19.6kW),L17(27.3kW), L18(9.4kW),L19(10kW) | 0.08066            | 0.644                            | 1.02                        |

Note: In the results of the planning, figures outside the bracket indicate the bus numbers when installing DG after optimization, the figures in brackets indicate the optimal installation capacity.

Compared the four schemes in Table 3, the DG capacity requirements are different under different targets. The renewable energy utilization of scheme 1 is the largest, but it is largely at the expense of static voltage stability and investment cost. The static voltage stability of scheme 2 is best, but the scheme did not reach the requirement of maximization of renewable energy utilization, economy is not cost-effective. The investment cost of scheme 3 is minimum, this scheme only reached the economy, but did not consider the objective of maximizing renewable energy utilization, and it is at the expense of the static voltage stability. In scheme 4, renewable energy consumptive capacity is not the biggest, static voltage stability is not the best, investment cost is not the lowest. But the scheme 4 is a combination of these three cases, it makes the renewable energy utilization to maximize, and takes into account the economic problems and micro-grid static voltage is stable, thus obtains a best result.

**Table 4.** The system voltage which before and after the optimization configuration of distributed generation

| Node number | Pre configuration voltage(p.u.) | Post configuration voltage (p.u.) |
|-------------|---------------------------------|----------------------------------|
| 1           | 1.033                           | 1.010                            |
| 2           | 0.996                           | 1.002                            |
| 3           | 0.943                           | 0.964                            |
| 4           | 0.954                           | 0.978                            |
| 5           | 0.947                           | 0.944                            |
| 6           | 0.913                           | 0.935                            |
| 7           | 0.927                           | 0.927                            |
| 8           | 0.956                           | 0.966                            |
| 9           | 0.915                           | 0.935                            |
| 10          | 0.936                           | 0.927                            |
| 11          | 0.913                           | 0.916                            |
| 12          | 0.966                           | 1.01                             |
| 13          | 0.973                           | 0.988                            |
| 14          | 1.000                           | 1.00                             |

Before configuring the DG, the system node voltage level is generally low, there are more than one node voltages beyond the limit, and the operation state of the system is not reasonable, as Table 4
shows. After configuring the DG, the voltage offset of the system has been reduced a lot, and the voltage distribution of the system node is reasonable. Therefore, the reasonable allocation of DG can effectively improve the voltage level of the micro-grid.

5. Conclusion
In this paper, based on the typical micro-grid calculation system, a multi-objective optimization model is established. It takes into account the economy, reliability and environmental protection of the micro-grid. This model has three advantages, which are the largest renewable energy utilization, static voltage stability of micro-grid and the minimum cost of DG investment considering environmental benefits. The particle swarm algorithm is used to solve the optimal DG installation location and capacity. The multi-objective model of DG planning can effectively coordinate the relationship among different objectives, it obtains a maximum renewable energy utilization, economic balance and static voltage of micro-grid stability, and meets the requirements of the designers of the DG planning. The simulation shows that the optimization scheme proposed in this paper has certain advantages. The scheme has reached the requirement of maximizing the renewable energy utilization in the premise of static voltage stability.

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