An Optimal Droop Control Method of DC Micro-grid with Local Loads

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Abstract. An optimal droop control optimization method is proposed of the DC micro-grid. First, a modeling of the DC micro-grid is made based on the idea of model equivalence. And then, the traditional particle swarm optimization (PSO) is improved by introducing adaptive learning factors and inertial weights. Finally, based on the improved PSO algorithm, the droop parameters are optimized to optimize the system performance. The simulation results show that even under the dual effects of line impedance and local load, the system can still achieve a high accuracy of current sharing and has a significant suppression effect on the bus voltage deviation.

1. Introduction

So far, the distributed energies based on clean energies have been widely used. To solve the problem of the reliable network access, a micro-grid has been proposed as an optimal solution. A DC micro-grid has many advantages over an AC micro-grid, and it has become the hot research topics.

The main objectives of DC micro-grid operation control is to reasonably distribute the output power among the distributed power sources so as to maintain the balance of system energy supply demand [1]. A droop control, as a way to realize control tasks without communication network, has gradually become the most important control means. However, when the traditional droop control method is faced with the system with line impedance not to be ignored, the effect of these line parameters on the power distribution of the converter cannot be treated, and there is no effective compensation method for the bus voltage deviation caused by droop coefficient, and when the system is added with local load, these effects will be further deepened [2]. For this reason, many scholars have put forward a variety of solutions, mainly divided into three categories:

a) The adjustment methods of the droop coefficients in the control structure to enhance the accuracy of current sharing. For example, the droop coefficient compensation method based on output virtual impedance in [3-4], by which the load current sharing deviation caused by line imbalance can be compensated.

b) The longitudinal intercept compensation methods based on the relationship between voltage and current. For example, the secondary compensation strategy of droop control based on average voltage and current method in [5-7].

c) The other new types of droop control strategy. [8] Proposes a droop control strategy of High-Order Current-DC voltage with flexible droop coefficients. The improved droop control strategies based on fuzzy algorithm and consistency algorithm have been proposed in [9-11].

There are some problems in the above methods, such as no consideration of the impact of local load
on the system, too much dependence on the stability of communication system, complex control mode and low control accuracy. In this paper, a multi-source DC micro-grid system with local load is established firstly, and considering the influence of line impedance on power distribution of converter, a more compatible control strategy with droop control mode is found to regulate the output of converter and control the bus voltage at rated value.

2. Modelling of DC Micro-Grid

2.1. The rules of current sharing in converter

The DC micro-grid consists of a DC bus, a grid-connected inverter and n DG units, as shown in Fig.1.

\[ U_{dc_{\text{ref}}} = U_0 - R_d I \]  \hspace{1cm} (1)

Where \( U_{dc_{\text{ref}}} \) represents the reference value of output voltage of each converter, which determines the dynamic output voltage of DG unit in the system, \( U_0 \) is the expected value of bus voltage, \( I_0 \) is the output current of the converter, \( R_d \) is the droop coefficient, which can be expressed as the equivalent resistance at the outlet of the converter. In DC micro-grid, \( U-I \) double closed-loop control is generally adopted for the control mode of each converter, and droop control is used as the outer loop of double closed-loop control.

The droop control makes the output of the converter according to the required droop curve, in which the droop coefficient meets the constraints of Eq. (2).

\[ R_d \leq \frac{\Delta U_{\text{max}}}{I_{\text{maxj}}} \]  \hspace{1cm} (2)

Where, \( \Delta U_{\text{max}} \) is the maximum allowable voltage deviation of the DC bus, and \( I_{\text{maxj}} \) is the maximum output current of the \( j \)th converter. In principle, the converter needs to distribute the output current in proportion according to its rated capacity, otherwise the relative current distribution error will occur. The DC micro-grid equivalent model in Fig.2 is used to illustrate, where, \( R_d (j=1,2,\ldots,n) \) is the line resistance; \( R_{\text{load}} \) is the...
Equi-value resistance of the load; $U_j$ is the power supply voltage in the inner loop. Assume that the actual bus voltage is $U_{dc}$, the relationship between each DG parameter and the line parameter is shown in Eq. (3).

$$I_{oj} = \frac{U_j - U_{dc}}{R_{dj} + R_{Lj}} = \frac{U_{dc, \text{refj}} - U_{dc}}{R_{Lj}} \quad (3)$$

In actual situations, $R_L$ cannot be ignored, and the output relationship between any 2-DGs can be obtained by solving simultaneous equations consisting of Eq. (3) and Eq. (1).

$$\frac{I_{oi}}{I_{oj}} = \frac{R_{dj} + R_{Lj}}{R_{di} + R_{Li}} = k^* \quad (4)$$

Eq. (4) is the matching relation that $R_{Lj}$ should satisfy, where $i, j=1, 2, \ldots, n, i \neq j$. Eq. (4) shows that if “$R_d + R_L$” does not meet the above $k^*$ relation, the relative current sharing error will be generated:

$$\Delta I_{o_{ij}} = \left| \frac{I_{oi}}{I_{oj}} - \frac{R_{dj} + R_{Lj}}{R_{di} + R_{Li}} \right| \quad (5)$$

Therefore, the basic idea of the integrated droop control is to adjust $R_{dj}$ to make $R_d + R_L / R_{di} + R_{Li}$ meet the proportion $k^*$ to eliminate the current sharing error, and adjust $U_{oj}$ to change the $U_{dc, \text{refj}}$ to compensate the bus voltage deviation.

### 2.2. Equivalence of the local loads

The DC micro-grid model of 4-DGs with local load is shown in Fig.3. Where, $R_{nj} (j = 1, 2, 3, 4)$ respectively represent the local load of each distributed structure.
In order to simplify the analysis process of the impact of $R_{BJ}$ on the system, an equivalent method is proposed. The main idea of the equivalence is to use the principle that the power consumed on the line before and after equivalence is constant, which is shown in Fig.4.

Move $R_B$ to the common load side, and parallel with the common load to the DC bus in the same form. It can be seen from Fig.4 that the equivalent resistance on the line is changed from $R_{Lj}$ to $R_{eq}$ after the equivalence, $U_{dc,refj}$ and $U_{dc}$ remains unchanged in the equivalent process. At this point, the power consumed on the line can be expressed as:

$$P_{R_{eq}} = \frac{(U_{dc} - U_{dc,refj})^2}{R_{Lj}}$$

Of which:

$$P_{R_{eq}} = P_{oj} - P_{Bj}, \quad P_{R_{eq}} = P_{oj}$$

$$I_{Bj} = \frac{R_{Lj} + R_{load}}{R_{Lj} + R_{Bj} + R_{load}} I_{oj}$$

$$U_{Bj} = U_{dc,refj}$$
By combining Eq. (6), Eq. (7) and Eq. (8), the relationship between $R_{Lj}$ and $R_{eq}^{Lj}$ can be obtained:

$$R_{eq}^{Lj} = \frac{R_{Bj} R_{Lj}}{R_{Lj} + R_{Bj} + R_{load}}$$  (9)

Eq. (9) satisfies the new matching relationship Eq. (10).

$$\frac{I_{ol}}{I_{oj}} = \frac{R_{dj} + R_{eq}^{Lj}}{R_{di} + R_{eq}^{Lj}} = k^*_B$$  (10)

The purpose of the equivalence rule is to better quantify all the relevant resistance values into $R_{linej}^{eq}$, which can be represented by Eq. (11):

$$R_{linej}^{eq} = R_{Lj} + R_{dj}$$  (11)

The resulting bus voltage deviation $\Delta U$ can be expressed as:

$$\Delta U = I_{oj} R_{linej}^{eq}$$  (12)

### 3. Optimization of Droop Control for DC Micro-Grid

#### 3.1. Improvement of PSO

It is well known that the D-dimensional search equation of PSO can be expressed as:

$$V_{D}^{M+1} = w V_{D}^{M} + c_{1} r_{1}(P_{D}^{M} - X_{D}^{M}) + c_{2} r_{2}(G_{D}^{M} - X_{D}^{M})$$  (13)

$$X_{D}^{M+1} = X_{D}^{M} + V_{D}^{M+1}$$  (14)

where $D$ and $M$ respectively represent the dimension of the particle and its number of iterations; $V_{D}^{M} = (V_{D}^{1}, V_{D}^{2}, ..., V_{D}^{M})$ and $X_{D}^{M} = (X_{D}^{1}, X_{D}^{2}, ..., X_{D}^{M})$ respectively represent the velocity and position of the particle; $w$ is the inertia weight; $c_{1}$ and $c_{2}$ correspond to the learning factors of the individual particles and groups, which are constants; $r_{1}$ and $r_{2}$ are the random numbers in the interval of [0,1], and $P_{D}^{M}$ and $G_{D}^{M}$ are the optimal values of the individual particles and the entire population of particles.

The search performance of PSO depends on the parameter selection of the algorithm to a great extent, among which the parameters that have the most profound impact on the performance include $c_{1}$, $c_{2}$ and $w$. The traditional PSO method with fixed parameters does not have advantages in solving slightly complex problems, this study will take different strategies for $c_{1}$, $c_{2}$ and $w$ respectively. The parameter selection strategy proposed in this paper is shown in Eq. (15).
\[
\begin{align*}
C_1 &= (C_{1\text{foot}} - C_{1\text{init}}) \frac{T}{T_{\text{max}}} + C_{1\text{init}} \\
C_2 &= (C_{2\text{foot}} - C_{2\text{init}}) \frac{T}{T_{\text{max}}} + C_{2\text{init}} \\
W &= (W_{\text{foot}} - W_{\text{init}}) \frac{T}{T_{\text{max}}} + W_{\text{init}}
\end{align*}
\]

(15)

Where, \(C_{1\text{foot}}, C_{1\text{init}}, C_{2\text{foot}}, C_{2\text{init}}, W_{\text{foot}}\) and \(W_{\text{init}}\) respectively represent the initial and final values of each parameter. \(T\) and \(T_{\text{max}}\) respectively represents the current iteration number and the maximum number of iterations. Eq. (15) shows that the value of \(c_1\) and \(c_2\) depend on the initial and final values set, and they vary with the number of iterations.

### 3.2 Droop control strategy for DC micro-grid

By using the excellent characteristics of PSO in searching function extremum and the basic idea of droop control, two important droop parameters \(R_d\) and \(U_0\) can be used to form current error function and bus voltage deviation sub function in the form of function variable, and then the above sub function can be used to form the objective function \(F_t\). In this way, the problem of parameter adjustment of droop control is transformed into the problem of function extremum optimization, which gives full play to the common characteristics of PSO and droop control. In the optimization of droop parameters, the aim is to find the minimum value of \(F_t\), and the droop parameter corresponding to the minimum value is the best droop parameter. For 4-DGs system, \(R_d\) and \(U_0\) can form 8-Dimensional matrix together:

\[
R_{d1}, R_{d2}, R_{d3}, R_{d4}, U_{01}, U_{02}, U_{03}, U_{04}
\]

Where \(n\) represents the number of particles. The 8-Dimensional matrix means that every particle has 8-D, and \(R_{d1}, U_{01}, R_{d2}, U_{02}, R_{d3}, U_{03}, R_{d4}, U_{04}\) respectively correspond to the droop parameters of DG1 ~ DG4. Based on the 4-DGs DC system in Fig.3, the output current error sub term of the converter can be expressed as:

a) The current sharing error function can be defined as:

\[
I_{\text{error}} = \sum_{j=1}^{n} \sqrt{(I_{oj} - I_{o\text{ave}})^2}
\]

(16)

Where \(I_{o\text{ave}}\) is the average value of the output current of all the converters. Eq. (16) is established under the condition that the capacity of each DG unit is the same, otherwise, the relative current distribution error relationship Eq. (5) shall be followed. In the above two formulas, \(I_{oj}\) can be calculated by KVL and KCL, which as shown in formula (17):

\[
U_j = R_{\text{linej}}^{eq} I_{oj} + I_L R_{\text{loadj}}^{eq}
\]

\[
R_{\text{loadj}}^{eq} = R_{\text{loadj}} / / R_{B1} / / R_{B2} / / R_{B3} / / R_{B4}
\]

\[
I_L = \sum_{j=1}^{4} I_{oj}
\]

(17)
b) The bus voltage deviation can be defined as:

$$U_{\text{error}} = \sqrt{\left(U_N - \frac{1}{4} \sum_{j=1}^{4} (U_{\text{j}} - \Delta U)\right)^2}$$  \hspace{1cm} (18)

Where $U_N$ is the bus voltage rating which is preset, $U_{\text{error}}$ indicates the degree of the deviation of the bus voltage from $U_N$ and determines the voltage that each DG needs to compensate.

At this point, the objective function can be designed in the form of a weighted sum:

$$F_i(R_{\text{dn}}, U_{\text{en}}) = w_i I_{\text{error}} + w_u U_{\text{error}}$$  \hspace{1cm} (19)

$w_i$ and $w_u$ respectively correspond to the weights of each error term. Their values determine the functional preferences implemented by the objective function. Considering the influence of many system variables on the accuracy of current sharing of the converter, this paper takes current sharing of the converter as the primary control task from the perspective of improving the reliability of equipment operation, therefore, the weight coefficients are set as $w_i > w_u$.

4. Simulation and Comparison of Results

In order to verify the effectiveness and real-time performance of the proposed control strategy, the simulation platform of the low-voltage DC micro-grid is constructed as shown in Fig.3. The simulation is divided into two stages. In the first stage, the improved PSO is compared with the traditional PSO. In the second stage, the effectiveness and real-time performance of the proposed droop control strategy is mainly verified. The comparison object is the classical droop control method based on PI regulation in [12]. In the process of the simulation, the current sharing accuracy and bus voltage deviation suppression accuracy are used as two important reference indexes to measure the advantages and disadvantages of the proposed method.

4.1. CASE I

The parameter settings of the system model are shown in Tab 1. The optimal algorithm parameters corresponding to the improved PSO and the traditional PSO are shown in Tab 2, the other basic algorithm parameters are set as: $n=100$, $M_{\text{max}}=100$, $w_u=0.4$, and $w_0=0.1$. Under such a condition of these parameters, the optimal solutions based on the improved PSO and traditional PSO have been obtained, and the corresponding results are shown in Tab 3. Fig.5 shows the comparison of the iterative processes for finding the optimum droop parameters based on them.

It can be seen from Fig.5 that the improved PSO has a $F_i$ approaching 0 after about 50 generations, while the traditional PSO convergence process is much slower, and it can be found that its search process is more likely to fall into local extremum during repeated simulations.

| Parameter                        | Symbol | Value | Unit |
|----------------------------------|--------|-------|------|
| DC Bus Voltage                   | $U_N$  | 400   | V    |
| Power Level Of Converters        | (DG1–DG4) | 28   | kW   |
| Line Resistance                  | $R_{L1}$ | 0.2  | Ω    |
|                                  | $R_{L2}$ | 0.3  |      |
|                                  | $R_{L3}$ | 0.35 |      |
|                                  | $R_{L4}$ | 0.5  |      |
| Local Resistance                 | $R_{L1}$ | 12   |      |
|                                  | $R_{L2}$ | 15   |      |
|                                  | $R_{L3}$ | 16   |      |
|                                  | $R_{L4}$ | 18   |      |
| Public Load                      | $R_{\text{load}}$ | 15.32 | Ω    |
| Total Load Power                 | $P_{\text{load}}$ | 53   | kW   |
| Switching Frequency              | $f_s$  | 30    | kHz  |
Figure 5. Comparison of iterative processes for finding the optimum droop parameters with traditional PSO and improved PSO

Through the comparison of $F_t$, it can be concluded that the improved PSO is much higher than the traditional PSO in terms of convergence accuracy; in terms of program running speed, the improved PSO is also faster than the traditional one.

Table 2. Optimal Algorithm Parameters

| Parameter     | Improved PSO | Traditional PSO |
|---------------|--------------|-----------------|
| $c_{1\_init}$ | 0.389        | $c_1$ = 0.415   |
| $c_{1\_foot}$ | 1.075        |                 |
| $c_{2\_init}$ | 1.205        | $c_2$ = 0.980   |
| $c_{2\_foot}$ | 0.210        |                 |

| Inertia weight | $w_{\_init}$ = 0.5 | $w$ = 0.400 |
|----------------|---------------------|-------------|
|                | $w_{\_foot}$ = 0.2  |             |

Table 3. Comparison of Simulation Results

| Parameter                  | Improved PSO | Traditional PSO |
|----------------------------|--------------|-----------------|
| Optimal objective          | 0.0311       | 0.2037          |
| function value              |              |                 |
| Simulation time (sec)       | 1.5740       | 2.1844          |

4.2. CASE 2
The advantages of the improved PSO proposed in this paper have been verified in CASE 1. When $F_t$ reaches the global optimal value of 0.0311, the corresponding optimal droop parameters are shown in Tab 4.
Table 4. List of the Optimal Droop Parameters

| The best droop parameters found by improved PSO | Converter |
|-----------------------------------------------|-----------|
| $R_{d1}=0.1788 \Omega, U_{05}=409.7521 \text{V}$ | DG1       |
| $R_{d2}=0.1191 \Omega, U_{06}=409.7381 \text{V}$ | DG2       |
| $R_{d3}=0.0897 \Omega, U_{07}=409.7349 \text{V}$ | DG3       |
| $R_{d4}=0.0001 \Omega, U_{08}=409.7329 \text{V}$ | DG4       |

By transmitting these parameters to the SIMULINK model for droop control of each unit. The results are shown in Fig.6 and Fig.7. Fig.6 is shown the output current and $I_{\text{error}}$ obtained by the droop control based on the improved PSO, and Fig.7 is shown the actual DC bus voltage $U_{dc}$ and its deviation value $\Delta U$ in the corresponding case. In this example, the sampling time of the system is 0.35s. According to the above analysis, under the condition that the rated capacity of each DG unit is the same, that is, the output current of each unit tends to be the same. It can be seen that the current sharing error $I_{\text{error}}$ is reduced to $4 \times 10^{-3}$ A, and $U_{dc}$ can be ensured to stably operate near the set nominal value. The above results indicate that the droop control based on improved PSO can accomplish the task of current sharing and greatly reduce the bus voltage deviation at the same time well.

![Figure 6. Comparison of output current of each converter](image)

![Figure 7. Comparison of real-time voltage of DC bus](image)

Then, the load power changes are shown in Tab 5, the total load power increases and each DG unit is close to fully loaded.

After running the improved PSO program, the following iteration diagram is obtained in Fig.8. The droop parameters corresponding to $F_{t}=0.0371$ are determined as $R_{d1}=0.0999 \Omega, U_{05}=408.3671 \text{V}$; $R_{d2}=0.0882 \Omega, U_{06}=408.6018 \text{V}$; $R_{d3}=0.0962 \Omega, U_{07}=408.4105 \text{V}$; $R_{d4}=0.0854 \Omega, U_{08}=408.4098 \text{V}$. 
Table 5. The Variation Table of System Parameters

| Parameter       | Symbol | Range   | Unit |
|-----------------|--------|---------|------|
| Local Resistance| $R_{b1}$| 12 → 8  |      |
| Local Resistance| $R_{b2}$| 15 → 8  |      |
| Local Resistance| $R_{b3}$| 16 → 5  | Ω    |
| Local Resistance| $R_{b4}$| 18 → 5  |      |
| Public Load     | $R_{load}$| 15.32 → 60 |      |

Total Load Power $P_{load}$ 107 kW

Simulation time when data is abrupt: 0.4s

Figure 8. Iterative process of droop control for improved PSO with increased load

These parameters are inputted into the Simulink model for simulation, and the results are compared with the simulation results of the droop control based on PI adjustment, the comparison results are shown in Fig.9 and Fig.10.

Figure 9. Comparison of output current of each converter
The sampling time of both the images is 0.8s and the load power suddenly increases from 53kW to 107kW at 0.4s. It can be seen from Fig.9(a) that even if the loads suddenly change at 0.4s, the droop control based on the improved PSO can still accurately control the output current of each converter so that they continue to approach the same, and $I_{error}$ is reduced to $5 \times 10^{-3}$A. At the same time, it can be seen from Fig.10 (a) that the bus voltage can be maintained at 400V after the loads suddenly change, and $\Delta U$ can almost be negligible; Fig.9 (b) and Fig.10 (b) respectively show the current sharing and the bus voltage control effect of the droop control based on PI adjustment. It can be clearly seen that $I_{error}$ reaches $2 \times 10^{-2}$A under this method, therefore, the accuracy of current sharing is slightly inferior to the result obtained by the method proposed in this paper. In term of bus voltage deviation suppression, $\Delta U$ reaches 4V after the loads mutation.

![Figure 10. Comparison of real-time voltage of DC bus](image)

Although the droop control based on PI adjustment can achieve 0-error current sharing and the suppression of bus voltage deviation effect in 2-DGs system in [12], it cannot achieve the best control effect in the system of Fig.3 due to the system static error, which is also proved that the proposed method in this paper has stronger adaptability.

It follows that no matter what the rated capacities of the 4-DGs are, as long as the output is distributed in terms of $B_k$, the relative error $I_{error}$ can be minimized. If the capacities of the 4-DGs differ from each other, one of the DGs only needs to be marked as the leading unit, which generally is the unit with the smallest capacity, and the capacities of the other 3-DGs are distributed according to the proportion $B_k$ with the leading unit.

5. Conclusion

This paper presents an optimal droop control method of the DC micro-grid with local loads. In the modeling aspect, a model equivalence method of local load is proposed. In the algorithm aspect, an improved PSO is proposed, which has higher convergence accuracy, faster running speed and better overall performance than the traditional PSO. In the control method aspect, a droop control method based on the proposed improved PSO. The system constructed based on the method is simple. The droop
parameters can be adaptively modified in real time. Even under the extreme conditions, the method can still achieve a high control accuracy. The method has a strong adaptability, and can be applied to the system with multiple control objectives.

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