Power Optimization Strategy of DC Microgrid Based on Droop Control

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Abstract. As an efficient way to consume new energy, DC microgrid has received extensive and international attention. However, the control of the DC microgrids has not taken into account the difference in operating cost of micro sources, resulting in low operating efficiency. Therefore, this paper establishes an economic model for the DC microgrid, with the goal of minimizing operating cost, the optimal operating condition of the system is solved. On this basis, a secondary power optimization control strategy is proposed. Based on the simulation platform, the feasibility of the proposed strategy is verified under different operating conditions. The results show that the proposed power optimization strategy can effectively reduce the system operating cost by about 1.49%.

Keywords: DC microgrid, droop control, power generation cost, secondary power control.

1. Introduction

As new energy power generation technologies continue to advance, microgrids have drawn a lot of interest as a practical way to consume new energy. Compared with the AC microgrids, DC microgrids are simpler to operate, less expensive, and have better controllability.

Micro-sources and energy storage units in the DC microgrid are connected to the DC bus through the converter [1]. The converter on the energy storage side usually adopts DC droop control, which can realize proportional distribution of power and has high reliability. Aiming to address the issues of randomness of photovoltaic and unreasonable power distribution, by using a nonlinear function to improve the traditional droop curve, an adaptive piecewise droop control was proposed in [2]. Combined with the characteristics of droop control, a general compensation approach was proposed in [3], which can adjust the parameters by the consistency and fuzzy algorithms to improve droop control. Considering the impact of battery State of Charge (SoC), an improved droop control was proposed in [4], which can effectively solve the impact of line impedance mismatch on current distribution accuracy by improving the droop coefficient. In order to achieve the charge balance, the operation mode of the DC microgrid is divided according to the state of the energy storage units and the load, on this basis, an improved droop control was proposed in [5] by using a low-speed communication network. As more and more distributed new energy generation units are connected to microgrids, in order to enhance the stability of DC bus voltage under disturbances, a virtual DC generator control strategy is proposed in [6, 7] by simulating the electromechanical characteristics of DC generators.

In addition, it is indicated in [8] that equipment loss, energy storage characteristics, investment cost, operation and maintenance cost, energy storage expenditure and other parameters are related to energy storage power generation costs. However, droop control does not take into account the cost of energy storage generation, resulting in negative effects such as low energy storage utilization, resource waste and equipment life loss. Therefore, in order to ensure the safe and reliable operation

of the system, the power flow of the dc microgrid must be optimized, and the cost of energy storage power generation must be considered.

Based on the characteristics of droop control of DC microgrid, the economic optimization model of DC microgrid is established, and the optimal conditions of power generation cost of DC microgrid are solved. On this basis, a secondary power optimization controller is designed. According to the output characteristics of the droop converter, the output power of the energy storage units is rationally allocated, which ensures the voltage stability of the DC bus and reduces the operating cost.

In Section II, the principle of DC droop control strategy is briefly introduced, and the power distribution relationship between converters in parallel system is analyzed. In Section III, the energy storage power generation cost model and the economic model of the DC microgrid are established, and a secondary power optimization controller is proposed. In Section IV, a simulation platform is built to verify the effect of the proposed control strategy. The entire paper is concluded in Section V.

2. The principle and characteristic analysis of droop control

This section briefly introduces the droop control strategy of DC microgrid, and analyzes the power distribution relationship between droop converters in detail.

2.1. The principle of DC droop control strategy

Droop control is a common method for converter in DC microgrid. The principle of Droop control strategy can be illustrated by the equivalent circuit shown in Fig.1. R_1 and R_2 are the output impedance equivalent to the droop coefficient. R_{line1} and R_{line2} are the line impedances connected to the DC bus. U_1 and U_2 are the voltage at both ends of the converter. U is the DC bus voltage, I_{oi} is the output current of the converter.

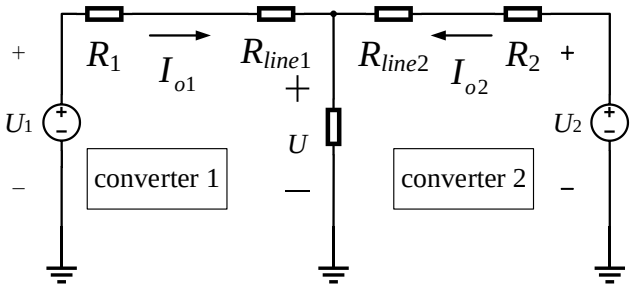


Figure 1. Equivalent DC droop circuit

According to Fig.1 and Kirchhoff 's voltage law, the relationship between the output current of converter 1 and converter 2 is shown in (1).

$$\frac{I_{o1}}{I_{o2}} = \frac{R_2 + R_{line2}}{R_1 + R_{line1}} \tag{1}$$

It can be seen from (1) that the power distribution between the converters and the deviation of the bus voltage are related to the output current of the converter. When a large R_i is selected, R_1 is much greater than R_{line1}, R_2 is much greater than R_{line2}, as shown in (2), a more precise power distribution can be obtained.

$$\frac{I_{o1}}{I_{o2}} \approx \frac{R_2}{R_1} \tag{2}$$

The above formula shows that by adjusting the droop coefficient, the influence caused by the line impedance can be effectively eliminated, so that the system can be flexibly adjusted according to the

characteristics and control requirements of the converter, and the controllability of the current distribution between converters can be realized. Power allocation can be achieved by adjusting the droop coefficient. Therefore, the droop control can be expressed as (3), which can make the system more reliable and less susceptible to external disturbances.

$$U_{oi} = U_{refi} - k_i(P_{refi} - P_{oi}) \tag{3}$$

Where, U_{oi} denotes the terminal voltage of the i-th converter, U_{refi} denotes the rated output voltage of the i-th converter, k_i denotes the droop coefficient of the i-th converter, P_{refi} denotes the given power of the i-th converter, and P_{oi} denotes the output power of the i-th converter.

2.2. Analysis of power distribution relationship between converters in parallel system

It can be seen from part A that the output power distribution between converters can be realized by droop control. However, when the droop coefficient is fixed, this power distribution relationship cannot be changed, and there are certain limitations. Therefore, as shown in (4), the introduction of compensation item ΔU can further adjust the power distribution relationship between Distributed Generations (DGs).

$$U_{oi} = U_{refi} - k_i(P_{refi} - P_{oi}) + \Delta U \tag{4}$$

The droop control strategy can adaptively adjust the output power of the DG according to changes in load to maintain power balance in the system. However, with a fixed droop coefficient, it is difficult to adjust the power distribution relationship between DGs. In order to achieve secondary power regulation between DGs under stable voltage, the droop characteristic can be increased from curve 1 to curve 2.

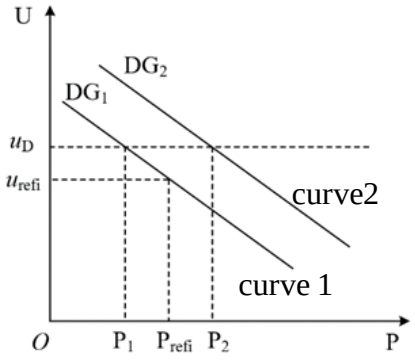


Figure 2. The characteristic of Droop Control

In short, the droop control strategy can achieve power distribution between converters by adjusting the droop curve. By introducing a compensation term, we can further adjust the power allocation relationship to achieve more accurate control, which can improve the flexibility and controllability of the DC microgrid system.

3. Proposed Control Structure

3.1. Energy storage power generation cost modeling

At present, the widely used energy storage devices are electrochemical energy storage and flywheel energy storage.

The essence of electrochemical energy storage is the electrochemical process of current flowing into the battery, through the electrode, electrolyte and electrolyte. Lithium battery energy storage has the characteristics of long life, high energy density and fast charging and discharging speed. Sodium-

ion battery energy storage has the characteristics of high power density, wide working temperature range and long cycle life. Unlike electrochemical energy storage, flywheel energy storage stores energy by physical means. When working, the flywheel is coordinated by a reversible two-way motor and a flywheel, and the flywheel is driven by electric power to rotate at a high speed, thereby converting electric energy into mechanical energy and storing it. It has the characteristics of green environmental protection, high energy efficiency and low operating cost.

Different types of energy storage have different output characteristics and output costs. According to [8], the cost coefficient of the *i*-th energy storage device in the system is defined as α_i, β_i, and γ_i. Therefore, the output cost C_i of the *i*-th energy storage can be uniformly expressed in the form of a quadratic function as shown in (5).

$$C_i(P_i) = \alpha_i P_i^2 + \beta_i P_i + \gamma_i \tag{5}$$

3.2. Economic modeling of the DC microgrid

Based on the analysis of the energy storage output cost, considering that there are *N* energy storage units in the DC microgrid, the overall operating cost C_i of the system is the lowest target, and the objective function shown in (6) can be established.

$$\min\ F = \sum_{i=1}^{N} \alpha_i P_i^2 + \beta_i P_i + \gamma_i \tag{6}$$

Considering that the cost of short-distance DC transmission is small, it is assumed that the output power of each energy storage is balanced with the load power, and the equality constraints shown in (7) can be obtained.

$$\sum_{i=1}^{n} P_i = P_{\text{Load}} \tag{7}$$

In addition, considering the upper limit $P_{i,\max}$ and lower limit $P_{i,\min}$ of the output of the *i*-th energy storage unit in each system, the inequality constraints shown in (8) can be obtained.

$$P_{i,\min} \le P_i \le P_{i,\max} \tag{8}$$

The comprehensive (6)-(8) can be used to construct the economic model of DC microgrid with multiple energy storage units. In order to simplify the analysis, the following DC microgrid composed of two energy storage units is taken as an example to derive the optimal economic operation conditions. Considering that the output of the energy storage unit does not exceed the limit, the Lagrangian function shown in (9) can be constructed.

$$\begin{aligned} G(x, y, z, \lambda) = {} & C_1(P_1) + C_2(P_2) \\ & + \lambda [C_1(P_1) + C_2(P_2) - P_{Load}] \end{aligned} \tag{9}$$

Where λ is the lagrangian multiplier.

According to the KKT condition, the partial derivative of the above formula can be obtained in (10).

$$\begin{cases} \dfrac{\partial G}{\partial P_1} = \dfrac{\partial C_1(P_1)}{\partial P_{G1}} - \lambda \\ \dfrac{\partial G}{\partial P_2} = \dfrac{\partial C_1(P_2)}{\partial P_2} - \lambda \\ \dfrac{\partial G}{\partial \lambda} = P_1 + P_2 - P_{\text{Load}} \end{cases} \tag{10}$$

When (10) is 0, and the simultaneous available (11) is the condition for the minimum operating cost of the system.

$$\frac{\partial C_1(P_1)}{\partial P_1} = \frac{\partial C_2(P_2)}{\partial P_2} = \lambda^* \tag{11}$$

Where λ^* is the optimal solution of the Lagrangian function.

Specifically, in a variety of DC microgrids with different power generation costs, λ^* can be expressed as (12).

$$\lambda^* = \frac{\partial C_i(P_i)}{\partial P_i} = 2\alpha_i P_i + \beta_i, i = 1, 2, \ldots, n \tag{12}$$

Combined with the power balance relationship shown in (7), (12) can be simplified to (13).

$$\lambda^* = \frac{P_{load} + \sum_{i=1}^{n} \frac{\beta_i}{2\alpha_i}}{\sum_{i=1}^{n} \frac{1}{2\alpha_i}} \tag{13}$$

By making the shadow price of each energy storage converter equal to λ^* in the operation process, the optimal economic control of the DC microgrid can be realized, and the operation cost can be reduced while ensuring the stable operation of the system.

3.3. Optimizing control

On the basis of the above analysis, the secondary economic control shown in (14) is introduced into the DC droop control.

$$\Delta U = G_{pi}(s)\square(\lambda_i - \lambda^*) \tag{14}$$

Where $G_{pi}(s) = k_p + k_i/s$ is the transfer function of PI controller, k_p is the proportional parameter and k_i is the integral parameter.

In summary, the secondary power optimization strategy based on droop control proposed in this paper is divided into power distribution control loop, droop loop, voltage loop, current loop and PWM generation loop. When for all λ_i, there is $\lambda_i = \lambda^*$, the power allocation strategy is considered to be optimal. The controller control system is shown in Fig.3.

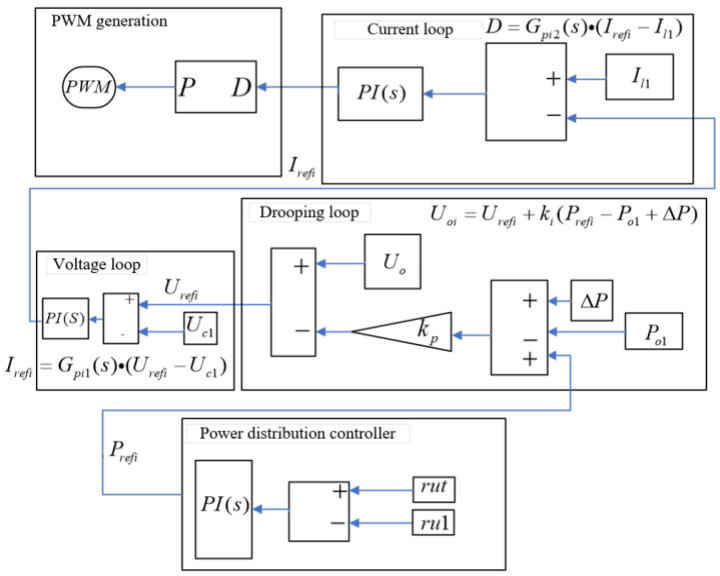


Figure 3. Control system block diagram

4. Simulation results

In this section, a simulation platform is built based on Matlab / Simulink. Under various operating conditions, the effectiveness of the power optimization strategy proposed in this paper is verified.

4.1. Simulation Environments and Systems

As shown in Fig.4, the system contains three distributed DC power supplies, and each energy storage converter on the DC side is connected to the DC bus of the DC microgrid through the line impedance Z_1、Z_2、Z_3. Three power supplies supply the load together.

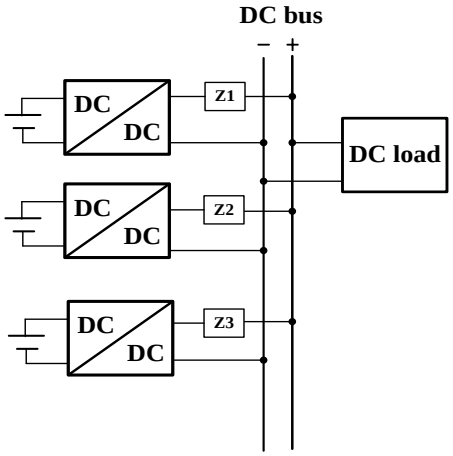


Figure 4. Simulation system

The rated voltage U_{ref} of the droop control link of the micro power supply is 230V, the droop coefficient K_P is 0.008, and the rated power P_{ref} is 500kW. The proportional parameter $k_{pv}=0.06$ and the integral parameter $k_{pi}=25$ of the PI controller in the voltage outer loop; the proportional parameter $k_{pi}=30$ and the integral parameter $k_{ii}=700$ of the PI controller in the inner current loop. The line impedance is set to 0.2Ω, and the rated value of DC bus voltage is 230V.

4.2. The effect of power optimization

The power optimization strategy is not used at $0\le t<1s$, as shown in Fig.5, the output power of each converter is 500kW. And the power ratio of the DC load output is 1:1:1. According to the structure of three DGs connected in parallel with the DC bus, the voltage of the three converters is 230V, and the fluctuation difference between them is very small and negligible.

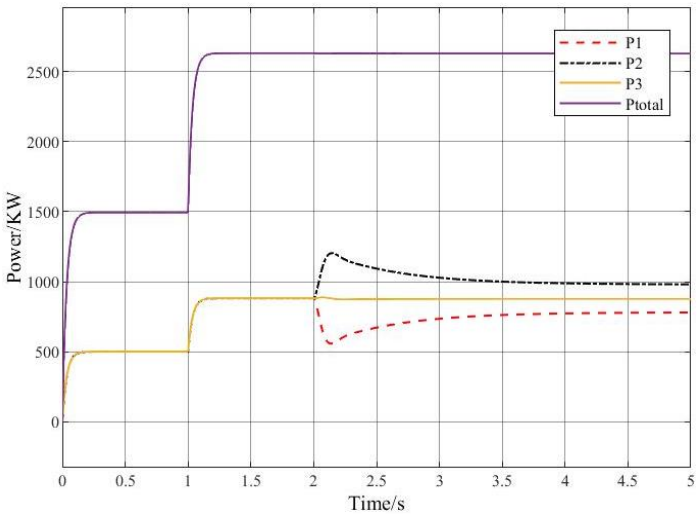


Figure 5. The output power of each converter

When the load is connected at $0 \le t < 1s$, the total active power of the whole system reaches 2628.9kW, and the output power of each converter increases and converges to 881.7kW, and the power ratio of the DC load output is also 1:1:1. Fig.6 is the economic coefficient diagram of the three converters, and the change of the shadow price of each converter in the simulation is drawn. As shown in Fig.6, the shadow price corresponding to each converter also increases. The shadow price of DG1, DG2 and DG3 increases from 95.35$/KW, 77.27$/KW and 86.14$/KW to 166.92$/KW, 133.63$/KW and 148.61$/KW, respectively.

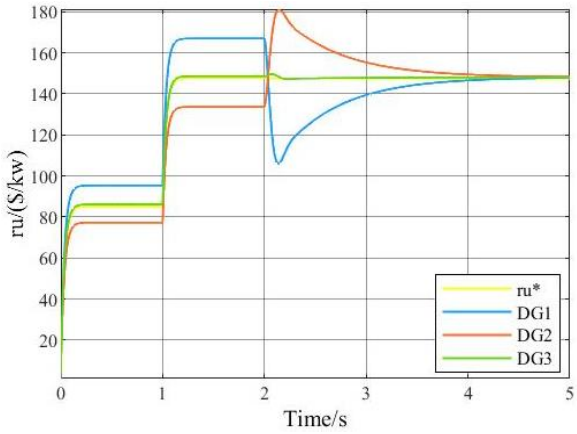


Figure 6. Economic coefficient diagram of each distributed unit

Due to the increase of system load, the DC bus voltage fluctuates from 229.5V to 227.8V as shown in Fig.7, and stabilizes at 229.2V after 0.2s.

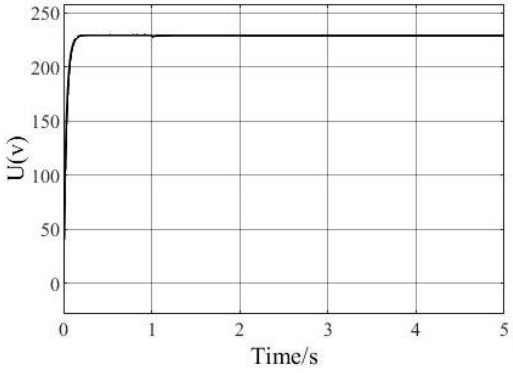


Figure 7. DC bus voltage

The power optimization strategy is adopted at $t = 2s$, so that the output power ratio of each converter to the DC load is changed from 1:1:1 to 29:38:33. The output power of the converter DG2 with smaller incremental cost of power generation increases, and the output power of the converter DG1 with larger incremental cost of power generation decreases. After 1.8s, the economic coefficient of each converter DG is convergent. It is calculated that only the droop control method is used when $1 \le t < 2$ seconds, and the cost of the whole system is 201809 $. At this time, the power generation cost of the whole system is minimized. The power optimization control is implemented after two seconds, and the entire system costs 198808$. Without taking into account the power restriction of micro-power generation, it can be concluded that implementing this power optimization approach can lower the cost by roughly 1.49%. At the same time, there is no large fluctuation of bus voltage, which verifies that the power optimization control method of DC microgrid based on droop control mentioned in this paper can effectively guarantee the stability of DC bus voltage.

5. Conclusion

In this paper, the power optimization problem of droop DC microgrid system is studied. Based on the economic model of DC microgrid, a secondary power optimization control method is proposed.

By dynamically adjusting the output power of each energy storage converter during operation, the shadow price is consistent to achieve system output cost optimization. The simulation results show that the proposed optimal control can reduce the operation cost and has little effect on the DC bus voltage.

References

[1] Hu Changling, Shi Junze. An adaptive droop control strategy for DC microgrid [J]. Electrical Technology, 2023, (08): 169-171.

[2] Liu Haoyang, Zhao Xingyong, Li Guijun, et al. Research on photovoltaic DC microgrid based on improved adaptive piecewise droop control [J]. Renewable energy, 2023, 41 (09): 1214-1221.

[3] Zhu Shanshan, Wang Fei, Guo Hui, et al. Review of DC microgrid droop control technology [J]. Chinese Journal of Electrical Engineering, 2018, 38 (01): 72-84.

[4] Yang, Zeng, He.Robust droop control method of DC microgrid energy storage unit based on SOC equalization [J]. Electricity, 2022, (11): 1-10.

[5] Wang Chao, Cao Wei, Zhang Xuhang, et al. A multi-energy storage operation method for DC microgrid with improved droop control [J]. Electrical drive, 2023, 53 (01): 74-80.

[6] Wang Zhengnan, Zhang Xinhui, Peng Ke, et al. Inertia damping adaptive virtual DC generator control strategy [J]. Electrical measurement and instrumentation, 1-7.

[7] T Morstyn, Savkin A-V, Hredzak B, et al. Multi-Agent Sliding Mode Control for State of Charge Balancing Between Battery Energy Storage Systems Distributed in a DC Microgrid [J]. IEEE TRANSACTIONS ON SMART GRID, 2018, 9 (5): 4735-4743.

[8] Gong Jingying.Research on operation control strategy of microgrid cluster based on consensus algorithm [D]. Shenyang University of Technology, 2023.