Research on Optimal Energy Storage Strategy Based on Consistency Algorithm

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Abstract. With the acceleration of globalization and economic development, the microgrid combining renewable energy generation, storage and load has become the unit controlling the entire system, through the autonomous microgrid cluster to more efficient, reliable and economical use of renewable energy to meet the multiple needs of the power system. This paper proposes a scheme to optimize energy storage strategy by using consistency algorithm. By improving sag control, optimizing energy storage unit design and adjusting SOC balance between the same/different capacities, the efficiency and stability of DC microgrid can be improved. The scheme can achieve SOC balance and voltage regulation, avoid voltage quality degradation, and improve the reliability and practicability of distributed energy storage system. In the simulation experiment, no matter the capacity of Distributed Energy Storage Unit(DESU) is the same or different, the energy storage state can be balanced and the output active power ratio can be maintained, which further verifies the feasibility and advantages of the scheme.

Keywords: Consistency algorithm, optimization of energy storage strategy, improvement of sag control, DC microgrid.

1. Introduction

With the acceleration of globalization and economic development, the industrialization system continues to expand and scale, and the demand for energy is also growing rapidly. At present, China still mainly relies on traditional primary energy sources such as coal and oil, and the depletion trend of these resources has been very obvious [1-3]. At the same time, China takes carbon peaking and carbon neutrality as important policy goals in the context of The Times. The development of renewable energy such as solar energy and wind energy has become a priority choice, and more and more people have begun to explore renewable energy and adopt distributed power generation schemes [4-6]. However, due to the instability of renewable energy generation, it needs to have a certain impact on the load and the grid. As a result, people are starting to combine renewable energy generation, storage, and load to form microgrids. From the perspective of utility, microgrids can be regarded as units that control the entire system [7]. In simple terms, microgrid is to integrate distributed generation, load, energy storage devices, converters and monitoring and protection devices into a small power supply system and can achieve flexible operation mode. By establishing autonomous microgrid groups to utilize renewable energy with higher efficiency and reduce its impact on load and power grid, the reliability and economy of the system can be greatly improved to better meet the multiple demands of the power system in the context of globalization [8].

In reference [9], an economical distributed energy storage control strategy is adopted to solve the problem of high cost during the interconnected cooperative operation of autonomous microgrids. The strategy uses the battery energy storage operating cost model considering line loss, and adopts the consistency algorithm to solve iteratively, so as to realize the economic distribution of output power among each energy storage unit. Reference [10] proposes a simplified control strategy, which uses the dynamic diffusion algorithm to distribute communication, and considers the influence of communication sampling time on the dynamic performance and stability of the system. While optimizing the two-layer control gain, it also improves the important parameters such as the communication sampling period. Finally, the effectiveness and feasibility of this strategy are verified by MATLAB/Simulink simulation. Reference [8] proposes a distributed energy storage control

strategy based on diffusion algorithm, which can realize saggeless control and accurately balance the charge and discharge power of each energy storage device. The results of RTLAB simulation show that the strategy is effective and practical. Reference [11-12] proposes a new dynamic energy distribution strategy which uses virtual DC motor control technology to enhance the stability and disturbance immunity of the system and realizes the charge and discharge state balance among various energy storage units by introducing a voltage drop regulator. In addition, the consistency algorithm is used to enhance the scalability of the system. The simulation results show that the strategy effectively improves the dynamic energy distribution level of the distributed energy storage system and has practical application value and broad development prospects. Reference [13] proposes a novel optimal operation strategy based on adaptive diffusion algorithm. This strategy can control the marginal cost of distributed power supply by updating the node status value in real time and combining with weighting factors. Simulation analysis shows that the proposed adaptive diffusion algorithm has the ability of real-time detection of distributed network node information and can effectively adapt to environmental changes. Reference [14] points out that there is a linear relationship between the charge and discharge efficiency of the energy storage system and the output power and optimizes the operating cost of the energy storage system by using the principle of incremental cost consistency.

Based on the above research, this paper optimizes the energy storage unit in DC microgrid and uses the consistency algorithm to improve the sag control. This approach can improve the efficiency and stability of distributed energy storage units, thus enhancing the practicality of the entire system.

2. DC microgrid system structure and traditional sag control

2.1. DC microgrid structure

A typical DC microgrid system architecture includes solar power plants, wind power plants, loads, and energy storage units (as shown in Figure 1). The solar panel and fan operating in the maximum power point tracking control mode are generally paralleled with the common bus to maximize the output power of the photovoltaic cell and fan. When DC microgrid operates in island mode, the outlet voltage of each distributed power conversion circuit can be coordinated by controlling the charge and discharge of the energy storage unit (wind converts AC into DC power transmission, and then converts DC/DC voltage to DC load from the load end or converts DC into AC power to AC load from AC/DC again). To realize the power balance of DC microgrid and reduce the voltage fluctuation of common bus. Because the line inductance is much smaller than the line resistance in a low-voltage DC microgrid, the inductive component can be ignored for further analysis.

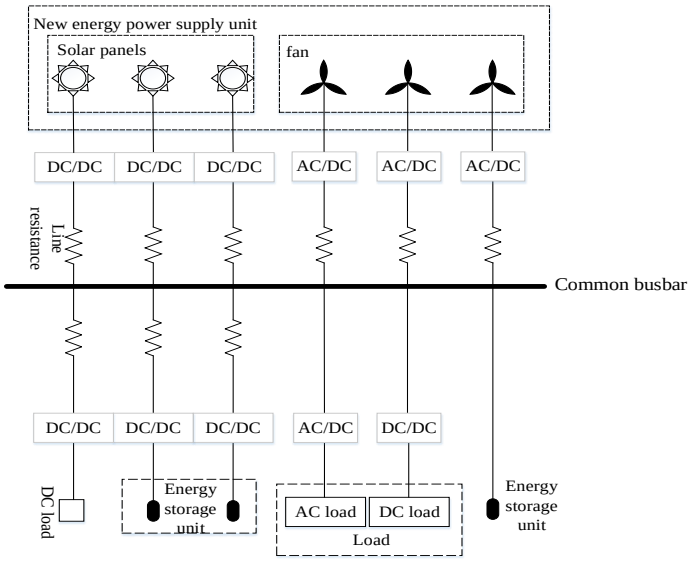


Figure 1 DC microgrid structure

2.2. The shortcomings of traditional droop control

Assuming that there are three groups of distributed energy storage units (DESU), the equivalent circuit diagram is shown in Figure 2. In DC microgrid, the expression can be obtained.

$$U_{r1} = U_r - I_i R_i (i = 1,2,3) \tag{1}$$

In the equation, Ur1 is the reference value of output voltage. If the system is in an ideal condition, the output voltage reference value is equal to the bus voltage rating [15], which can be seen.

$$I_1 / I_2 = (R_{12} + R_2) / (R_{11} + R_1) \tag{2}$$

By integrating the above equation, the SOC equation of the distributed cell can be obtained

$$SOC_m = SOC_{m1} - 1/C_m \int_0^x I_1 dx \quad (m=1,\ 2,\ 3) \tag{3}$$

Where SOC_m is the current state of charge of $DESU_m$; SOCm1 is the initial state of charge. C_m is the capacity of $DESU_m$.

Take the derivative of the above equation, and you get

$$dSOC_m = -I_1 / C_m \tag{4}$$

As can be seen from the above equation, the change speed of SOC_m is related to the size and capacity of the charge and discharge current of DESU.

By sorting out equations (2), (3) and (4), we can see

$$dSOC_1 / dSOC_2 = (R_{12} + R_2) C_2 / (R_{11} + R_1) C_1 \tag{5}$$

According to equation (5), SOC balancing between $DESU_s$ can be achieved by adjusting parameter R under the idealized condition that DESU battery capacity and equivalent line impedance are equal. According to the analysis results in Figure 3, the traditional sag control has the following problems: First, in Figure 3-1, the active power is not evenly distributed, coupled with the capacity of different $DESU_s$ and the impact of initial SOC, resulting in SOC imbalance between $DESU_s$ with different capacities. Secondly, because sag control is differential control [16], when the system load increases, the PCC point voltage will exceed the specified range after 0.5 seconds, which may affect the normal operation of the load (see FIG. 4 and FIG.5). Therefore, in order to achieve SOC balance between $DESU_s$ and maintain voltage stability, more reasonable control methods need to be studied.

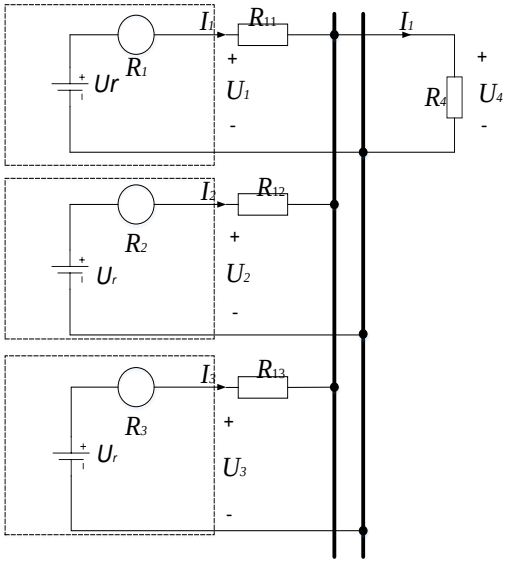


Figure 2 Distributed cell equivalent circuit diagram

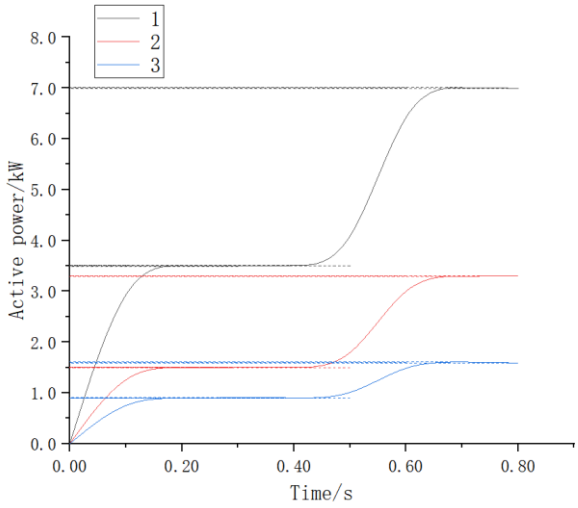


Figure 3 Active power simulation waveform under traditional control

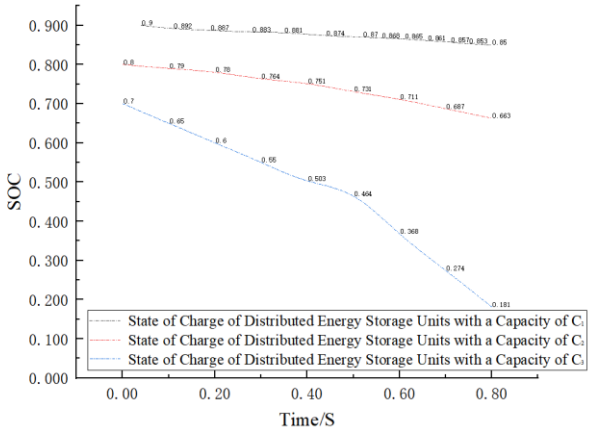


Figure 4 State of Charge (SOC) simulation waveform under traditional control scheme

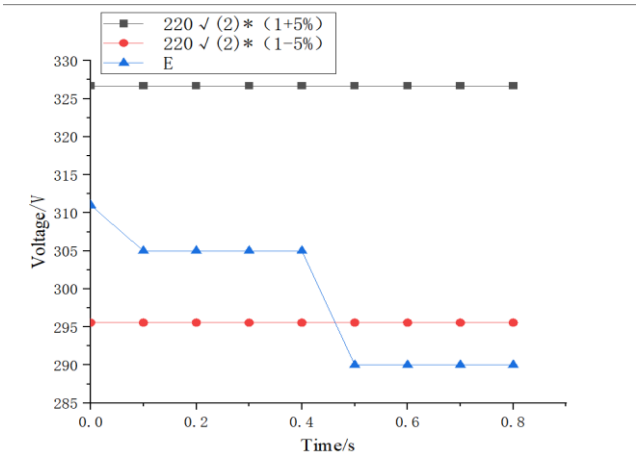


Figure 5 Voltage simulation under traditional control scheme

3. Establishment of topology structure and algorithm model

3.1. Topology of consistent algorithms

Graph theory is a branch of mathematics that studies the structure of graphs and networks. It can convert complex real problems into mathematical models and solve these problems using graph theory algorithms. In the consistency algorithm, the complex communication relationship between

nodes leads to the consistency problem. In order to solve the data consistency problem, the algorithm needs to complete various complex operations, such as data replication, conflict detection and data merging. For distributed power grid, undirected graph is usually used to describe the network structure, because the line of undirected graph is bidirectional, which can facilitate information exchange and energy sharing. Undirected graphs are better able to handle the dependencies between bidirectionally connected nodes and lines than directed graphs, while the physical space and management scope of distributed grids can limit their topology, making them often described as finite graphs. However, when a distributed grid is interconnected with other grids or energy systems, the entire system can be seen as an infinite graph because it can be extended indefinitely. Figure *G (V,E)* is used to describe the topology network structure between distributed energy storage units, where *V* represents a node set $V=\{1,2,3,4\ldots\ldots n\}$,*E* represents an edge set $E \subseteq V \times V$, each equivalent battery energy storage unit is regarded as a node *V*, and the communication line between adjacent nodes is regarded as an edge in the edge set *E*. If there is a communication line between node *i* and node *j*, node *i* is said to be the neighbor of node *j*. Let's call it $N_i=\{j \in V \mid (i, j) \in E\}$. It should be emphasized that the topology diagram only reflects the connections between nodes, and cannot reflect the characteristics of the power system.As shown in Figure 6.

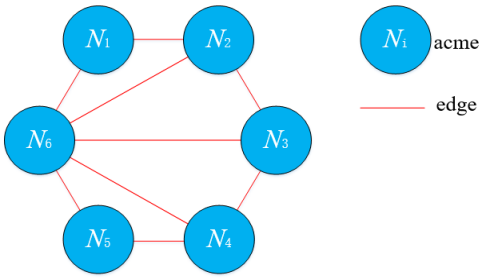


Figure 6 Power System Topology Network Diagram

If an undirected graph *G* is connected, the required condition is if and only if there is a path between any of its vertices *i* and node *j*. A connected graph can be represented by an *n*×*n* symmetric adjacency matrix A, where the element in row *i* and column *j* is taken a_{ij}.

$$\begin{cases} a_{ij} = 1(i = j) \\ a_{ij} = 0(i \neq j) \end{cases} \tag{6}$$

According to the Laplace matrix,

$$L = D - A \tag{7}$$

Then the element *lij* in L can be expressed as

$$l_{ij} = \begin{cases} \sum_{i \neq j} a_{ij}, (i = j) \\ -a_{ij}, (i \neq j) \end{cases} \tag{8}$$

3.2. Consistency Algorithm

Consistency algorithm is widely used in distributed control of microgrid. The basic goal is to make the state variable of each node approach the same value continuously from the initial value until it converges, so as to reach a consensus through the iterative process. Consistency algorithm includes continuous consistency algorithm and discrete consistency algorithm. In most cases, the discrete consistency algorithm is used in the field. The discrete consistency algorithm is described in this paper. The iterative process for the consistency algorithm is shown in the following equation.

$$x_l(t+1) = \sum_{m=1}^{n} d_{lm} x_m(t) \tag{9}$$

The matrix is

$$X\left[t+1\right] = DX(t) \tag{10}$$

$x_l(t+1)$ is expressed as the state variable of node l after t+1 passage. $x_m(t)$ represents the state variable of node m after t times; d_{lm} represents the matrix coefficient after state change; D represents the change matrix of the corresponding state.

In order to make the iterative performance of the consistent algorithm better, the convergence accuracy δ is derived. Then the original equation can be reduced to

$$x_l(t+1) = \sum_{m=1}^{n} d_{lm} x_m(t) + \delta f\left[x(t)\right] \tag{11}$$

The matrix is

$$X\left[t+1\right] = DX(t) + \delta F\left[t\right] \tag{12}$$

Where $f\left[x(t)\right]$ is the x(t) deviation function of the state variable.

In a distributed communication network, each energy storage device works cooperatively through information exchange with surrounding nodes, and then iteratively updates according to the state transition matrix D. The state transition matrix D is a key factor in the convergence speed of the consistency algorithm. Therefore, the state transition matrix coefficient dlm is determined by referring to the construction method proposed in relevant Reference [14], so as to optimize the performance of the algorithm.

$$d_{lm} = \begin{cases} 2/(y_l + y_m + 1), m \in Y_l \\ 1 - \sum_{m \in Y_l} 2/(Y_l + Y_m + 1), l = m \\ 0, \text{Other situations} \end{cases} \tag{13}$$

y_l and y_m indicates the number of neighbors of nodes l and m.

If a double random matrix is chosen as the state transition matrix D, then the state variable of $x_l(t)$ each node will gradually tend to the average value of all node state variables when iteratively updating using the consistency algorithm. In this way, the consistent convergence of the initial state variables can be achieved [17-19]. The original equation can be reduced to:

$$x_1(\infty) = x_2(\infty) = \cdots\cdots = x_n(\infty) = 1/n(\sum_{l=1}^{n} x_l(0)) \tag{14}$$

$x_l(0)$ is the initial state variable at node l.

4. Consistency algorithm simulation

4.1. SOC Balancing Principles

Assume that there are three *DESUs* of different capacities in the power system, and the initial *SOCs* are different. When using the consistency algorithm, DESU will be based on the equation.

$$E_i = E_{ref} - mP_i - G_p(s)(\beta_{SOC_{ave}} - \gamma_{SOCi}) + Dk_Q \int_0^t Q_i dt \tag{15}$$

The level of its SOC regulates the active power output, so that the SOC reduction of DESU with high SOC is larger than that of DESU with low SOC, gradually reducing the SOC difference between each DESU, and finally achieving SOC balance. Similarly, according to the capacity of the DESU,

the active power will also be adjusted differently, which is directly proportional to the capacity of the DESU. In addition, with the balancing of SOC, the SOC balancing factor of each DESU will gradually tend to zero, and finally realize the traditional sag control, and the voltage remains unchanged, thus solving the problem of voltage deviation in the traditional SOC balancing scheme.

4.2. Voltage regulation principle

When the load of power system becomes heavier, the traditional sag control scheme may lead to voltage deviation and affect voltage quality. In order to solve this problem, a voltage regulator $Dk_Q\int_0^t Q_i dt$ is introduced to balance the voltage. The voltage regulator in the traditional sag control scheme contains an integral component, which can shift the sag curve upward to eliminate the voltage deviation. In this control scheme, the voltage and current are measured by the voltage and current transformer, and the active and reactive power output of the inverter is calculated according to them. Next, adjacent DESU agents exchange SOC information, according to the equation

$$\begin{cases} \beta_{SOC_{ave_i}}(k+1)=\gamma_{SOC_i}(k)+\sigma\sum\theta_{ij}(k+1), i\neq j \\ \theta_{ij}(k+1)=\theta_{ij}(k)+\beta_{SOC_{ave_j}}(k)-\beta_{SOC_{ave_i}}(k), i\neq j \end{cases} \tag{16}$$

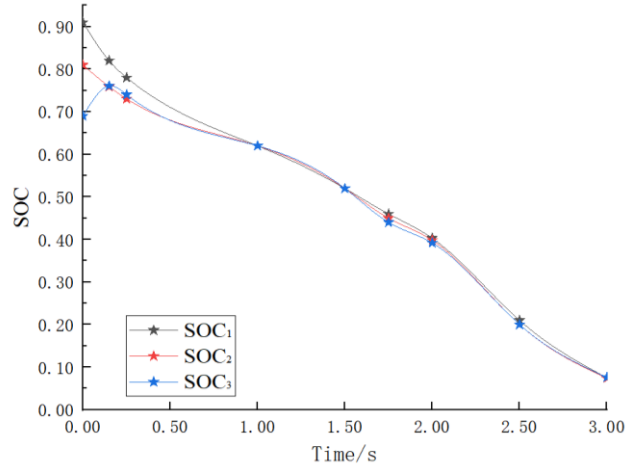
In the above equation, $\beta_{SOC_{ave_i}}(k+1)$ SOC average value of DESU of station i obtained after k+1iteration calculation; $\gamma_{SOC_i}(k)$ Represents the SOC value of DESU i obtained after calculation of k+1 iteration; σ represents the scale coefficient; $\theta_{ij}(k)$ represents the cumulative difference between the two DESU agents responsible for storing it, with an initial value of 0; $\beta_{SOC_{ave_j}}(k)$ and $\beta_{SOC_{ave_i}}(k)$ represents the SOC average value of DESU i and j after k iteration calculation. The reference value of SOC equalization factor and voltage is calculated by the above equation, and the purpose of constant voltage is finally achieved.

4.3. Simulation Analysis

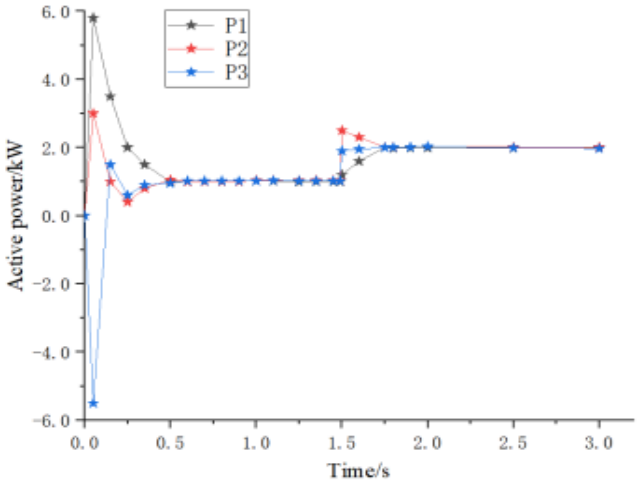
In order to verify the influence of the scheme on the control effect, a simulation model was created, which included three DESU with different capacities, each DESU had different line impedance values, and each DESU used the same inverter to power the load. The parameter values listed in Table 1 were used in the simulation and experiment process to simulate the real working conditions. Simulation results are shown in FIG. 7 and FIG. 8.

Table 1 Simulation and experiment parameters

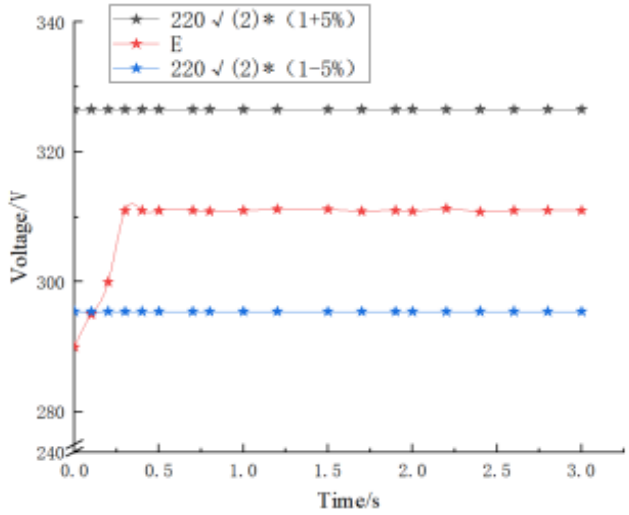
Parameters		Simulation	Experimental results
Rated voltage E_{ref}/V		311	100
Rated V_{ref}/V		311	100
Inverter DC side voltage V_B/V		800	230
$DESU_1$'s capacity C_1/Ah		3000	50
$DESU_2$'s capacity C_2/Ah		2000	100
$DESU_3$'s capacity C_3/Ah		1000	——
Sag coefficient	m/(10-3 rad/W)	0.032	0.018
	Kp/(10-3 var)	0.25	0.045
	Kq/(10-3 var)	0.0148	0.0128
	Ki/(10-3 rad)	0.045	0.021
Load 1	P_1+jQ_1	4kW+j2 k var	200W+j100 var
Load 2	P_2+jQ_2	2kW+j1 k var	100W+j50 var



(a) S OC

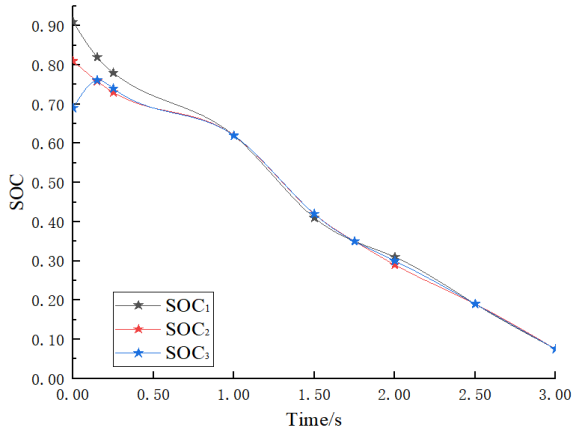


(b) Active power

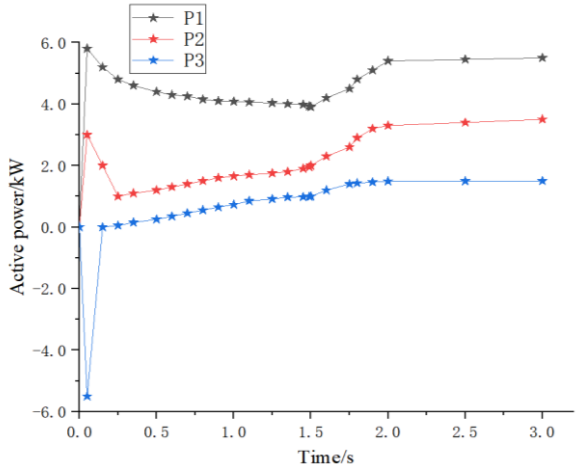


(c) Voltage

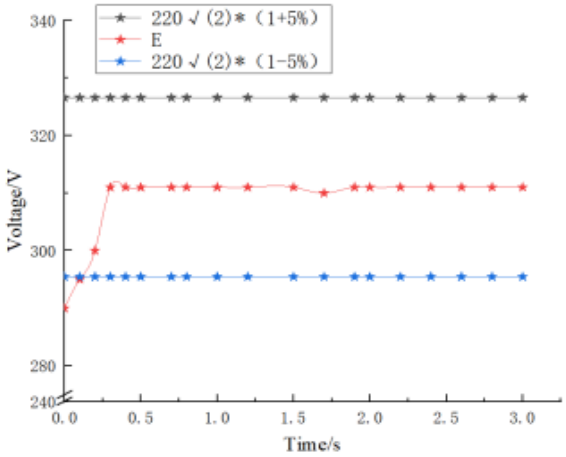
Figure 7 Simulation waveform of the scheme adopted by DESU inverter with the same capacity.



(a) SOC



(b) Active power



(c) Voltage

Figure 8 Simulation waveforms of DESU inverters with different capacities

It can be seen that the SOC equalizing algorithm proposed in this paper can adjust the output voltage of the inverter in time under load changes and the operating conditions of different capacity/same capacity units, so as to maintain it within the standard operating range without voltage fluctuation, thus avoiding the decline of the voltage quality of the power grid. After SOC balancing is achieved by the proposed scheme, the output active power ratio of DESU inverters with the same/different capacities is (1∶1∶1) and (3∶2∶1) respectively, which is consistent with the capacity ratio of DESU. Therefore, in practical application, it is necessary to further adjust and control the

output power ratio between each unit on the basis of DESU capacity ratio according to the needs and requirements of system design, so as to realize the efficient and stable operation of the system.

5. Conclusions

Aiming at the problems caused by the traditional droop mode of DC microgrid, this paper puts forward the optimal energy storage strategy of consistency algorithm. Through the simulation analysis of the consistency algorithm, this paper draws the following conclusions:

(1) In this paper, the consistency algorithm is used to improve the sag control and optimize the design of the energy storage unit in the DC microgrid, improve the efficiency and stability of the system, and improve the voltage stability problem, improve the reliability and practicability of the distributed energy storage system.

(2) The proposed strategy transforms the operation optimization problem into the distribution consistency problem and explains the topological structure graph theory and consistency algorithm in detail.

(3) Through the simulation analysis of the proposed scheme, no matter the capacity of DESU is the same or different, the energy storage state can be balanced, and the offset value of voltage and frequency can be effectively adjusted when the load changes, so as to avoid the voltage quality decline.

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