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Research on Power Distribution Technology of Multi-group Hybrid Energy Storage Unit in DC Microgrid

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Abstract

This paper takes the hybrid energy storage system (Hybrid Energy Storage System, HESS) acting on DC microgrid as the research object. By analyzing the role of droop control in power distribution and voltage equalization, a power distribution technology between multiple hybrid energy storage units (Hybrid Energy Storage Unit,HESU) of DC microgrid is proposed. After that, the simulation model of the above system is built in the Matlab/ Simulink to analyze the working process of the mixed energy storage unit under different working conditions. The simulation shows that the control strategy which have been proposed can ensure that the hybrid energy storage system working in DC microgrid can satisfy the total power demand of the system, and ensure the reasonable distribution of the power demand of DC microgrid between the hybrid energy storage units.

Keywords

DC microgrid; Hybrid energy storage system; Droop control.

1. Introduction

Currently, the world's demand for energy is increasing, and the negative effects brought by the large use of fossil energy accelerate the development of renewable clean energy. As an important means to connect renewable clean energy to the grid, microgrid is also developing rapidly. At present, photovoltaic (PV) units and energy storage units in microgrid are mostly in DC form. At the same time, compared with AC microgrid, DC microgrid has no problems such as phase, harmonic current and reactive power transmission, which reduces energy loss. Therefore, in recent years, the research on DC microgrid is gradually warming up [1]. DC microgrid can be used as part of the main grid and can also work independently in island mode. The instability of new energy output appears when DC microgrid works in island mode which means that the microgrid loss the support of main grid . Therefore, the hybrid energy storage system can well overcome the intermittency, volatility and randomness of the new energy generation in the isolated island mode of DC microgrid. at the same time, it also plays the role of peak shifting filling, backup power supply, power quality control in microgrid [2-3].

Existing energy storage elements and power energy storage elements are two kinds of energy storage elements, among which, the representatives of energy storage elements are various batteries, and the representatives of power energy storage elements are super capacitors (Super Capacitor,SC). The energy type energy storage unit is characterized by high energy density, long discharge time, low cost, slow response speed and limited cycle times, which is suitable for long-term continuous and stable discharge; the characteristics of power type energy storage unit are high power density, fast response speed, high cost and high cycle number, which is suitable for high-power short-time discharge.

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Hybrid energy storage system (HESS) which is an ideal scheme to meet the demand of capacity and power and charge-discharge characteristics of DC microgrid is a combination of two types of energy storage components to realize the complementary advantages and disadvantages of the two kinds of components.In order to enable HESS to work efficiently, the power demand of the entire microgrid needs to be reasonably distributed according to its nature, so that HESS represented by battery and SC can work in a division of labor, so as to satisfy the power demand of the entire microgrid [4].In reference [5], in order to achieve the purpose of DC bus voltage regulation and system power balance, HESS is coordinated and controlled in a hierarchical way .But, this control method only aims at the situation that there is only one group of HESU in the system. With the development of DC microgrid, a single HESU can not satisfy the development needs. Therefore, the future research direction and focus will be to study the collaborative work of multiple sets of hybrid energy storage devices.

At present, the control methods in microgrid mainly focus on droop control and improved droop control based on droop control [6]. As the main control strategy of decentralized control, droop control does not need global communication. Reference [7] compares and summarizes droop control and improved droop control in DC microgrid at present.

Based on the droop control idea, a DC microgrid model with multiple HESU is built, and the power distribution between multiple mixed energy storage units is studied. Thus, the required power of DC microgrid system is reasonably distributed among HESU units, and the DC bus voltage is consistent, which makes the whole DC microgrid run stably.

2. DC microgrid

At present, microgrid can be divided into three categories: AC microgrid, DC microgrid and AC-DC microgrid. Most of the new energy generation units and battery energy storage units in the microgrid generate DC power, and as part of the common loads in the microgrid, such as mobile phones, computers, electric vehicles and variable frequency air conditioners, are used by converting alternating current into direct current, which leads to the existence of a large number of power electronic converters in the AC microgrid, which leads to the existence of energy Waste. However, DC microgrid can avoid the loss of this part of energy to a certain extent, improve energy utilization and save energy. And DC microgrid has no phase, reactive power and other issues. Therefore, the research and development of DC microgrid has attracted the attention of domestic and foreign research institutions and scholars [8].The basic structure of DC microgrid proposed by FREEDM center of the United States should be connected by DC bus to energy storage unit, photovoltaic power generation unit and variable alternator [9]. Figure 1 is a brief structure diagram of DC microgrid. Among them, according to different requirements, the type and number of units in different DC microgrid are slightly different. DC microgrid is connected with AC grid through AC / DC converter. When there is a problem or fault in the large grid or microgrid, the DC microgrid can be disconnected from the large grid and work in island mode. Solar power unit and DC energy storage unit(ESU) are connected with DC bus through DC / DC converter. Load is connected with DC bus through DC / DC converter and DC/AC converter respectively according to their working characteristics.

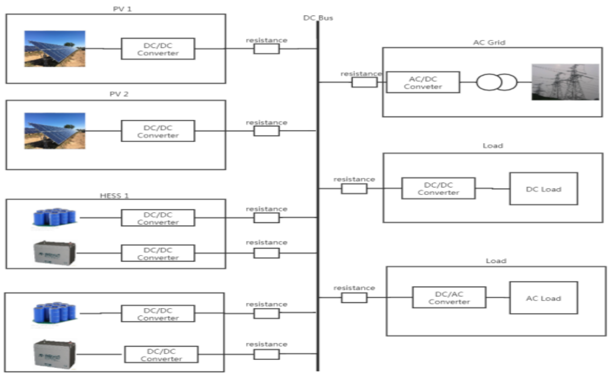

Figure 1. Schematic diagram of DC microgrid structure

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The control methods of DC microgrid energy storage system are centralized control and decentralized control. Among them, centralized control needs to collect the information of each unit of the microgrid in the central controller, which greatly depends on communication, which leads to the reliability of the entire microgrid affected by the communication lines and central controller. Moreover, if the centralized controller or communication line fails, the whole microgrid system will crash,in that way,it may cause huge damage to the society. Decentralized control moves the control part down to each unit of microgrid. The distributed controller only obtains the corresponding control signal through the change of each unit's own state, which eliminates the communication between each unit and the central controller.

3. Control strategy of hybrid energy storage system

As an energy supply device of DC microgrid, HESS has the advantage of high flexibility compared with the traditional large-scale energy storage system(ESS), and has been applied more and more in the construction of DC microgrid. The function of HESS in DC microgrid mainly includes the following parts: ① It can optimize the load curve and reduce the cost of electricity, and play the role of cutting peak and filling valley; ② Hess can stabilize the power fluctuation in the DC microgrid, stabilize the voltage of DC bus, and improve the power quality; ③HESS can supply the uninterrupted power at the important load for a period of time and improve the system Stability. In recent years, the concept of smart grid has gradually become the focus of scholars in various countries. In order to gradually realize the smart grid and improve the flexibility and stability of the grid, the communication connection between ESU is essential.

Due to the asymmetry of functions, parameters and communication among the HESU in DC microgrid, the control difference will be caused. At the same time, the global communication required by traditional centralized control has poor stability and high cost, which limits its application in DC microgrid. Decentralized control can control each unit of DC microgrid independently without exchanging information with central controller. Therefore, the possibility of system crash caused by centralized control communication error is reduced.

3.1 State evaluation of hybrid energy storage system

HESS is usually consisted of energy and power storage devices. At present, the most wide-ranging used HESS are usually consisted of batteries and super capacitors. Usually, two kinds of energy storage devices are connected with DC bus through DC / DC converter to compensate DC bus power fluctuation directly. The structure can make different control strategies which decided by the characteristics of different energy storage elements, and can realize the charge and discharge process of energy storage elements while ensuring the stability of DC bus voltage. For example, some scholars have proposed a control method for this topology, that is, the super capacitor is used to compensate the bus voltage fluctuation while using the battery to maintain the port voltage of the super capacitor and the stable of the battery SOC[10].

There are two or more kinds of energy storage elements in HESS, and there are many different working modes under different working conditions.HESS can work in the following modes depending on the bus power requirements characteristics[11].

Mode 1: energy mode (output).When the bus power demand $P_{need} \geq 0$ at the same time the bus power is low and the fluctuation is small, the battery of energy storage device can meet the bus power, and Hess can be supplied by battery alone. In the meantime, the supercapacitor of power type energy storage device can maintain its own SOC consistency.When Hess works in mode 1, its maximum output power and equivalent SOC can be derived from the formula(1):

$$P_{HESS.\max} = P_{B.\max} \tag{1}$$

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In the formula, $P_{HESS.\max}$ is the maximum output power of the HESU, and $P_{B.\max}$ is the maximum output power of the battery.

$$SOC_{HESS} = SOC_B \tag{2}$$

In the above formula, SOC_{HESS} is the equivalent SOC of HESU and SOC_B is the SOC of battery cell.

Mode 2: mixed operation mode (output). When the bus power demand $P_{need} \geq 0$ is high or there are high-frequency fluctuations, the single battery function is not enough to meet the bus power change, then the super capacitor is put into use as a supplement to deal with the high power demand or high-frequency power fluctuation, prevent the bus voltage from large deviation or fluctuation, and stabilize the bus voltage. When Hess works in mode 2, its maximum output power and equivalent SOC are

$$P_{HESS.\max} = \min\{(1+\alpha)P_{b.\max}, (1+\frac{1}{\alpha})P_{SC.\max}\} \tag{3}$$

$$SOC_{HESS} = SOC_{SC} \tag{4}$$

In the formula, $P_{SC.\max}$ is the maximum output power of supercapacitor and SOC_{SC} is the SOC of supercapacitor cell.

It is defined α as the load power distribution ratio between battery and super capacitor.

$$\alpha = \frac{P_{SC}}{P_B} \tag{5}$$

In the formula, P_{sc} is the super capacitor output power; P_B is the battery output power.

Mode 3: energy mode (recovery). When the bus power $P_{need} < 0$ is low and the fluctuation is small, the battery of ESU can absorb the bus power, then HESS can be operated by battery alone. Meanwhile, the supercapacitor of power type energy storage device can maintain its own SOC consistency. When Hess works in mode 1, the maximum absorbed power and equivalent SOC are

$$P_{HESS.chr.\max} = P_{B.chr.\max} \tag{6}$$

$$SOC_{HESS} = SOC_B \tag{7}$$

In the formula, $P_{SC.chr.\max}$ is the maximum power absorbed by the HESU and $P_{B.chr.\max}$ is the maximum charging power of battery.

Mode 4: mixed operation mode (recycling). When the bus power is high or there is high-frequency fluctuation, the single battery function is not enough to meet the bus power change, then the super capacitor is put into use as a supplement to deal with the high power recovery demand or high-frequency power fluctuation, prevent the bus voltage from large deviation or fluctuation, and stabilize the bus voltage. When Hess operates in mode 4, the maximum power absorbed and the equivalent SOC are

$$P_{HESS.chr.\max} = \min\{(1+\alpha)P_{b.chr.\max}, (1+\frac{1}{\alpha})P_{SC.chr.\max}\} \tag{8}$$

$$SOC_{HESS} = SOC_{SC} \tag{9}$$

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In this formula, $P_{SC.chr.\max}$ is the super capacitor maximum charge power. Similarly, see formula (5).The operating conditions of hybrid energy storage unit under different working modes are given in Table 1 .The switching conditions between different modes are shown in Table 1.

Table 1. Mode operation conditions

Mode	Operating conditions
Mode1	$0 \le P_{need} \le P_{B.\max}, SOC_{HESS} > \mathrm{SOC}_{\mathrm{HESS.min.1}}$
Mode2	$0 \le P_{need} \le P_{(B+SC).\max}, SOC_{HESS} > \mathrm{SOC}_{\mathrm{HESS.min.2}}$
Mode3	$P_{\mathrm{B}.chr.\max} \le P_{need} \le 0, SOC_{HESS} < \mathrm{SOC}_{\mathrm{HESS.max.3}}$
Mode4	$P_{(\mathrm{B+SC}).chr.\max} \le P_{need} \le 0, SOC_{HESS} < \mathrm{SOC}_{\mathrm{HESS.max.4}}$

Note: $SOC_{HESS.\max.i} i = 1,2,3,4$ is the upper and $SOC_{HESS.\min.i} i = 1,2,3,4$ is the lower limits of SOC for mode 1 to mode 4.

3.2 Control strategy of hybrid energy storage system

First, taking the classical topology of DC microgrid shown in figure 1 as an example, a simplified DC microgrid composed of two groups of mixed energy storage units and loads is established. The load is used to simulate the power demand in DC microgrid. Each group of HESU are connected to the DC bus through DC converter, and each group of HESU are droop controlled by the local controller, which can not only ensure that the energy storage unit can supply the DC microgrid power demand according to the droop coefficient, but also ensure that each HESU will not be overcharged or over discharged, thus extending the service life of the HESU.

3.2.1 Droop control of hybrid energy storage system

The droop control strategy is adopted in the distributed HESS. As a classical DC microgrid control strategy, droop control can distribute power to the ESU without communication. The basic V-I expression is as follows:

$$U_{oi} = U_{rated} - R_{di} I_{oi} \tag{10}$$

Among them, U_{oi} is the output voltage of the DC converter connected to the DC bus, U_{rated} is the rated voltage of the DC bus, R_{di} is the droop coefficient of the ESUi, I_{oi} is the output current of the DC converter; $i = 1,2,3......n$

It is assumed that the rated voltage of each converter the DC bus voltage is equal,then can obtain the following formula:

$$\begin{cases} U_{oi} = U_{rated} - (R_{di} + R_{linei}) I_{oi} \\ U_{oj} = U_{rated} - (R_{dj} + R_{linej}) I_{oj} \end{cases} \tag{11}$$

In this formula, R_{linei}、R_{linej} are the line impedance.

Formula (12) can be obtained from formula(11)

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$$\frac{I_{oi}}{I_{oj}}=\frac{R_{dj}+R_{linej}}{R_{di}+R_{linei}} \tag{12}$$

The output current of each converter controlled by droop control is proportional to the sum of line impedance and virtual impedance.

Since the line impedance is smaller than the droop coefficient, for the sake of simplifying the analysis, the line impedance is ignored, there are the following formula:

$$\begin{cases} U_{oi}=U_{rated}-R_{di}I_{oi} \\ U_{oj}=U_{rated}-R_{dj}I_{oj} \\ U_{oi}\approx U_{oj}\approx U_{bus} \end{cases} \tag{13}$$

In the formula(13), U_{bus} is the DC bus voltage.

The formula (15) can be derived from formula (14):

$$\frac{I_{oi}}{I_{oj}}=\frac{R_{dj}}{R_{di}} \tag{14}$$

From equation (14) to equation (15), the output power ($P_{o1}\sim P_{on}$) of N HESU in microgrid has the following relationship:

$$P_{o1}:P_{o2}:\cdots:P_{on}=\frac{1}{R_{d1}}:\frac{1}{R_{d2}}:\cdots:\frac{1}{R_{dn}} \tag{15}$$

By setting a reasonable droop coefficient, the load in DC microgrid can be achieved, and each HESU can output in proportion to meet the load demand.The droop coefficient will act on the droop control in the form of virtual resistance as shown in formula (12) and (14). When the DC bus power demand changes, the output current will also change. When the output current increases, the output voltage will decrease, and the variation of voltage meets the requirement as the following formula:

$$\Delta U=R_{di}I_{oi}\le\Delta U_{\max} \tag{16}$$

In the formula (16), $\Delta U_{\max}$ is the maximum allowable bus voltage fluctuation range, 5% of DC bus rated voltage is selected as the maximum allowable bus voltage fluctuation.

Therefore, according to formula (16) and equation (17), the droop coefficient of HESU can be obtained from the following formula:

$$R_{di}=k\frac{\Delta U_{\max}U_{rated}}{P_{\max i}} \tag{17}$$

In the formula (17), k is the droop coefficient factor, which is usually taken as $0<k<1$.

Meanwhile, according to the mode switching conditions in Table 1, the working mode of each hybrid energy storage unit will change, which will lead to different calculation methods of output power and equivalent SOC of HESU. Therefore, when the HESU works in different modes, formula (17) should also change as the following formula

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$$R_{di,t} = k\frac{\Delta U_{\max} U_{rated}}{P_{\max i,t}} \tag{18}$$

As shown in Figure 2, the calculation block diagram of droop coefficient of hybrid energy storage unit is shown.

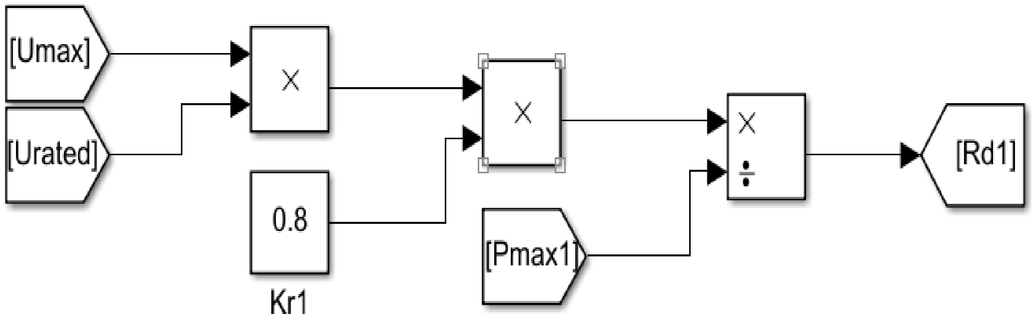

Figure 2. Block diagram of droop coefficient calculation

As shown in Figure 2, $U_{\max}$ is the maximum allowable fluctuation value of DC bus voltage, taking positive value as calculation value, U_{rated} is rated voltage value of DC bus, K_{r1} is adjustment coefficient, $P_{\max 1}$ is maximum allowable output power of HESS.

As shown in Figure 3 is the control block diagram of the system.

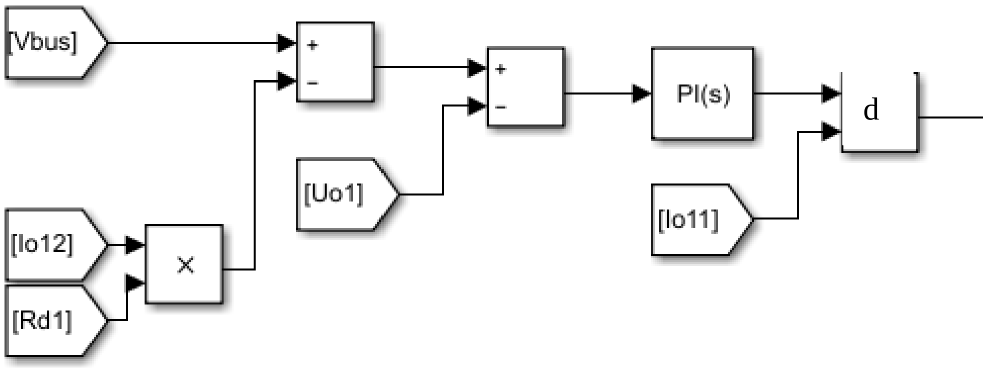

Figure 3. Control block diagram of droop control

Among them, V_{bus} is the rated voltage of the DC bus , I_{o12} is the current measured at the place where the HESU is connected to the DC bus, I_{o12} is the droop control coefficient of the first group of HESUs, U_{o1} is the voltage at which the hybrid energy storage system is connected to the DC bus, and I_{o11} is the output current before the HESU is connected to the boost converter.

3.2.2 Stability analysis of droop control

Two groups of equal capacity ESUs and the system composed of load are taken as the system structure of stability analysis to carry out droop control stability analysis. Fig. 4 shows the control structure diagram of the first energy storage unit for stability analysis [12].

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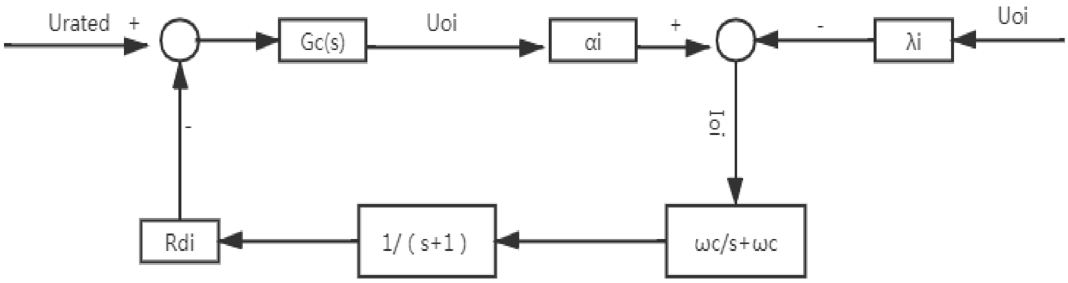

Figure 4.control block diagram of stability analysis

In the figure 4, the closed-loop transfer function of DC voltage is $G(s)=1/(\tau s+1)$, τ is the time constant under the action of switch, which can be approximated as $G(s)=1$; the updating and adjusting link of droop coefficient can be equivalent to the inertial link, and ω_c is the cut-off frequency of current low-pass filter link [13].

$$\begin{cases} U_{oi}(s)=U_{rated}-R_{di}\dfrac{1}{s+1}\dfrac{\omega_c}{s+\omega_c}(\alpha_i U_{oi}-\lambda U_{oi}) \\ U_{oj}(s)=U_{rated}-R_{dj}\dfrac{1}{s+1}\dfrac{\omega_c}{s+\omega_c}(\alpha_j U_{oj}-\lambda U_{oj}) \end{cases} \tag{19}$$

$$\begin{cases} \alpha_i=\dfrac{R_{line,j}+R_{load}}{R_{line,i}R_{line,j}+R_{line,i}R_{load}+R_{line,j}R_{load}} \\ \alpha_j=\dfrac{R_{line,i}+R_{load}}{R_{line,i}R_{line,j}+R_{line,i}R_{load}+R_{line,j}R_{load}} \\ \lambda=\dfrac{R_{load}}{R_{line,i}R_{line,j}+R_{line,i}R_{load}+R_{line,j}R_{load}} \end{cases} \tag{20}$$

$R_{line,i}, R_{line,j}, R_{load}$ are line impedance of energy storage unit and load impedance.The simultaneous equations (11), (19) and (20) can be used to describe the characteristic equation of the system.

$$As^4+Bs^3+Cs^2+Cs+E=0$$
$$\begin{cases} A=1 \\ B=(2+2\omega_c) \\ C=1+4\omega_c+\omega_c^{\ 2}-(\alpha_i+\alpha_j)R_{di} \\ D=2\omega_c+2\omega_c^{\ 2}-(\alpha_i+\alpha_j)(1+\omega_c)\omega_c R_{di} \\ E=\omega_c^{\ 2}-(\alpha_i+\alpha_j)\omega_c^{\ 2}R_{di}+(\omega_c R_{di})^2(\alpha_i\alpha_j-\lambda^2) \end{cases} \tag{21}$$

When the hybrid energy storage control system satisfies the Routh criterion and satisfies the condition at the same time, the control system is stable.

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4. System simulation and example analysis

In order to verify the effect of the control algorithm in the DC microgrid multi group hybrid energy storage system, a DC microgrid composed of two groups of equal capacity hybrid energy storage units is built in Matlab/ Simulink. The selection of parameters is shown in Table 2.

Table 2. System parameters

Parameter		
HESS1	Battery capacity	Supercapacitor capacity
	0.5Ah	4C/F
HESS2	Battery capacity	Supercapacitor capacity
	1Ah	4C/F
DC Bus	Rated voltage	
	400V	

As shown below, the working waveforms of the DC microgrid with two groups of hybrid energy storage units under load are shown.

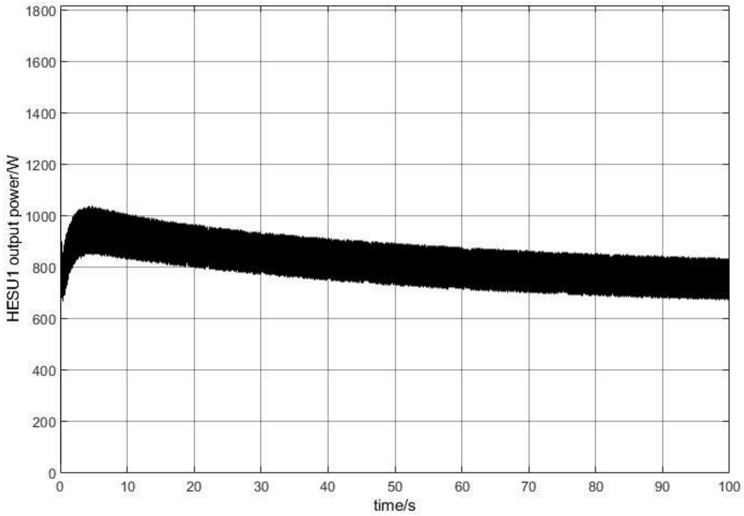

Figure 5. Actual power output of hybrid energy storage unit1

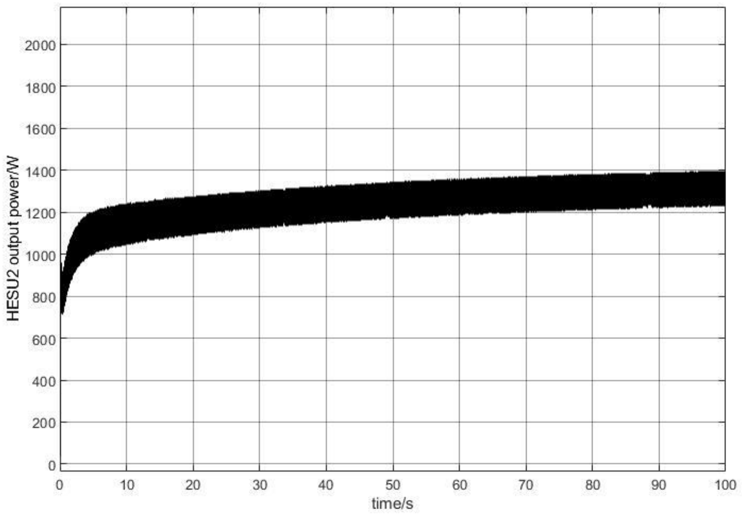

Figure 6. Actual power output of hybrid energy storage unit2

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Figure 5 and Figure 6 show the actual power output of hybrid energy storage unit 1 and 2. From the figure 5 and 6, the actual power output of the two groups of hybrid energy storage units is finally stabilized at about 700W and 1300W respectively, which can supply the control of droop control on both, and they work together to satisfy the power demand of DC microgrid.

Figure 7 shows the total actual power output of the hybrid energy storage system.

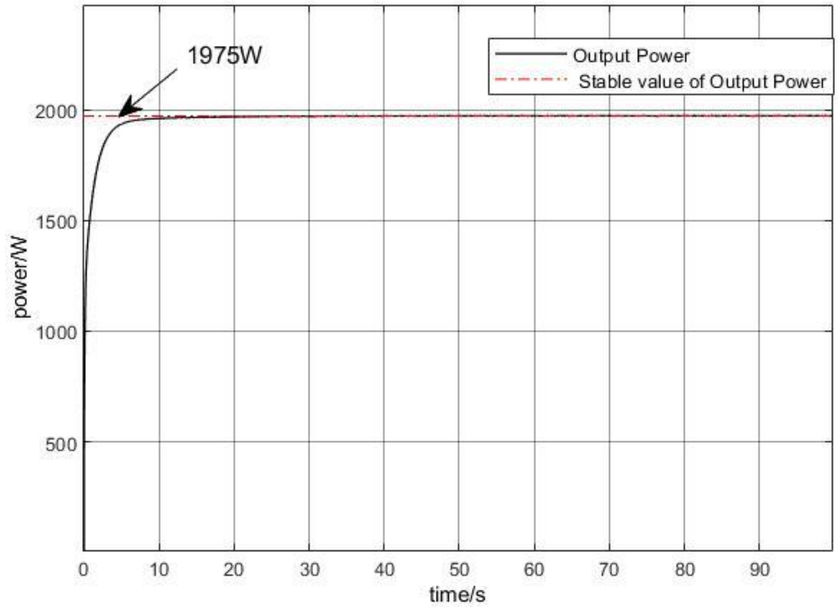

Figure 7. Actual power output of hybrid energy storage system

It can be seen from Figure 7 that under the control of droop control strategy, the HESS can finally stabilize the system output at about 1975w, and the gap with the rated load 2kW is about 1.5%, meeting the power requirements of the system.

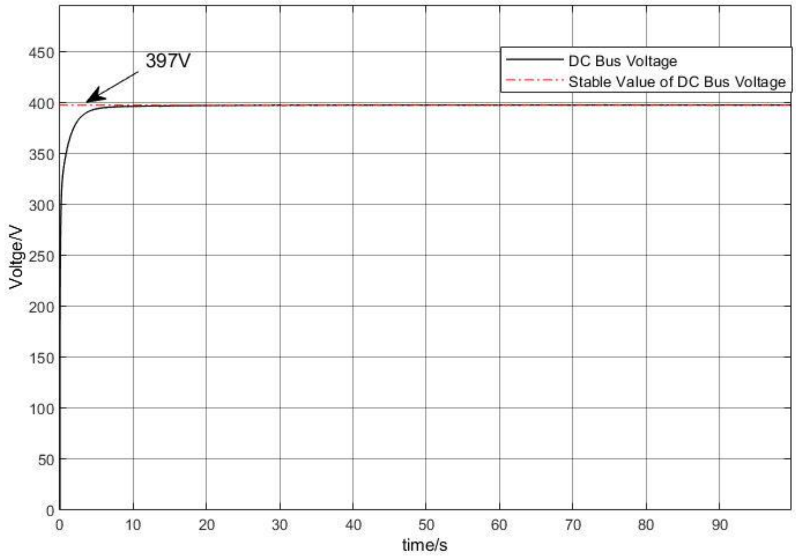

Figure 8. DC microgrid bus voltage

As can be seen from figure 8, the bus voltage of DC microgrid with HESS reaches 397v in less than 10 seconds, and the difference between rated bus voltage of 400V and rated bus voltage can be controlled within 1%, which fully meets the control requirements of droop control, and can stably control the normal operation of DC microgrid, and droop control can keep the bus voltage stable before the excessive discharge of HESS stable.

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5. Conclusion

The DC microgrid with multiple groups of hybrid energy storage units can supply the normal power load of DC microgrid working in island mode. The two kinds of energy storage elements cooperate with each other. The energy type energy storage unit can supply the low-frequency long-time discharge, while the power type energy storage unit can supply the high-frequency and short-time discharge of the system. The two complement each other and can make up for the shortcomings of the two. At the same time, in the case of studying the power distribution of the two, if more state variables about energy storage elements can be added, the control accuracy or reaction time can be further improved. In the future, the microgrid with multiple groups of hybrid energy storage units should be more widely studied.

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