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	Given Name	Jingsong
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	DERI Energy Research Institute
	Address	Nanjing, China
	Email	wangjingsong@deri.energy
Author	Family Name	Li
	Particle	
	Given Name	Peng Yun
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	State Grid Jiangsu Electric Power Company Nantong Power Supply Company
	Address	Nantong, China
	Email	
Author	Family Name	Gong
	Particle	
	Given Name	Chengming
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	DERI Energy Research Institute
	Address	Nanjing, China
	Email	
Author	Family Name	Li
	Particle	
	Given Name	Donghui

	Prefix	
	Suffix	
	Role	
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	Organization	State Grid Jiangsu Electric Power Company Nantong Power Supply Company
	Address	Nantong, China
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Author	Family Name	Fan
	Particle	
	Given Name	Chunyang
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	State Grid Jiangsu Electric Power Company Nantong Power Supply Company
	Address	Nantong, China
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Keywords	Electric vehicles - Hybrid AC/DC microgrid - DC bus - Stability control	



Flexible Control Strategy of DC Bus for Hybrid AC/DC Microgrid with Electric Vehicle

Jingsong Wang^{1(✉)}, Peng Yun Li², Chengming Gong¹, Donghui Li², and Chunyang Fan²

¹ DERI Energy Research Institute, Nanjing, China
wangjingsong@deri.energy

² State Grid Jiangsu Electric Power Company Nantong Power Supply Company, Nantong, China

Abstract. As a new type of microgrid structure, hybrid AC/DC microgrid can efficiently consume photovoltaic-based distributed renewable energy, fitting for the circumstances where electric vehicles work as the main load. Unlike the voltage of AC bus, the DC bus voltage of the hybrid AC/DC microgrid has typical low inertia guaranteed by the power electronic equipment connected to it. Thus, how to enhance the DC bus inertia of hybrid AC/DC microgrid system and improve the stability of DC bus voltage become particularly important. To solve these two problems, this paper presents a flexible method of coordinated control of microgrid bus voltages. The P/U droop characteristics of DC ports of power electronic equipment, such as energy storage and charging and discharging equipment for electric vehicles are taken into account, meanwhile the power reserve rate and energy reserve rate of various distributed renewable energy are comprehensively considered. Under the use of curve translation and other adjustment methods flexibly, DC bus voltage stability is maximized in different working conditions and stable operation of the hybrid AC/DC microgrid system is guaranteed. The validity of the proposed method is also verified by establishing a matlab/simulink simulation system.

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Keywords: Electric vehicles · Hybrid AC/DC microgrid · DC bus · Stability control

1 Introduction

Global warming has become one of the biggest challenges human beings face. Promoting the use of electric vehicles sheds new light on the reduction of CO₂ emissions [1–3]. Aiming to promote the development of electric vehicles in China, *Guidelines on Electric Vehicle Charging Infrastructure Development* (2015–2020) was issued by the National Development and Reform Commission as early as 2015. At present, however, the primary energy form of China is still mainly coal. Thus, it does no help in energy conservation and emission reduction by charging electric vehicles directly connected to the power grid [4, 5].

To realize charging energy vehicles with renewable energy, photovoltaic system and energy storage are built in charging stations, forming a microgrid system with electric vehicles [6]. In order to raise the efficiency of renewable energy consumption, not only DC bus is applied to realize the interaction between electric vehicles and energy storage, but also the microgrid mentioned above construction is employed to build the hybrid AC/DC microgrid system [7].

The stability of the DC bus in hybrid AC/DC microgrid system is the basis of the stable operation of the microgrid system [8–10]. At present, in actual hybrid AC/DC microgrid projects with electric vehicles, usually only one device connected to DC bus is selected as the voltage source, and other devices operate in the current source mode. As a result, the stability of the DC bus is completely limited to the device's power range and stability while the reliability of the system is low. Therefore, how to improve the stability margin of the DC bus becomes particularly important.

The AC droop control method has been widely used in the field of AC system frequency and voltage control, and applied in some engineering pilots [11–13]. Prior researches on DC droop voltage control methods applied to DC bus have not been able to demonstrate how to realize flexible and stable control of DC bus in a hybrid AC/DC system, nor how to apply it in engineering when considering comprehensively the flexibility of the charging and discharging of electric vehicles, energy storage, and distributed renewable energy [14–17]. Therefore, researches and validations are still needed.

Based on the research of the existing DC bus droop control method, this paper proposes a DC bus voltage flexible control method of the AC/DC hybrid microgrid with direct participation of electric vehicles. A matlab/simulink simulation system is built to verify the effectiveness of this method which is applied in actual projects.

2 Hybrid AC/DC Microgrid System with Electric Vehicles

The traditional microgrid system has mainly AC bus, through which renewable energy power generators, energy storage, load and power grid exchange energy. The main load of the microgrid system studied in this paper is DC charging, and the main renewable energy power generation unit of the microgrid is photovoltaic system, which is also the most efficient conversion to DC. Therefore, the AC/DC hybrid microgrid with DC bus for energy interaction is more suitable for the microgrid system with electric vehicles. The flexible control strategy of DC bus for hybrid AC/DC microgrid is accomplished by power electronic equipment and microgrid controllers connected to DC bus. The detailed description is as follows.

The structure of hybrid AC/DC microgrid system with electric vehicles is shown in Fig. 1. The primary equipment of the microgrid includes PV power generation units, energy storage units, charging and discharging equipment for electric vehicles, four-quadrant AC/DC converters (short for AC/DC), power distribution switches and loads. The main secondary equipment includes a microgrid controller and microgrid energy cloud software.

2.1 Primary System Structure

The microgrid system studied in this paper is composed of two parts: AC part and DC part. Within the microgrid, the photovoltaic system, energy storage and charging and discharging equipment of the DC part exchange energy through the DC bus. For two-way energy interaction, the AC part is connected to the large power grid through an AC switch, and there is also some AC load on AC side.

2.2 Secondary System Structure

The secondary system consists of two parts: a microgrid controller and microgrid energy cloud software.

The microgrid controller collects DC bus voltage, PV, energy storage, AC/DC, and charging and discharging equipment output current through DC Hall sensors.

The microgrid controller communicates with the microgrid energy cloud through Internet. Since the stability control issue mainly discussed in this paper is mainly completed in the microgrid controller and various power electronic devices, the microgrid energy cloud is not described much.

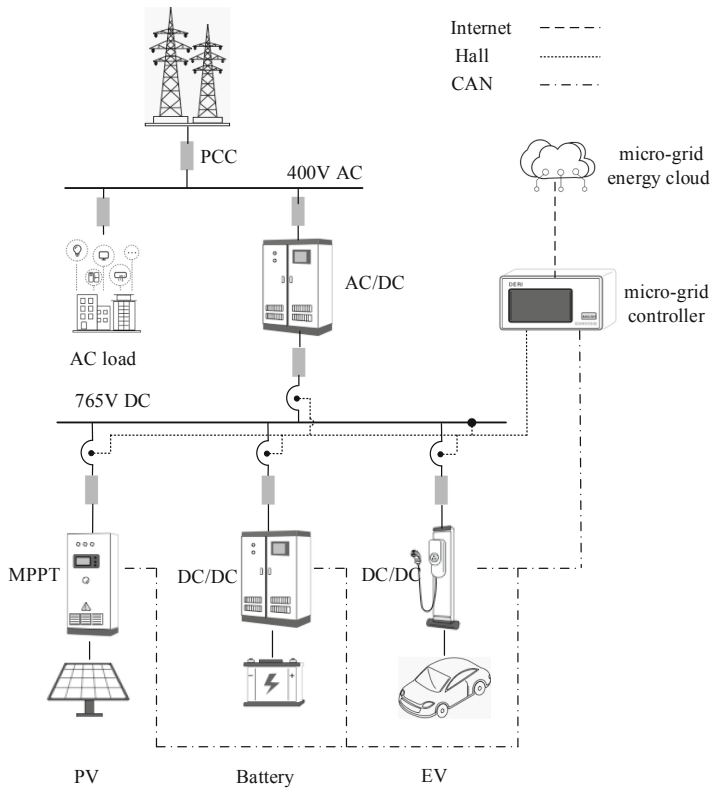


Fig. 1. The system structure of hybrid AC/DC microgrid

AC/DC. The topology and control loop of AC/DC are displayed in Fig. 3.

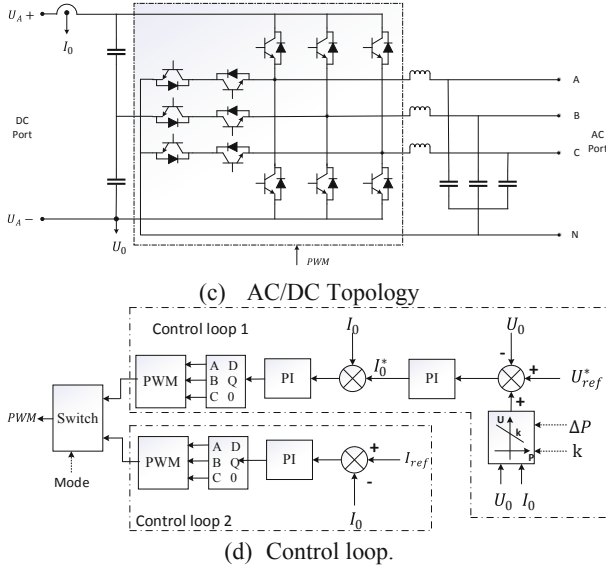


Fig. 3. The topology and control loop of AC/DC

AC/DC equipment adopts T-type three-level topology, which can realize bidirectional power interaction. Figure 3 (b) gives the control logic of DC port, which is similar to DC/DC and won't be detailed here.

Droop Control. The droop control loop is written:

$$U_0^* = U_{ref}^* - k(P_{out} - \Delta P) \quad (1)$$

where U_0^* is the reference voltage of the voltage outer loop, U_{ref}^* is the rated voltage set by the power electronic device, k is the droop coefficient, P_{out} is the current output power, and ΔP is the power change rate adjusted by the microgrid controller.

The value of ΔP and k is set. When ΔP is set to 0, the actual reference voltage U_0^* of the voltage outer loop will decrease as the output current increases, which shows the droop control characteristic. When ΔP is not 0, not only U_0^* of the voltage outer loop decreases as the output current increases, but the rated voltage U_{ref}^* set by the power electronic device also changes, i.e., the droop curve has shifted.

3.2 Flexible Control Strategy of DC Bus Voltage

The flexible control strategy of bus voltage is realized by microgrid controllers, and its control logic diagram is illustrated in Fig. 4.

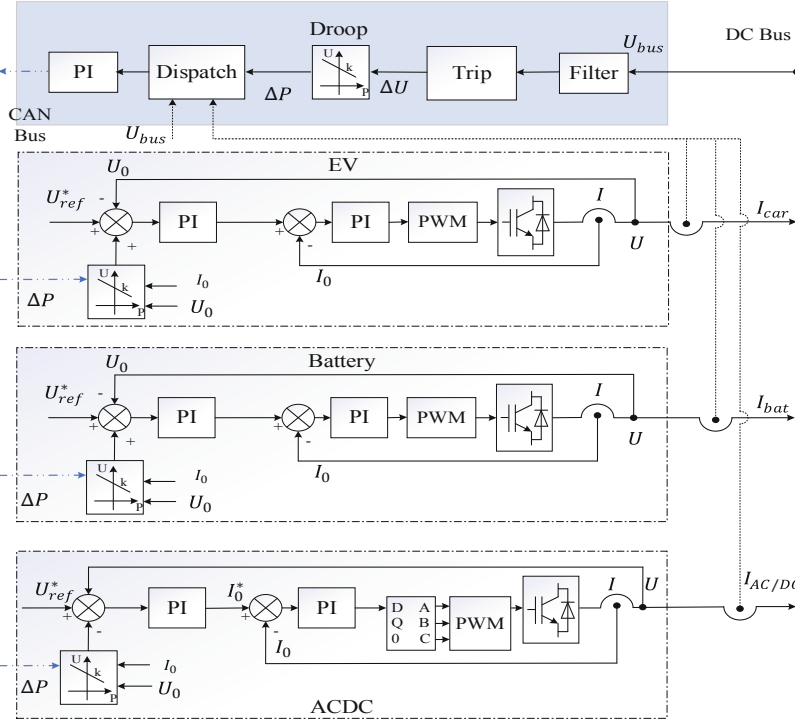


Fig. 4. The diagram of flexible control logic block

The core idea of flexible control is to calculate the shortfalls of DC bus system power through the change of DC bus voltage, and select the appropriate power electronic equipment to compensate for it, and finally achieve the purpose of DC bus voltage stabilization.

Figure 4 presents a logic diagram of three-node system in bus flexible control where the control method can be decomposed into three parts: trip logic, system droop curve computational logic, and power distribution logic. Elaborations respectively are as follows.

Trip Logic. The bus voltage trip logic triggers the process and output difference of current voltage. The voltage trip criterion is written:

$$|U - U_n| > \Delta U_{set} \quad (2)$$

where U is bus voltage, U_n is the bus rated voltage, ΔU_{set} is the voltage deviation set-value. The setting principle is that the equipment connected to DC bus can operate normally within this range.

At this time, the output voltage fluctuation value is $\Delta U = U - U_n$.

Droop Curve Computational Logic. The main function of the droop curve calculation logic is to calculate the droop curve of microgrid system in real time, and output the unbalanced power value of the system according to the voltage value output by the start-up logic.

For example, in Fig. 4, the control system is composed of two DC/DC and one AC/DC in parallel. Each power electronic device has a U/P droop due to its virtual impedance, so the virtual impedance of the DC bus system is parallel connection of the impedances of three power electronic modules.

It should be noted that only when the device is running in voltage source mode with droop loop can the virtual impedance of the device be calculated into the system impedance. In other words, virtual impedance of the device should not be calculated in parallel with DC bus system when the device is running in current source mode or in a fault state.

Power Distribution Logic. The droop curve calculation logic has calculated the system power fluctuation value, and the power allocation logic allows the user to achieve the final power allocation. The calculation method is as follows:

- (1) Each drooping node can be artificially set a weight coefficient δ ($\delta \in [0, 1]$). Increase the setting value if you want the node to participate in the adjustment first;
- (2) The device is in a locked state, that is, if the node state is abnormal and the regulated power cannot be output, then the device is locked and will not participate in adjustment;
- (3) Calculate the power reserve rate. Take P_n as the rated output power of the power electronic equipment participating in the control, and P as the current output power, then the power reserve rate of the droop device at this moment is:

$$\beta = |P_n - P|/P_n \quad (3)$$

4. Calculate the energy reserve rate. For the energy storage device, the energy reserve rate is calculated as follows:

$$\gamma = (W_n - W)/W_n \quad (4)$$

Where W_n is the rated capacity of energy storage. W is the current capacity value of energy storage. For actual control system, the energy reserve rate can be directly replaced by the stored energy SOC (State-of-charge) value ($[0, 100]$). For non-energy storage power electronic equipment set $\gamma = 100$;

5. For a non-locked device, the competition coefficient is:

$$\partial = \delta \times \beta \times \gamma \quad (5)$$

For the locked device, $\partial = 0$;

6. Sort the competition coefficients of each drooping node in descending order;
7. The total power fluctuation value calculated by the droop curve computational logic is distributed according to the competition coefficient calculated in step 5). The principle of allocation is to prioritize drooping nodes, the number of which can be more than one, that are ranked first. After allocating to each node through the CAN bus, this control is completed.

3.3 Impact Analysis Droop Factor of Stability

The value of the droop coefficient will affect the stability of the system. Literature [18] and literature [19] discussed the stability of multi-machine parallel connection in detail using the small signal stability method. This paper uses a graphical method to qualitatively analyze the impact of different droop coefficients on system operation.

Take two modules in parallel as an example, as shown in the following figure:

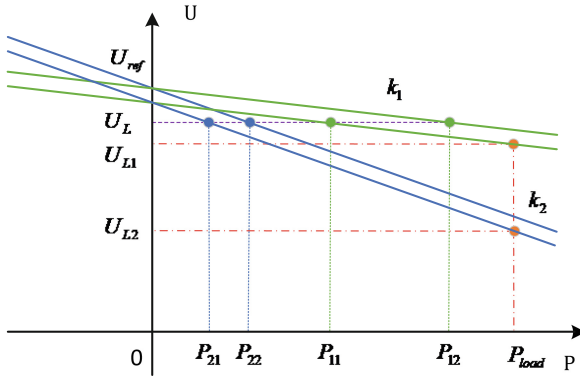


Fig. 5. Diagram of the effect of droop parameters on stability

Test case 1 is the combination of two modules with droop gain k_1 . Test case 2 is the parallel connection of two modules with droop gain k_2 . The k_1 is less than k_2 .

It can be seen that when the bus voltage changes from U_{ref} to U_L , the power difference of test case 1 is $P_{22} - P_{21}$, and the power difference of test case 2 is $P_{12} - P_{11}$. It can be seen that a larger droop gain has better current sharing performance.

In addition, when the system power output P_{load} , the voltage of test case 1 drops to U_{L1} , and the voltage of test case 2 drops to U_{L2} . This means that a small droop gain has better stability.

4 Test Verification

4.1 Test System

In order to verify the effectiveness of the method described, a test system was built based in matlab/simulink. Figure 5 shows the schematic diagram (Fig. 6).

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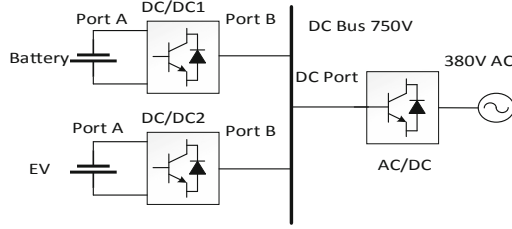


Fig. 6. Test system structure.

The initial equipment parameters and control parameters of each distributed power supply are displayed in the table below (Table 1).

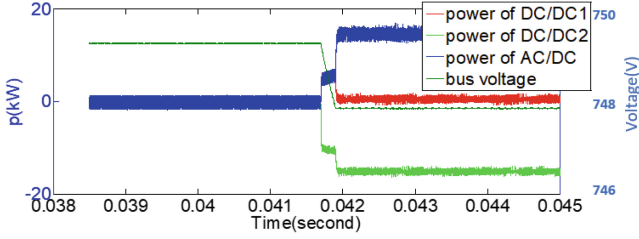
Table 1. System parameters

Device	$U_n(V)$	$P_n(kW)$	Soc	$k(V/kW)$	δ
AC/DC	750	60	/	1	1
Battery	750	15	50	4	1
EV	750	15	50	4	1

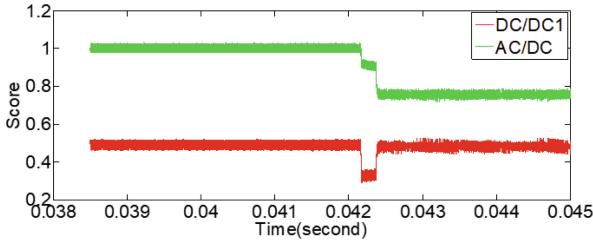
In the table: U_n is rated voltage, P_n is the rated capacity of distributed power supply, and SOC is the power of each distributed power supply. For systems without energy storage, the default SOC is 1, k is the droop coefficient of the distributed power supply, δ is manually set weight coefficient. The range of stable start-up voltage was [748, 752] V.

4.2 Test Cases

Case 1: Electric Vehicles Charging in Grid-Connected Mode. The initial test conditions were: DC/DC1 stabilized the voltage on port B; DC/DC2 worked in current source mode, and AC/DC in stable DC port voltage. After the test had started, DC/DC2 charged the electric vehicle at a constant power of 15 kW. The test results are as follows (Fig. 7).



(a) Voltage and power adjustment process.

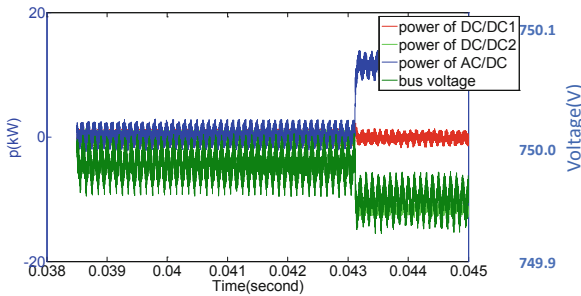


(b) Competition coefficient.

Fig. 7. Test results of case 1.

It is apparent that when DC/DC2 was charged at a constant power of 15 kW, bus voltage started to decline due to the drooping effects of DC/DC1 and AC/DC ports. When the voltage was below 748 V, the flexible control strategy of bus voltage came into effect. As can be seen from the competition scores of DC/DC1 and AC/DC in Figure (b), AC/DC has always had a high competition coefficient. The system added AC/DC power output to supplement the 15 kW charging power shortage. DC/DC1 did not output power under steady state.

In conventional engineering projects, energy storage will operate as a current source, and AC/DC stabilizes the bus voltage. The test results for this condition are as follows (Fig. 8):

**Fig. 8.** Test results of engineering conditions

It can be seen that in the conventional engineering projects, DC/DC1 will not participate in the system stability adjustment, and the power imbalance of the system is adjusted by AC/DC. Since there is no droop, the voltage fluctuation is small.

Case 2: Charging Regulation Process in Off-grid State. The initial test conditions were: DC/DC1 stabilized the voltage on port B; DC/DC2 worked in the current source mode, and AC/DC in current source mode; DC/DC1 maintained stable DC bus voltage. After the test had started, DC/DC2 charged the electric vehicle at a constant power of 15 kW. The test results are as follows (Fig. 9).

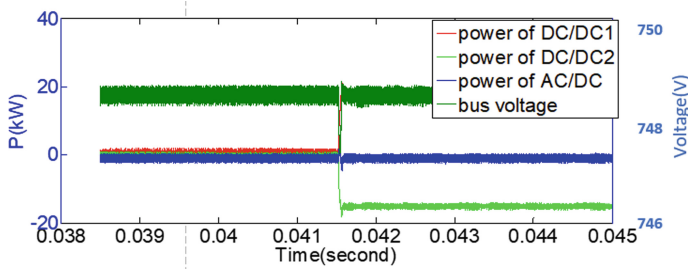


Fig. 9. Test results of case 2.

Because the system only had one voltage source, when DC/DC2 was charged at a constant power of 15 kW, the DC bus voltage descended due to the droop control of DC/DC1. After the voltage was under 748 V, DC/DC1 increased the power output to 15 kW, and the range of bus voltage was brought back to [748, 752] V, while the system entered steady state operation.

Under normal engineering conditions, the bus voltage is supported by DC/DC1, and the test data is as follows (Fig. 10):

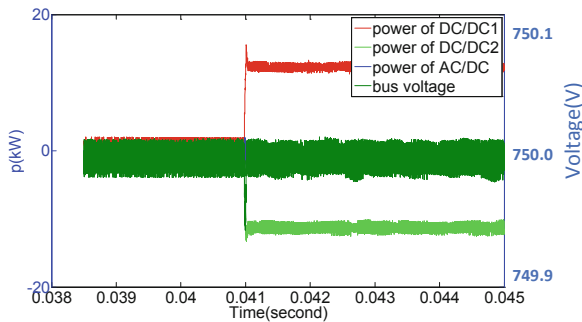


Fig. 10. Test results of engineering conditions

Since this working condition has only one source of stable DC bus, the test result under this working condition is basically consistent with the above result. The advanced nature of this solution can only be reflected when multiple voltage sources stabilize the bus at the same time.

Case 3: Supporting AC Load in Off-grid State. The initial test conditions were: DC/DC1 stabilized the voltage on port B with DC/DC2; AC/DC worked in current source mode. After the test had started, AC/DC generated power to the AC grid at a constant power of 15 kW. The test results are as follows (Fig. 11).

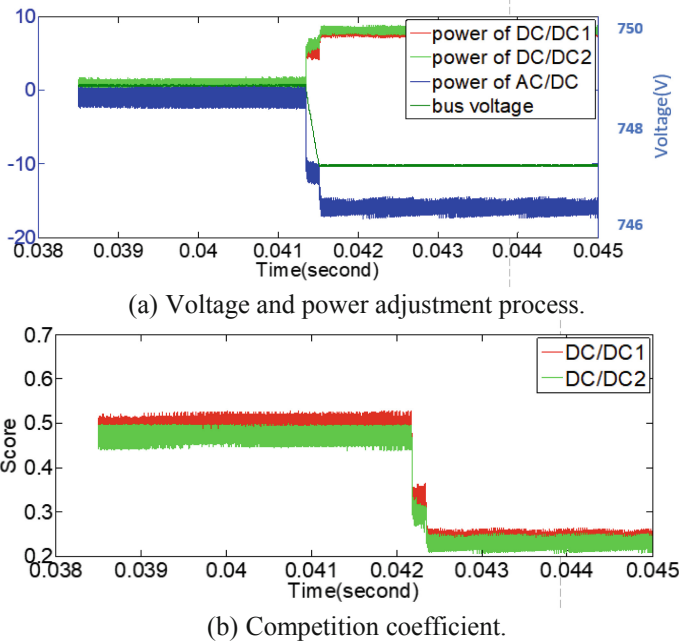


Fig. 11. Test results of case 3.

Similar to the previous two test conditions, DC bus voltage began to drop at the beginning stage due to the droop effect of DC/DC1 and DC/DC2 ports. The flexible control strategy of bus voltage started when the start value was lower. DC/DC1 and DC/DC2 shared the same original setting parameters. It can also be seen from Figure (b) that the two devices basically had the same competition coefficient. The average output of DC/DC1 and DC/DC2 was about 7.5 kW. As a result, the system entered a steady state and the bus voltage was stable at the set interval.

The bus voltage is supported by DC/DC1 in normal engineering conditions. The test data is as follows (Fig. 12):

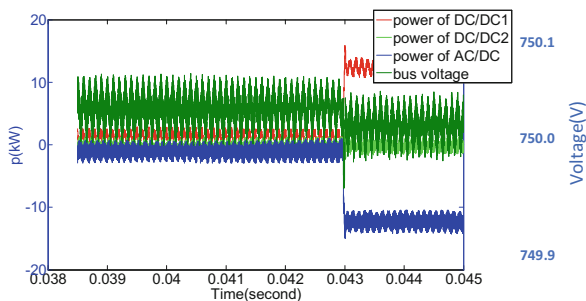


Fig. 12. Test results of engineering conditions

It can be seen that the power imbalance of the system is adjusted by DC/DC1, and the system will lose its stability after the AC power exceeds the maximum output power of DC/DC1.

From these three results, it can be seen that compared with power electronic devices without droop loops, when sudden power changes occur, power electronic devices could automatically distribute power according to their respective virtual impedance, and jointly support the stability of the bus; and the flexible control strategy of bus voltage could coordinate power electronic devices in different operating modes such as grid-connected mode and off-grid mode, it could also select devices with strong adjustment capabilities and keep the system voltage in the set range. Thus, the inertia and the power quality of DC bus are greatly improved.

5 Conclusion

This article focuses on the stability of the DC bus voltage of a hybrid AC/DC microgrid system with electric vehicles. The P/U droop characteristics of DC ports of power electronic equipment such as devices of energy storage, charging and discharging equipment for electric vehicles are fully utilized, meanwhile, the power reserve rate and energy reserve rate of different types of distributed energy are considered. Employing flexible adjustment methods like curve translation, the inertia of DC bus is improved, the stability of the microgrid system voltage is effectively guaranteed, and the power quality of DC system is promoted. The method described in this article has been widely used in charging system in the TELD company, integrating photovoltaics energy storage and charging for electric vehicles, which guarantees the safe and stable operation of the system and brings great economic benefits.

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