Power coordination control strategy of microgrid based on photovoltaic generation

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Abstract. In order to solve the large-scale grid-connected photovoltaic cells caused by power fluctuations, power quality decline and other issues. This paper proposes and researches a power coordination control strategy for microgrid based on photovoltaic power generation. The principle of photovoltaic cells and the switching of maximum power point tracking and limited power mode are studied. The stability control methods of DC bus voltage, AC bus wire and frequency are studied. The model of microgrid is established and moreover, based on the power of microgrid and the charging state of storage battery, the operation of microgrid is divided into different working modes. The stable operation of microgrid is realized by adjusting the output power of each unit in different working modes. The calculation shows that the control strategy can effectively reduce the power fluctuation in the microgrid and improve the output power of renewable energy. Finally, the feasibility and effectiveness of the proposed methods are verified by experiments.

1 Introduction

Due to the global energy over-consumption and environmental pollution are becoming more and more serious, the renewability and non-pollution of solar power let it be favored by social development. Photovoltaic cells convert light energy directly into electricity through photovoltaic effect, which has sufficient cleanliness, While protecting the environment, it effectively solves the problem of limited conventional energy[1]. However, the large-scale use of photovoltaic cells can cope with the energy crisis, because of its own intermittent shortcomings of power generation, when grid-connected, it will cause power fluctuation and reduce power quality, thus limit power generation, while the proposal of microgrid proposes to solve such problems.

Microgrid can be divided into DC microgrid, AC microgrid and AC-DC hybrid microgrid according to different forms of electric energy[2-3]. AC-DC hybrid microgrid has AC bus bar and DC bus bar, which can provide electric energy for AC load and DC load at the same time. It not only omits multiple power conversion links, simplifies microgrid structure and distributed power supply mode, but also improves operation efficiency and economy. And the control methods are more flexible. Therefore, in islands[4], remote mountainous areas and other places which cannot be connected to the

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large grid, AC-DC hybrid microgrid operation is more effective. This paper takes the isolated island mode of optical storage diesel AC-DC hybrid microgrid as the research object, focusing on its control strategy.

The control objective of AC-DC hybrid microgrid is to ensure the stability of DC bus bar voltage, AC bus bar voltage and frequency[5]. The coordinated control strategy of hybrid microgrid was studied in Reference[6-7]. The operation effects of microgrid power balance, maximum power output of micro-source and minimum energy interaction between AC and DC buses were achieved. Literature[8] presents a hierarchical control strategy for AC/DC hybrid microgrid, which solves the power control problem of parallel bidirectional AC/DC converters. However, the above control strategies do not take the frequent switching of control strategies into account due to bus voltage fluctuations. Reference[9] considers the power control strategy of DC microgrid and divides DC microgrid into four working modes based on power. However, it does not consider the shortage of photovoltaic power supply.

Considering the limitation of energy storage capacity, mode switching of photovoltaic power generation units and combined power supply of diesel generators, this paper proposes a power coordination control strategy under islanding mode of AC/DC hybrid microgrid. Based on the system power and the state of charge (SOC) of storage battery, this method determines the different working modes of each module in the microgrid under different operating conditions, and realizes the coordinated power control of the microgrid based on photovoltaic power generation.

2 Principle of photovoltaic power generation

Photovoltaic power generation is a way of conversion of light energy into electricity through photovoltaic effect of semiconductor materials[10].The surface of photovoltaic cells is covered with a thin sheet of metal-film semiconductor. When sunlight illuminates the semiconductor materials and electromotive force is generated at both ends of the semiconductor materials. The principle of photovoltaic power generation is shown in Figure 1.

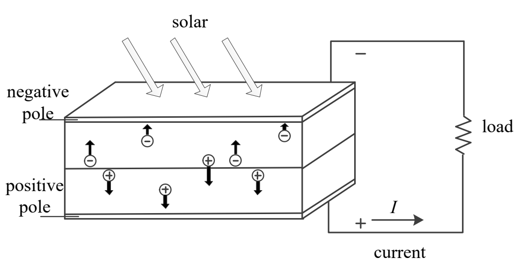

Fig. 1. The principle of photovoltaic power generation.

The photovoltaic cell is equivalent to a PN junction. When P-type and N-type semiconductor materials are combined, The electrons in the N-type region will diffuse into the P-type region, holes in the P-type region will diffuse into the N-type region, forming barrier wall. At this time, N-type is charged positively, P-type is charged negatively, and the whole is not charged. At this time, strong built-in electrostatic field will be generated inside the semiconductor, forming P-N junction, as shown in Figure 2.

When sunlight irradiates the PN junction, a new pair of holes-electrons will be formed in the barrier area. Because of the strong built-in electrostatic field in the barrier area of PN junction, the pair of holes-electrons in the barrier area will be generated or the pair of holes-electrons in the barrier area will be generated outside the barrier area but spread to the inside of the barrier area. Under the action of the built-in electrostatic field, the direction of the movement begins, electrostatic field, the direction of movement begins. As the electrons leave the barrier region, the potential in P region increases and the potential in N region decreases. Photogene rated electromotive force is generated at both ends of PN junctions. As shown in the principle of photovoltaic power generation in Fig. 1, Assume that PN junctions are connected to loads, there is an uninterrupted potential difference at both ends of the circuit when sunlight illuminates.

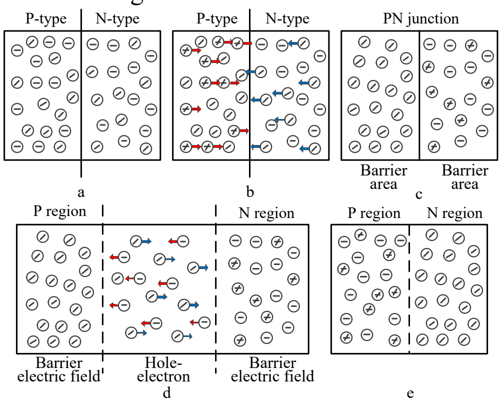

Fig. 2. Working principle of PN junction.

3 AC/DC hybrid microgrid structure

The hybrid microgrid structure studied in this paper is shown in Figure 3. It composed of three parts: DC subnet, AC subnet and bidirectional AC/DC converter[11].

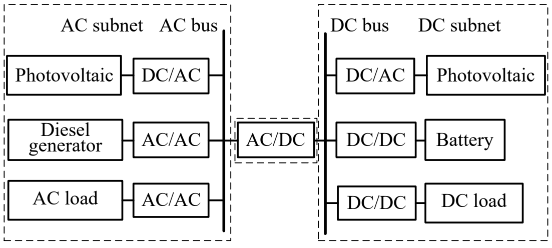

Fig. 3. Hybrid microgrid structure.

Among them, photovoltaic power generation works in the state of maximum power point tracking (MPPT) or limited power control; battery charge and discharge controls or no work; diesel generator starts when system power is insufficient; diesel generator performs load shedding operation when output power is insufficient to supply load power.

4 Power coordination control strategy in island mode

The AC-DC hybrid microgrid in islanded mode can be equivalent to a small isolated distribution power system. The power flow pattern is shown in Fig. 4.

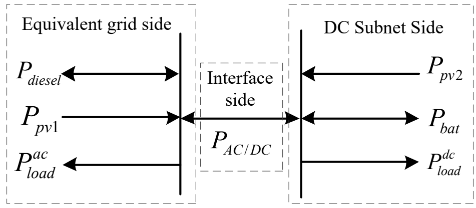

Fig. 4. Power flow in microgrid under islanding mode.

If P_{offnet} is system power, it can expressed by fomula(1).

$$P_{offnet} = P_{pv1} + P_{pv2} - P_{load}^{ac} - P_{load}^{dc} \tag{1}$$

P_{pv1} and P_{pv2} are the output power of AC and DC side photovoltaic respectively. P_{load}^{ac} and P_{load}^{dc} are AC and DC side loads respectively.

When $P_{offnet} < 0$,At this time, the supply of the system is less than the demand, and need battery to provide energy ;if $P_{bat,d,\max} > |P_{offnet}|$, and $SOC > SOC_{\min}$, At this time, the battery is discharged to maintain the power balance of the system, if $P_{bat,d,\max} < |P_{offnet}|$,and $P_{bat,d,\max} + P_{diesel,\max} > |P_{offnet}|$,diesel generators start quickly to provide energy for the system. When the output of diesel generators is not enough to supply all loads in the microgrid, the same meaning as $P_{bat,d,\max} + P_{diesel,\max} < |P_{offnet}|$,Load shedding is needed to balance the power of the system; if $P_{offnet} > 0$,This indicates that the excess energy in the microgrid is not absorbed. If $SOC < SOC_{\max}$, at this time, the battery is charged to make the system power balance. If $SOC < SOC_{\max}$, batteries cannot be recharged, and at this time, the photovoltaic unit runs in the limited power mode to maintain the power balance of the system[12].

Above mentioned $P_{bat,d,\max}$, is the maximum discharge power for batteries, $P_{diesel,\max}$ is the maximum output power of diesel generator， $SOC_{\min}$ and $SOC_{\max}$ are the limit and the upper limit of state of charge for storage battery.

The island mode power coordination control strategy is shown in Table 1.

Table 1. AC/DC Hybrid microgrid operating mode in isolated island mode.

Mode	Photovol-taic	Battery	Diesel	Load
①	MPPT	Charge	Standby	Normal
②	Limiting power	Standby	Standby	Normal
③	MPPT	Charge and discharge	Standby	Normal
④	MPPT	Discharge	Standby	Normal
⑤	MPPT	Discharge	Start up	Normal
⑥	MPPT	Charge	Start up	Load Cut

①When $P_{offnet} > 0$,The photovoltaic unit operates in MPPT mode. When the illumination is sufficient, the distributed generation unit can not only supply power to the AC and DC load, but also charge the energy storage unit. At this time, the bidirectional AC/DC converter is responsible for stabilizing the energy balance of the AC microgrid side, the energy storage unit is responsible for the voltage stability of the DC bus bar, and the energy storage unit charges and absorbs surplus power to maintain the voltage balance of the DC bus bar.

②On the basis of the mode ①, if at this time $SOC \geq SOC_{\max}$, then the storage unit is changed from charging to standby. At this time, the photovoltaic unit operates in the limited power mode.

③When $P_{offnet} = 0$, at this time, the photovoltaic power unit runs in MPPT mode, and the output power of photovoltaic power is equal to the total load demand of the system. According to the load situation of AC and DC sides and the generation capacity of AC and DC sides, the flow direction of the bidirectional converter is determined. When the residual energy of AC side occurs, the bidirectional converter transmits energy to DC side, and vice versa. Thus ,the overall power is balanced in the system, the bi-directional AC/DC converter works in the rectifier or inverter state and it is responsible for stabilizing the energy balance at the AC microgrid side, and the energy storage unit works in the charge-discharge mode to regulate the voltage stability of the DC bus.

④ When $P_{offnet} < 0$,System Power Detection $P_{bat,d,\max} > |P_{offnet}|$ and battery $SOC > SOC_{\min}$, discharge of energy storage unit maintains system balance.

⑤When $P_{offnet} < 0$,System Power Detection $P_{bat,d,\max} < |P_{offnet}|$ and $P_{bat,d,\max} + P_{diesel,\max} > |P_{offnet}|$ At this time, the battery and diesel generator can work together to meet the demand of load supply. The DC bus bar voltage of the energy storage unit can be regulated by discharge, and the diesel generator can provide insufficient energy for the system[13].

⑥On the basis of the mode ⑤, if $P_{bat,d,\max} + P_{diesel,\max} < |P_{offnet}|$ and $SOC \leq SOC_{\min}$, Diesel generator supply energy is insufficient to meet the system load demand, and when the battery reaches the lower discharge limit, the non-important load will be removed to maintain the important load power supply.

5 System power balance control

5.1 Control strategy of photovoltaic cells

As shown Fig. 5 in the control schematic diagram of photovoltaic cells, there are two working modes of photovoltaic cells. Generally, photovoltaic cells work in MPPT mode, providing as much renewable energy as possible. When the system has redundant power and the battery reaches the charging limit, the output power of photovoltaic cells needs to be reduced. At this time, the system switches to the Limited power control.

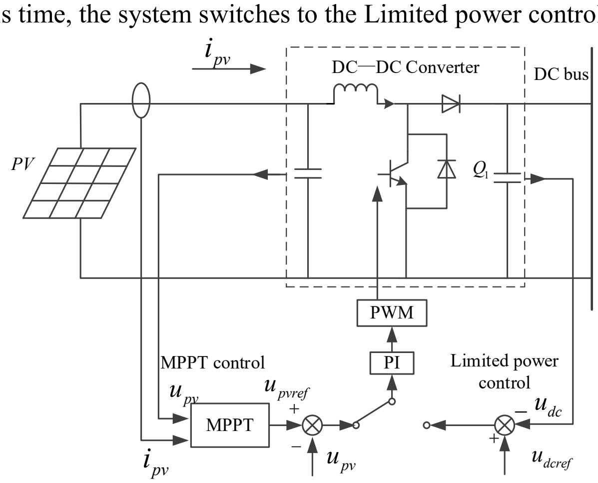

Fig. 5. Control principle of photovoltaic cells.

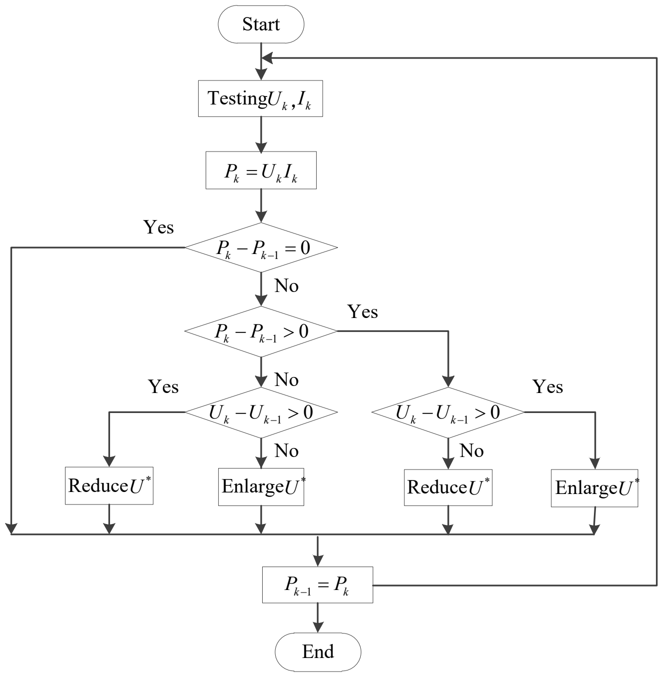

Fig. 6. Flow chart of perturbation observation method.

The maximum power point tracking control adopts disturbance observation algorithm. The principle of disturbance observation method is to sample and measure the output voltage and current of photovoltaic array before and after the change of natural environment parameters. According to the output power of photovoltaic array before and after the change of environmental parameters, the values of the two output power are compared. If the output power of the photovoltaic array increases after the change, the output power of the photovoltaic array will be reduced. One step can change the output voltage in the same direction; on the contrary, if the output power decreases after the change, the next step will change the output voltage in the opposite direction. The flow chart of the algorithm is shown in Figure 6.

Power Limiting Algorithmic Control Principle: When the output power of photovoltaic power generation system exceeds the demand power, photovoltaic output needs to be limited. The photovoltaic power generation system adopts constant voltage control mode. The difference between the given value of DC bus voltage and the measured actual value of voltage is used as the input of PI controller. The duty cycle of DC/DC converter is controlled to maintain the stability of DC bus voltage, so as to reduce the power generation of photovoltaic cells.

5.2 DC bus bar voltage stability control

Battery is the core of controlling DC bus bar voltage stability. There is a nPon-linear relationship between DC bus bar side support capacitor voltage and power difference between distributed power supply[14-15], energy storage and bidirectional converter can gain by formula(2).

$$C_{dc}U_{dc}\frac{dU_{dc}}{dt} = P_{DG} + P_{Bat} - P_{AC/DC} \tag{2}$$

In(2), C_{dc} is DC bus bar side capacitance，When the power shortage occurs in the system, the capacitor voltage on the DC bus bar side changed. As shown in formula (3).

$$dU_{dc}(t)=\sqrt{\frac{2}{Cdc}\int_{t}^{t+\Delta t}(P_{DG}(t)+P_{Bat}(t)-P_{AC/DC}(t)dt} \tag{3}$$

It can be seen from the above formula that when the power of the system is unbalanced, the change of DC voltage dU_{dc} and the average power gap $dP(t)$ in this period are as follows:

$$dP(t)=\frac{\int_{t}^{t+\Delta t}(P_{DG}(t)+P_{Bat}(t)-P_{AC/DC}(t)dt}{\Delta t} \tag{4}$$

By synthesizing (3) and (4), there is:

$$dP(t+\Delta t)=\frac{dU_{dc}^{2}(t+\Delta t)}{dU_{dc}^{2}(t)}dP(t) \tag{5}$$

It can be seen that the instantaneous power gap decreases gradually with the stabilization of the storage power or the power between the two-way converters. In this paper, the stable control of DC bus bar voltage is realized by PI control of bidirectional DC/DC converter of storage battery. The control principle is shown in Fig. 7.

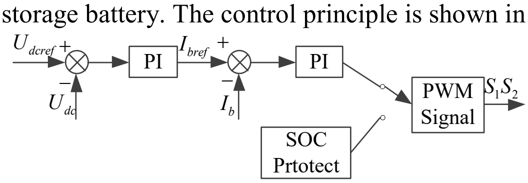

Fig. 7. Battery control principle.

5.3 AC bus bar voltage and frequency stability control

The voltage and frequency of the AC subsystem lose the support of the large grid when the microgrid is isolated. At this time, the hybrid microgrid maintains the stability of the voltage and frequency of the AC side through the bidirectional AC/DC converters between the AC and DC bus bars[16]. In this paper, the V/F control algorithm is used to realize the stability of AC bus bar.

The loop equation of AC/DC converter in dq coordinate is shown in equation (6).

$$\begin{cases} u_d-u_{cd}=L\frac{di_d}{dt}-L\omega i_q \\ u_q-u_{cq}=L\frac{di_q}{dt}-L\omega i_d \\ i_d-i_{ad}=i_{cd}=C\frac{du_{cd}}{dt}-C\omega u_{cq} \\ i_q-i_{aq}=i_{cq}=C\frac{du_{cq}}{dt}+C\omega u_{cd} \end{cases} \tag{6}$$

According to (6) and PI regulator, the voltage outer loop and current inner loop equation of V/F control can be obtained by formula (7) and (8).

$$\begin{cases} i_{dref} = \left(K_P + \frac{K_I}{s}\right)\left(u_{dref} - u_{cd}\right) - \omega C u_{cq} + i_{ad} \\ i_{qref} = \left(K_P + \frac{K_I}{s}\right)\left(u_{qref} - u_{cq}\right) + \omega C u_{cd} + i_{aq} \end{cases} \tag{7}$$

$$\begin{cases} u_{sd} = \left(K_P + \frac{K_I}{s}\right)\left(i_{dref} - i_{d}\right) - L\omega i_q + u_{cd} \\ u_{sq} = \left(K_p + \frac{K_I}{s}\right)\left(i_{qref} - i_{q}\right) - L\omega i_d + u_{cq} \end{cases} \tag{8}$$

From the above governing equations, the V/F control structure of bidirectional AC/DC converter can be obtained as shown in Fig. 8.

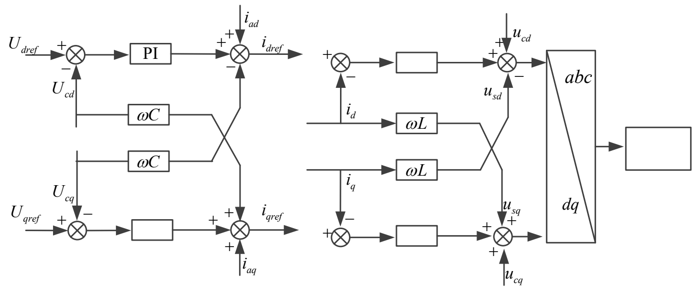

Fig. 8. V/F control structure.

6 Simulation verification

In order to verify the feasibility and validity of the above control strategy, a power control model in islanding mode of AC/DC hybrid microgrid is built in MATLAB/Simulink, and a series of simulations are carried out.

Set up the maximum output power of photovoltaic as 20 kW, the capacity of diesel generator 35 kW, the rated capacity of storage battery 80 Ah, the upper limit of storage battery is 80%, and the lower limit is 20%. And also, set up the rated power of bidirectional AC/DC converter as 50 kW, the switching frequency 5 kHz, the capacitance value of DC side 2200F, the inductance value of LC filter on AC side 2 mH, and the capacitance value as 6.85F.

Under mode ①, the photovoltaic battery operates in MPPT mode with sufficient illumination and it can charge the battery when the load is satisfied. When the illumination of the system is insufficient or the load of the system is increased, the battery is transformed from charging mode to discharging mode. After system power detection, the battery discharge is insufficient to meet the requirements, and the diesel generator is started. At this time, the system is transformed from mode ① to mode ⑤.

In order to verify the smooth switching from mode ① to mode ⑤, the initial illumination is set as $1000W/m^2$ and the illumination is switched to $500W/m^2$ in 2.5s.

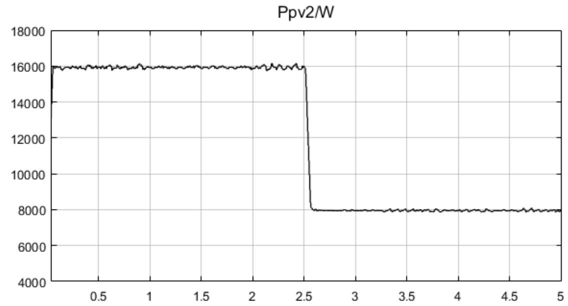

Fig. 9. DC side photovoltaic output power.

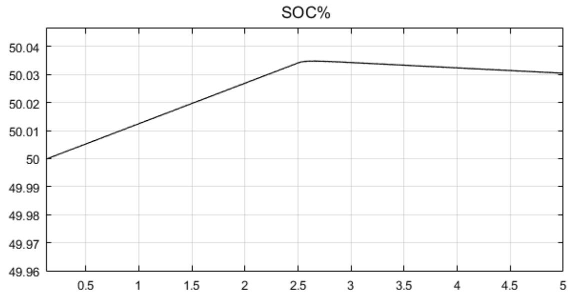

Fig. 10. SOC status of storage battery.

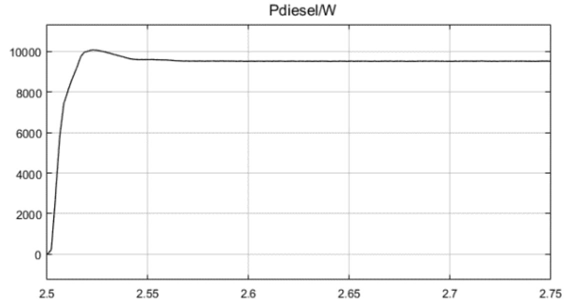

Fig. 11. Output power of diesel generator.

As shown in figs. 9, 10 and 11, the illumination intensity is reduced from $1000W/m^2$ to $500W/m^2$ at 2.5 s, and the photovoltaic output power is reduced from 16 kW to 8 kW, and the battery is changed from charging state to discharging state. According to the judgment of power determination, the remaining capacity of storage battery is insufficient to meet the load demand, and the diesel generator starts.

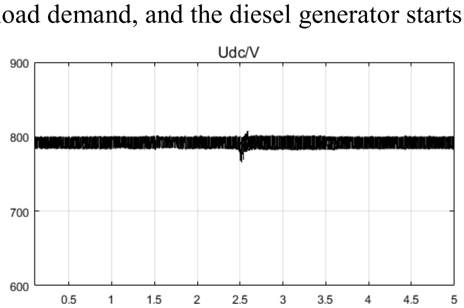

Fig. 12. DC Bus Voltage.

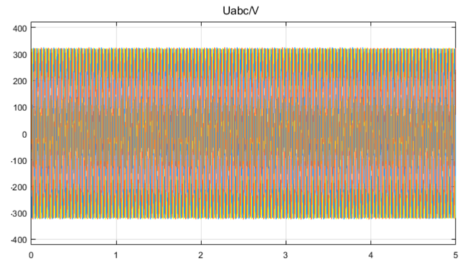

Fig. 13. AC Bus Voltage.

As shown in figs. 12 and 13, at 2.5s, due to the start of diesel generator, the DC bus bar voltage drops, and the bus bar voltage deviation is about 18V. Then the DC bus bar voltage keeps stable rapidly. The AC bus bar voltage remains stable.

On the basis of working mode①, when the distributed power generation is sufficient, the battery reaches the upper charge limit, and the photovoltaic power limit is controlled. The simulation results are shown in the following figure.

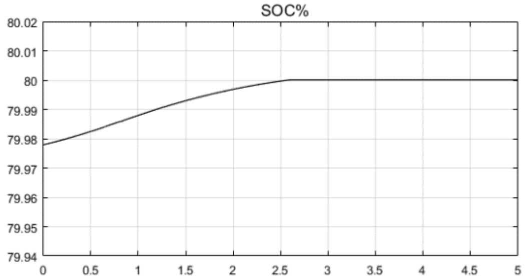

Fig. 14. SOC status of storage battery.

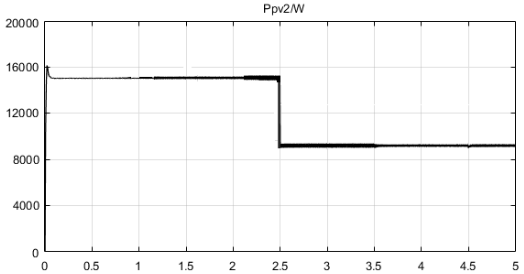

Fig. 15. Photovoltaic output power.

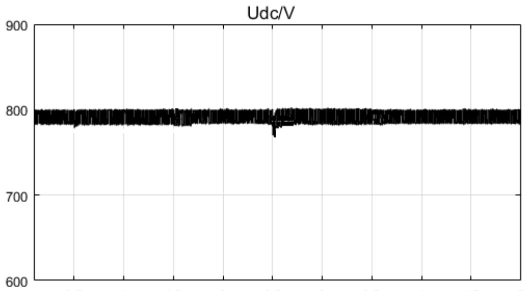

Fig. 16. DC bus voltage.

As shown in figs. 14, 15 and 16, the battery reaches the upper charge limit at 2.5s, and the photovoltaic power limit is controlled. At 2.5s, the DC bus voltage decreases, and the bus voltage deviation is about 20V, and then it keeps stable rapidly.

When the DC side load increases, the system works in mode⑥. The battery discharges and the diesel generator starts. When the SOC of the battery reaches the lower discharge limit, the system does not have enough power to supply the load, and the non-important load is removed.

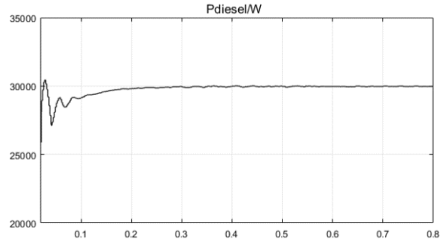

Fig. 17. Output Power of Diesel Generator**.**

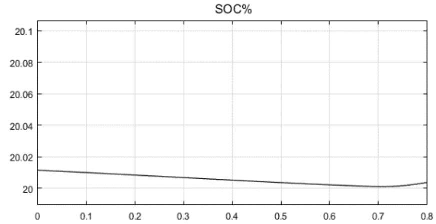

Fig. 18. SOC Status of Storage Battery.

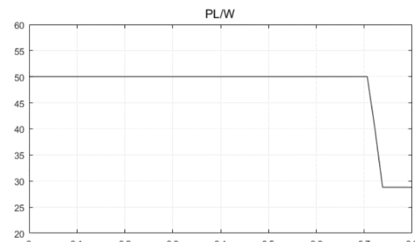

Fig. 19. Load output power.

As shown in figs. 17, 18 and 19, at 0-0.7s, the DC bus bar voltage is maintained by the combined supply of diesel generators and storage batteries. At 0.7s, because the battery reaches the lower discharge limit and the battery stops discharging, the output of diesel generator and battery cannot meet the power demand of the load, so load-shedding operation is carried out.

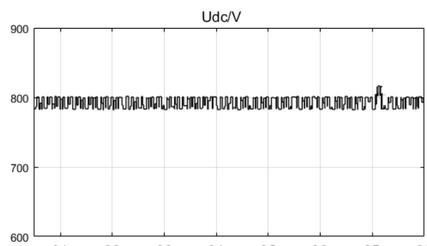

Fig. 20. DC bus voltage.

As shown in Fig. 20, when the load is cut off at 0.7s, the bus bar voltage rises with a deviation of about 18V, and then the bus bar voltage remains stable and the power balance of the system is maintained.

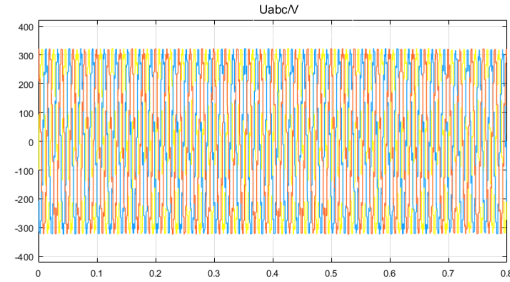

Fig. 21. AC bus voltage.

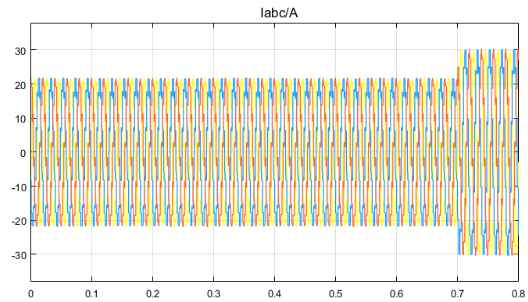

Fig. 22. AC bus current.

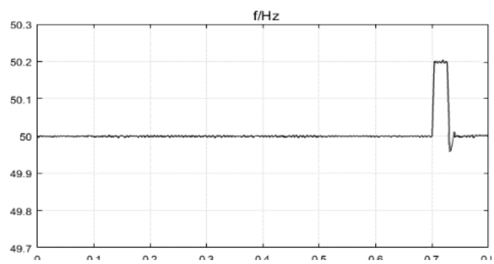

Fig. 23. AC bus frequency.

As shown in figs. 21, 22 and 23, the AC bus bar current rises instantaneously in 0.7s load-cutting operation. Due to the V/F control of bidirectional AC/DC converter, the AC bus bar voltage remains stability, and the AC bus bar frequency rises rapidly and remains stability, with a deviation of about 0.2Hz. It is proved that the AC bus bar voltage and frequency are stable successfully when the system is switching off load.

7 Experimental comparison

In order to verify the control strategy proposed in this paper, experimental verification is carried out. The experimental platform is based on the above AC-DC hybrid microgrid structure. The DC bus bar voltage is 800V, the AC bus bar voltage is 380V, and the frequency is 50Hz. Among them, the photovoltaic module of Tianhe Company is selected. The open circuit voltage of the photovoltaic cell is 36V, the short circuit current is 8.65A, the peak voltage is 30.4V, the peak current is 8.22A, and the power is 250W. The output power of the photovoltaic array is 20 kW. The lead-acid batteries of H7-80-L-T2-A, 80AH, TDL40000TE and 31.8 kW are selected as the storage batteries.

Table 2. DC Bus Voltage Deviation Comparison.

Mode	Simulation deviation/V	Experimental bias/V
①	16	35
②	20	38
③	15	36
④	17	37
⑤	18	36
⑥	18	37

Table 3. Comparison of Voltage and Frequency Deviation of AC Bus.

Mode	Simulation deviation		Experimental bias	
	Voltage/V	Frequen-cy/Hz	Voltage/V	Frequen-cy/Hz
①	13	0.12	27	0.18
②	15	0.2	30	0.28
③	12	0.14	28	0.26
④	12	0.12	37	0.25
⑤	16	0.2	36	0.29
⑥	17	0.2	37	0.31

Because the ambient temperature and solar illumination intensity cannot be kept constant during the experiment, the output power of photovoltaic system fluctuates greatly, which causes the bus voltage deviation to fluctuate greatly, and the deviation in the experiment process is larger than that in the simulation environment. However, the deviation ranges are within acceptable range.

8 Conclusions

In this paper, based on photovoltaic power generation, combined with batteries and diesel generators, the AC-DC hybrid microgrid system model is established, and the island mode power coordination control strategy of the AC-DC hybrid microgrid based on photovoltaic power generation is proposed. By judging the system power and battery charging status, the operation of the microgrid is divided into different modes, and the stability of the AC/DC hybrid microgrid in islanding mode is achieved through coordinated control among units in different modes. Finally, the effectiveness and feasibility of this method are verified by simulation and experiment.

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