

Control of Motor-generator Pair for Photovoltaic Power Grid Integration

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Abstract—Photovoltaic power (PV) is integrated into the grid through power inverters. But the inverters lead PV to lose some of the characteristics of conventional power sources that are conducive to grid stability, such as reduced inertia, reactive power regulation capability, and fault ride-through capability. After introducing the power angle characteristics of a motor-generator pair (MGP) and reviewing MGP's existing control methods and PV's characteristics, this paper proposes a DC voltage feedback control method that can make MGP follow the fluctuations of a PV source. The proposal is studied experimentally, with the following results: (1) An MGP system can follow the power fluctuation of PV by using a DC voltage feedback control method. (2) Such feedback enables the PV to have a self-synchronization characteristic, which enables PV to actively contribute to the stability of the grid.

Index Terms—Grid connection, motor-generator pair (MGP), renewable energy, self-synchronization characteristics.

I. INTRODUCTION

CURRENTLY, many countries have proposed the goal of building a power system using almost 100% renewable energy [1]–[4]. However, as the penetration of renewable energy in the grid increases, the stability characteristics of the grid become stressed [5]. In a traditional power grid, a synchronous generator is integrated with the power grid, so its rotor moment of inertia can take energy from, as well as give energy to, the power grid and help maintain the frequency stability of the grid [6]. The excitation system of the synchronous machine can actively adjust its reactive power output by adjusting the excitation current, which scarcely affects the active power transmission [7]. These characteristics of the synchronous machine enable it to actively maintain the stability of the power grid [8].

Renewable energy uses grid-integration inverters, and usually uses a constant-current control method. This control

method requires the inverter to control its output current with reference to the grid voltage [9]. Photovoltaic power (PV) has different power-voltage curves according to the light intensity and ambient temperature. For each curve, the output power can be calculated as a control reference for the inverter output current. This control method allows PV to inject active power into the grid even with some random fluctuations. However, a necessity for this control method is the stability of the grid voltage.

Renewable energy has not yet significantly penetrated the grid, so the voltage in the grid is still maintained by a large number of synchronous units. Once renewable energy more strongly penetrates the grid, with synchronous generators being largely replaced by grid-integration inverters, renewable energy will have to provide its own voltage reference, and the stability of the grid will be reduced. The operational stability of renewable energy grid-integration inverters will also be affected [10]. Therefore, allowing renewable energy to have the ability to actively contribute to grid stability is an important research topic [11].

In order to simulate the rotor inertia of synchronous generators, as early as 1997, A-A. Edris and other experts of the IEEE Task Force working group proposed the concept of a static synchronous generator (SSG). And the wind inertia and primary frequency modulation characteristics of a wind turbine are simulated in the wind power generation system [12]. In 2007, Hans-Peter Beck of the University of Clausthal, Germany, pioneered the concept of a virtual synchronous machine (VISMA), which simulated the moment of inertia and damping characteristics of synchronous generators by adopting the complete mathematical model of synchronous generators [13]. In 2008, Klaus Visscher proposed the concept of a virtual synchronous generator (VSG) based on the European joint project “VSYNC” [14]. The VSG can simulate the moment of inertia and damping characteristics of a synchronous generator. These studies have realized the virtual inertia characteristics of the inverter. By absorbing and releasing transient energy to suppress frequency fluctuations, the VSG helps to improve the frequency stability of the grid. In 2009, Zhong Qingchang, from Loughborough University in the United Kingdom, proposed the “synchronverter” [15]. The synchronverter incorporates a second-order mathematical model of a synchronous generator, which allows the inverter to more closely simulate the synchronous generator. Whether through virtual synchronization technology or additional damping control, it is essential to control the interaction

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between renewable energy sources and the grid. Therefore, if a synchronous machine is incorporated into the grid, it may provide inertia and help to regulate the voltage of the grid.

A motor-generator pair (MGP) consists of two synchronous machines and has been proposed to provide inertia not just for PV but for other renewable energy sources as well [16], [17]. MGP grid integration can provide sufficient inertia for high-penetration renewable energy grids, and with its electric excitation system, it can also flexibly provide a large amount of damping for the grid. Using its mechanical shaft isolation, MGP can also protect renewable energy sources in the event of a grid failure, so that renewable energy is not dropped off the grid and can continue to deliver power to the grid [18], [19]. Preliminary economic analysis shows that the investment cost of MGP accounts for about 5%–10% of the cost of a wind farm. Under the premise that it can improve the stability of the grid and increase the penetration rate of renewable energy, this cost is deemed acceptable [20]. Reference [21] proposes a power control method for MGP, but this method delivers constant input, which cannot make MGP follow the power output of renewable energy fluctuations. Recognizing the importance of having MGP follow the power fluctuation of renewable energy, this paper proposes a control method that can actively maintain the stability of the grid when the renewable energy is supplied to the grid through MGP.

The remainder of the paper is structured as follows. In Section II, the power angle characteristics and control method for MGP are introduced, and a relevant experiment is described. Section III describes the characteristics of each part of the PV-MGP system, together with the DC voltage feedback control method proposed in this paper. Section IV reports on the results of experiments to test the DC voltage feedback control method for PV-MGP integration. Section V describes the self-synchronization characteristics for photovoltaics with MGP. Section VI summarizes this paper's conclusions.

II. MGP POWER ANGLE CHARACTERISTICS AND CONTROL METHOD

The structure of a MGP system is shown in Fig. 1. The PV is integrated into the grid by MGP.

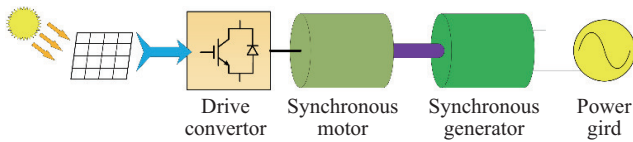


Fig. 1. Structure of MGP.

The two synchronous machines in the MGP system are identical except that one operates in generator mode and the other in motor mode.

For a system with two synchronous machines, it is necessary to analyze the power angle stability of two machines at the same time. Since the rotors of the two machines are connected, the phase difference β of the internal potential of the rotor is fixed, which makes the power angle characteristics of the MGP system differ from these characteristics of ordinary stand-alone

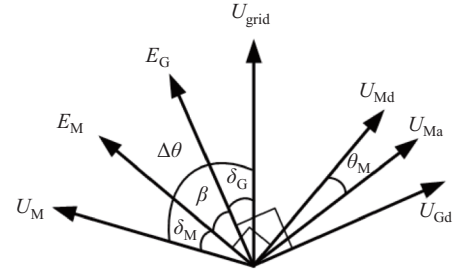


Fig. 2. Phase relationships of the motor-generator pair.

machines. The voltage phase relationships of the MGP system are shown in Fig. 2, where U_M is the output voltage of the grid-integration inverter, E_M is the internal potential of the motor, E_G is the internal potential of the generator, U_{grid} is the grid voltage, U_{Md} is the d-axis component of the stator voltage of the motor, U_{Ma} is the induced electromotive force of the motor A phase, U_{Gd} is the d-axis component of the stator voltage of the generator, δ_M is the motor power angle, δ_G is the generator power angle, and θ_M is the angle between U_{Ma} and U_{Md} . Similar to the case for conventional synchronous generators, the power angle of the MGP system is related to the transmission power.

For synchronous motors, the active power transmitted by it can be written simply as:

$$P_M = -\frac{U_M^2}{x_{Md}} \sin \delta_M \quad (1)$$

where U_M is the motor's terminal voltage, x_{Md} is the motor's stator d-axis reactance, and δ_M is the motor's rotor angle. Similarly, the active power transmitted by a synchronous generator can be expressed as:

$$P_G = \frac{U_G^2}{x_{Gd}} \sin \delta_G \quad (2)$$

where U_G is the generator's terminal voltage, x_{Gd} is the generator's stator d-axis reactance, and δ_G is the generator's rotor angle.

The corresponding relationships among the power changes and the rotor angles of the MGP are shown in Fig. 3. (It is assumed that the angle difference of the two rotors is zero, since the shafts of the two machines are coupled.)

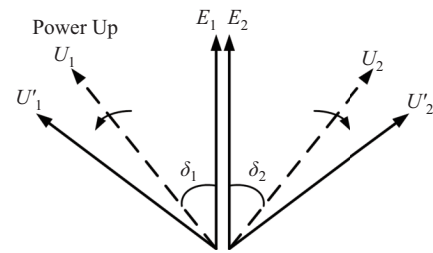


Fig. 3. Power angle characteristics of the MGP.

In order to study the power angle characteristics of a MGP, a power-angle characteristic experiment is designed. The schematic diagram of the experimental system is shown in Fig. 4. Two 5-kW synchronous motors are used to form

the MGP system. A 30-kW inverter simulates the renewable energy grid-connected inverter and drives the motor M. The grid is simulated by a four-quadrant programmable grid simulator. The experiment platform is shown in Fig. 5. The excitation current of the synchronous motor is controlled by a GDX-4 excitation controller. The voltage angles of motor and generator are measured by a power analyzer. The experiment data sheet of power analyzer is shown in Fig. 6. The experimental system parameters are shown in Tables I and II. The synchronous motor M is connected to the inverter, and the synchronous generator G is connected to the grid simulator through the switch K1. The motor terminal voltage is set to U_M , the generator terminal voltage is U_G , and the grid voltage (i.e., the grid simulator output voltage) is U_g . Setting the grid simulator frequency to a fixed value and making the inverter output frequency greater than the grid simulator voltage frequency, it can be predicted that the phase

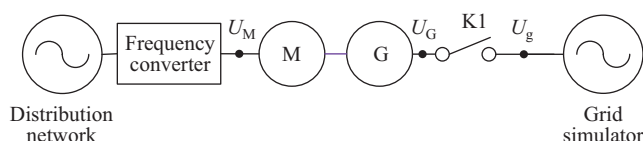
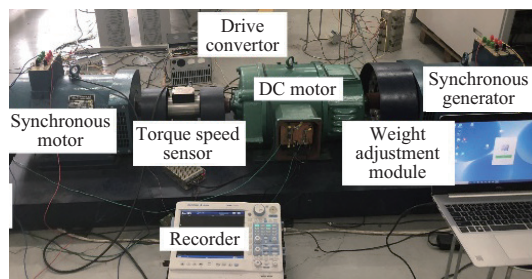


Fig. 4. Power angle characteristic experiment schematic.



(a) Experimental platform



(b) Grid simulator

Fig. 5. Experimental system to study MGP power angle characteristics.



Fig. 6. Experiment data sheet of power analyzer.

TABLE I
EXPERIMENTAL PARAMETER OF MGP-PV SYSTEM

Experiment parameter	Value
AC side line voltage (V)	380
Capacity of frequency convertor (kW)	30
Capacity of generator (kW)	5
Capacity of motor (kW)	5
Power frequency (Hz)	50
Programmable grid simulator (kW)	0–45
L_g (Ω)	0.005

TABLE II
SOME OF THE MOTOR PARAMETERS IN THE EXPERIMENT

Machine parameter	p.u. value	Machine parameter	p.u. value
r_s	0.003	r_f	0.0006
X_{sl}	0.13	X_{fl}	0.076
X_d	2.04	L_{dl}	0.229
X_q	1.93	L_{ql}	0.0812

difference $\Delta\theta$ between U_M and U_G will continue to increase. The active power transmitted by the MGP system is measured. In this way the power angle characteristics of the MGP can be obtained. The power analyzer can measure the motor terminal voltage, current, and corresponding input power as well as the generator terminal voltage, current, and corresponding output power, and can display the phase difference $\Delta\theta$ between U_M and U_G , as shown in Fig. 2. U_1 on the left side of Fig. 3 represents the terminal voltage of the motor A phase, I_1 is the motor phase A current, P_1 is the motor input active power, Q_1 is the motor input reactive power, S_1 is the motor input apparent power, λ_1 is motor A phase power factor; U_2 represents the generator terminal A phase voltage, I_2 is the generator A phase current, P_2 is the generator input active power, Q_2 is the generator input reactive power, S_2 is the generator input apparent power, and λ_2 is the generator A phase power factor. The phase diagram on the right side shows the phase relationship between U_M and U_G .

To verify the power angle characteristics of the MGP, the experimental procedure is as follows:

1) Add the rated excitation to the motor M, start the inverter, set the frequency of the inverter output voltage U_M to 50 Hz, and give G the rated excitation. Measure the phase of U_M and U_G at this time, with U_M as the reference voltage. The result is shown in Fig. 7(a).

2) Start the grid simulator, set its frequency to 49.9 Hz, measure the U_M , U_G and U_g phases. The results are shown in Fig. 7(b).

3) When U_G and U_g are coincident, it indicates that G satisfies the grid-integrated condition. At this time, K2 is closed and G is merged into the grid simulator. After grid connection, U_G and U_g are completely coincident, and are expressed as U_g .

4) After grid integration, U_M is used as the reference voltage; continue to measure the U_M and U_g phases. U_g rotates around U_M due to the frequency difference between the frequency converter and the grid simulator. This is equivalent to a gradual change of the phase difference of the voltages on both sides of the MGP—that is, a gradual change of $\Delta\theta$. The result is shown in Fig. 7(c).

5) Record the changes of P1 and P2 with $\Delta\theta$ during the experiment. The results are shown in Fig. 8.

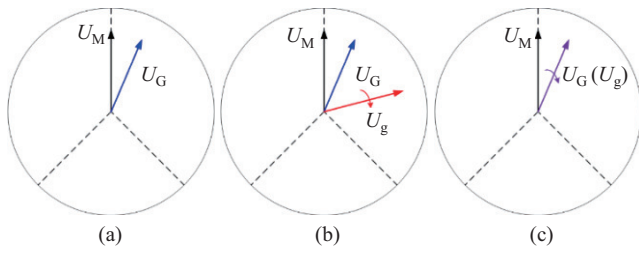


Fig. 7. Voltage phase relationships of the experiment. (a) Start up. (b) The generator is not integrated to the grid. (c) After grid integration.

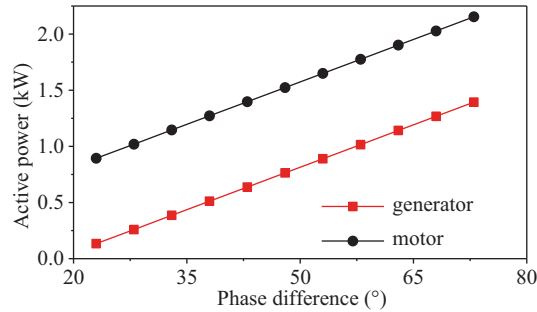


Fig. 8. Experimental result of the MGP power angle characteristics.

From the results shown in Fig. 7(a), it can be seen that in step (1), when the MGP system is idling, there is a phase difference between U_M and U_G , a phase difference that is measured to be 23.4° . This means that in normal operations, due to the deviation of the rotor position angle of the two machines, there is always a phase difference between the terminals of the two machines. This phase difference is the phase difference between the internal potentials of the two machines and is only related to the initial rotor position.

It can be seen from Fig. 7(b) that when the grid simulator starts working in step (2), due to the frequency difference, and when U_M is used as the reference voltage, the phase of U_G does not change, and U_g rotates clockwise. After calculation, the time required for U_g to rotate one revolution is about 100 s—that is, the reciprocal of the frequency difference of 0.01 Hz. Until a certain time, the phase of U_G and U_g are the same, and the generator can be put into the grid at this time. Thereafter, U_G and U_g rotate in phase. Since the

frequency difference always exists, $U_g(U_G)$ will continue to rotate clockwise around U_M , as shown in Fig. 7(c).

Due to the existence of the frequency difference, $\Delta\theta$ will continue to increase, and, as shown in Fig. 8, the transmission powers of the motor M and the generator G increase synchronously. Obviously, the transmission power of the MGP system is proportional to $\Delta\theta$. This result verifies the above analysis of the power angle relationship of the MGP system, and also shows that the power transmission of the MGP system can be controlled by controlling the source network phase difference $\Delta\theta$ of the MGP. This process can be achieved by controlling the source frequency difference of the MGP.

The main conclusions that can be drawn from these experiments are: (1) The two synchronous machines in the MGP have a deviation of the rotor position angle, which is reflected in the phasor diagram as the angle between the two internal potentials. Once the mechanical connection structure is determined, the initial deviation is fixed. (2) When the voltage phase on both sides of the MGP is used as a reference for measuring the power angle, the phase difference, of the voltages on both sides, is equal to $\Delta\theta$. (3) When the MGP is connected to the grid for power generation, $\Delta\theta$ has the same trend of change as the transmission active power, the power angle δ_M of the synchronous motor, and the power angle δ_G of the synchronous generator.

Therefore, the control mode of the MGP is to use the special power angle characteristic of the MGP to control the phase difference of the source network and thereby adjust the transmission power. Considering that the MGP is connected to two synchronous AC systems, if there are significant frequency differences between the two systems, it is possible that the phase difference of the source network is out of control, which in turn causes low frequency oscillation of the content of the MGP system. Based on the above analysis, reference [21] proposed the MGP power feedback control method shown in Fig. 9.

Since the frequency of the power grid continually changes, the frequency of the output voltage of the frequency converter must also be able to change and follow the grid frequency.

From Fig. 8, we can see that the source-grid voltage phase difference of the MGP system is proportional to the transmission power. The frequency difference between the terminal

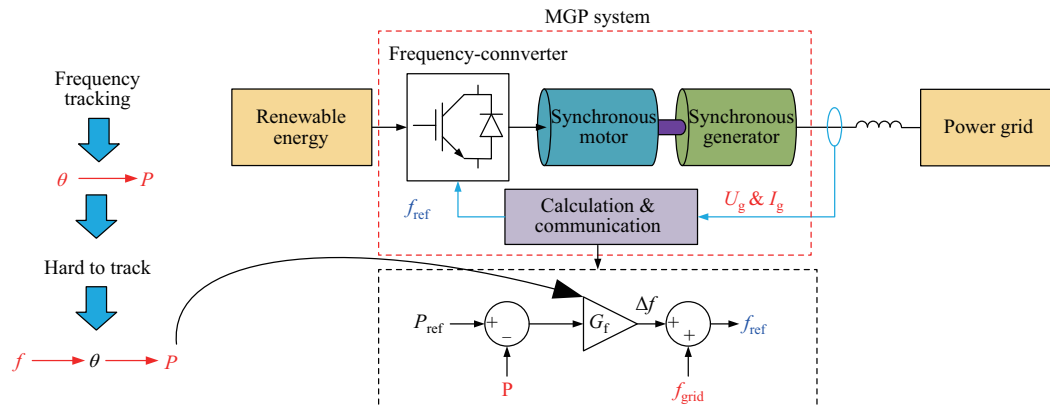


Fig. 9. Power feedback adjustment based on frequency modulation.

voltages of the two machines will affect the source-grid voltage phase difference and active power. So the frequency difference can be used to control the transmission of active power. When the actual transmission power is greater than the target power, we can increase the inverter output voltage frequency, and then widen the phase difference, thereby increasing the transmission power; when the actual transmission power is less than the target power, we can reduce the inverter output voltage frequency to reduce the transmission power. This control effect is achieved by the PI controller. Here, the difference between the actual power and the target power is the input signal. The signal is calculated by the PI controller to find the needed frequency adjustment Δf . Adding Δf to the detected frequency can control the frequency of the inverter output voltage. In this way, the transmission power can be controlled by the frequency difference.

III. PHOTOVOLTAIC GRID INTEGRATION CONTROL METHOD WITH MGP

The characteristics of PV are, of course, quite different from those of traditional thermal power units. The biggest difference is that the output power of PV is volatile and hard to control. The traditional thermal power unit makes use of chemical energy allowing for regulation the output power at any time. PV often requires the support of the grid to deliver power to the grid. Such a feature makes it necessary to predict the output power of PV based on the power feedback control when using MGP to integrate to the grid. On the one hand, this prediction process will cause delay in the output of the control system. On the other hand, if the predicted value is inaccurate, it will affect the stability and reliability of the control system [21]. Therefore, it is necessary to consider an improved control method for the MGP following the power fluctuation of PV based on the power output characteristics of PV, the DC voltage fluctuation characteristics of grid-integration inverters, and the operational control characteristics and power angle characteristics of MGP.

A. Photovoltaic Panel Operating Characteristics

The PV operating characteristics of a photovoltaic panel are shown in Fig. 10, including the stable and unstable operating areas. In the unstable operating area, the output power of the photovoltaic panel increases with an increase of

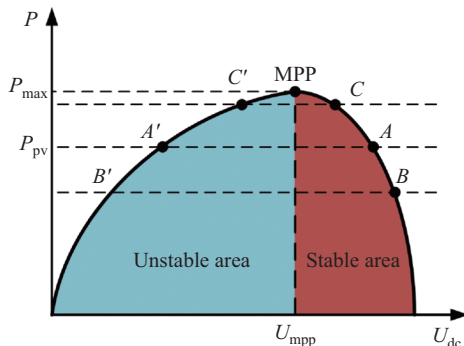


Fig. 10. Operating characteristic curve of photovoltaic panel.

the DC voltage, a monotonic rising characteristic. In the stable operating area, as the DC voltage increases, the output power of the photovoltaic panel decreases, a monotonic decreasing characteristic. The photovoltaic panel is normally required to operate in a stable area; otherwise the control system could make a judgment error, causing the control system to collapse.

Since the photovoltaic panel is connected to the grid-integration inverter, it contains a DC voltage-stabilizing capacitor. If the DC-side voltage is caused to change, the output power of the photovoltaic panel will change. Conversely, if the light intensity changes or the temperature changes, causing a change in the photovoltaic power curve, the output power of the photovoltaic panel will change, even when the DC voltage is constant. In the presence of changing illumination, it is sometimes necessary to control the DC voltage to hold the PV output power constant. And it is sometimes necessary to make the PV panel run at its maximum power point, designated MPP in Fig. 10. It is also possible to control the DC side voltage of the photovoltaic panel and flexibly control its output power.

It is assumed that the photovoltaic panel is integrated into the grid through an inverter. Under the condition that the external light intensity and temperature are constant—that is, the photovoltaic characteristic curve is constant—assuming that the initial operating point of the photovoltaic power source is at level A in Fig. 10 and in the stable operating area, the power of the photovoltaic power source changes. Then the inverter is required to match the change of the DC voltage. If the output power of the photovoltaic panel is increased, the reference value of the output power of the inverter can be made to increase. At this time, the discharge current of the DC capacitor increases, the voltage of the DC capacitor decreases, and the photovoltaic operating point will transit from point A to point B in the figure. If the output power of the photovoltaic panel is required to be reduced, the reference value of the output power of the inverter can be caused to decrease. At this time, the discharge current of the DC capacitor is reduced, the voltage of the DC capacitor is as described above, and the photovoltaic operating point will transit from point A to point C in the figure. However, if the photovoltaic power source is working at the A' point in the unstable area, and the demand for the output power of the photovoltaic power source increases, the output power of the inverter increases, the DC capacitor discharges outward, and the DC voltage decreases, causing the photovoltaic operating point to transit from point A' to point B' in the figure. The output is then reduced, which causes the DC voltage to continue to drop until the voltage collapses. Therefore, it is essential to maintain the DC voltage in a stable operating area during the operation of the photovoltaic panel to ensure effective control of the DC voltage.

B. DC Voltage Fluctuation Characteristics of the Grid-integration Inverter

Renewable energy grid-integration inverters are key components for connecting renewable energy and the MGP. The PV panel directly outputs DC; the inverter is used for DC/AC conversion, and then integrated into the grid. The grid-integration inverter has a power transmission control function, and the

reference value of the power transmission needs to match the power output of the renewable energy source.

For the grid-integration inverter, as shown in Fig. 11, when the output power is increased, if the power of the renewable energy is insufficient, the charging current of the DC capacitor will be less than the discharge current, and the capacitor voltage will decrease. When the output power of the transformer is reduced, if the power transmitted by the renewable energy source is excessive, the charging current of the DC capacitor is greater than the discharge current, and the capacitor voltage is increased. The voltage of the DC capacitor can only be stabilized if the power generated by the renewable energy matches the power delivered by the inverter.

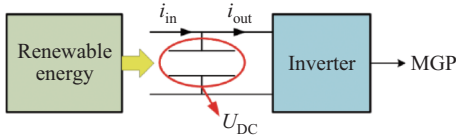


Fig. 11. Renewable energy adopting MGP for integrating to the power grid.

C. Inverter DC Voltage Feedback Control Method

From the previous analysis, we can see the following:

- 1) Within the stable operating range, the operating characteristics of the photovoltaic panel can be represented by a P-V curve, and as the voltage increases, the active power will decrease.
- 2) The fluctuation of the DC side capacitance of the inverter is related to the capacitor voltage and the charging current; if the instantaneous discharge current is greater than the charging current (the inverter output power is greater than the DC side input power), the capacitor voltage will decrease; otherwise, the capacitor voltage will increase.
- 3) When MGP is integrated into the grid, the frequency of the output voltage of the inverter can be actively adjusted, and the phase difference of the source network can be changed, thereby adjusting the output power of the inverter.

Consider the operational characteristics of each unit of the grid-integration system: One can adjust the output voltage of the inverter, control the output power of the MGP, and then adjust the DC side voltage of the inverter, thereby adjusting the photovoltaic output power and achieving the effect of the MGP tracking the photovoltaic output power. This paper therefore proposes a DC voltage feedback control method, as shown in Fig. 12.

The DC voltage feedback control system collects DC voltage as an input signal. It first compares the input signal with the target voltage to get ΔU and the frequency adjustment Δf through a PI adjustment link. Adding Δf to the base frequency provides the frequency reference value of the inverter. The output of PV is DC. When the power at the source changes, the DC voltage will also change, either increasing or decreasing. In order to stabilize the DC voltage of the inverter as the control target, the phase difference of the source network has to be changed to follow the power variation of the source. The change mode uses a method similar to the power feedback method to adjust the output frequency of the inverter, indirectly

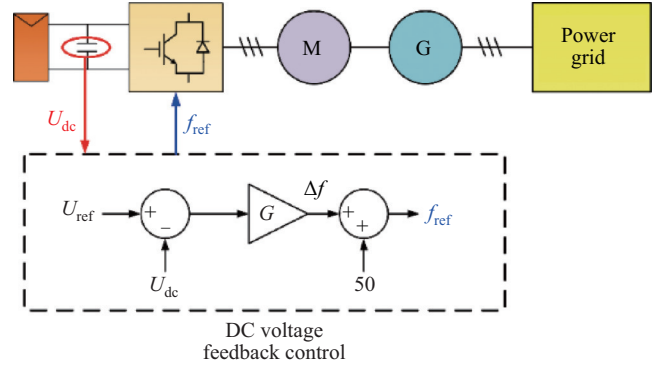


Fig. 12. Inverter DC voltage feedback control method.

adjusting the phase difference, and then controlling the power of the MGP. In this way, the MGP system can follow the power change of the photovoltaic output.

The core goal of the DC voltage feedback control method is not to keep the PV output DC voltage (inverter input DC voltage) stable, but to connect the PV to the grid through the MGP and cause the system to remain stable. The MGP system uses two synchronous motors to connect two AC systems, so the frequency of the two AC systems must be kept the same to prevent low-frequency oscillations inside the MGP system. The photovoltaic DC voltage and the inverter output frequency are therefore combined by DC voltage feedback as a control method. This control method is only applicable to MGP; it is the biggest difference between this method and other methods. Other existing DC voltage control methods cannot be easily applied to MGP systems.

Based on the DC voltage feedback control method, a validated experimental platform was established; the experimental platform is shown in Fig. 5 and Fig. 13. The experimental system parameters are consistent with the power angle characteristic experiment. A 10-kW photovoltaic simulator, shown in Fig. 13(a), is used to simulate the photovoltaic panel, and the DC current is output to the DC side of the drive inverter, which controls the motor's rotation. The DC voltage feedback control is achieved by the Programmable Logic Controller (PLC) control board shown in Fig. 13(b). The PLC control board collects the DC voltage signal of the inverter, and obtains the frequency reference value f_{ref} of the inverter output voltage by calculation. The inverter outputs voltage according to this reference signal to regulate the power output of the MGP.

IV. EXPERIMENTAL ANALYSIS

Experiment 1: to fix the light curve and adjust the DC voltage. First, the feasibility of DC voltage control needs to be verified. Therefore, it is necessary to verify whether the actual DC voltage can follow a given value when the DC voltage is adjusted with a fixed illumination curve.

Experimental steps:

- 1) Start the PV simulator and turn on the output. At this time, the PV simulator runs at the far right of the P-V curve. After the photovoltaic simulator outputs the current, the DC side of the inverter is charged and the inverter starts.

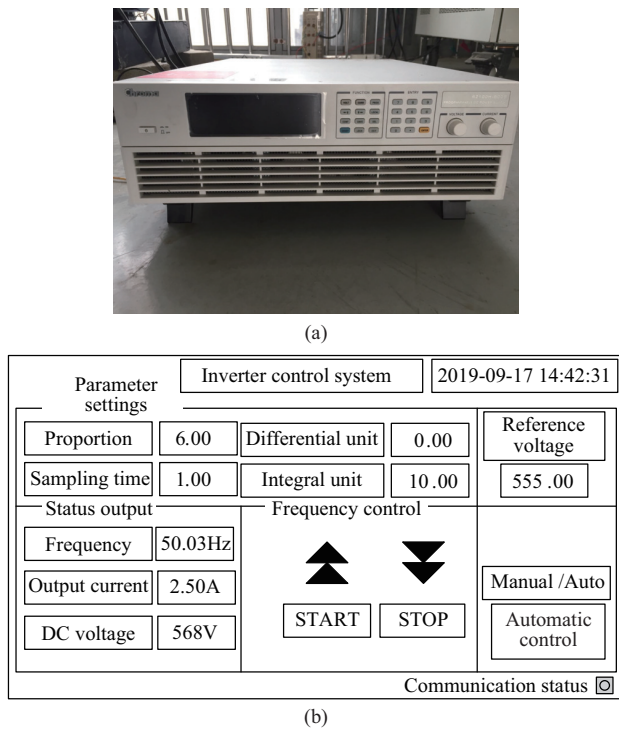


Fig. 13. Experimental platform of PV with MGP (a) PV simulator, (b) Panel of PLC controller.

2) Add excitation to the two synchronous machines, start the inverter, and adjust the synchronous motor to the synchronous speed. When the synchronous generator is in compliance with the grid integration conditions, the synchronous generator is integrated to the grid.

3) Turn on the PLC control board and adjust the DC side voltage reference value. Starting from 560 V, reduce the DC voltage reference value by 5 V every 10 s until 545 V is reached. The photovoltaic simulator output power is measured at this time.

The experimental results are shown in Fig. 14. During the experiment, the DC voltage can be changed by the control system command. When adjusting the DC voltage, the output current of the PV simulator will show output according to the preset five curves, as shown in Fig. 16. Therefore, as the reference value of the DC voltage is gradually reduced, the DC voltage is also gradually reduced, and the output current gradually increases. The output power of the DC power supply is also shown as output according to the P-V curve, so that as the DC voltage is gradually reduced, the output power is gradually increased. It can be seen from these experimental results that DC voltage feedback control can effectively adjust the DC side voltage of the inverter, and then adjust the output current and output power of the photovoltaic simulator; the adjustment result is determined by the running curve.

Experiment 2: to fix the DC voltage and change the PV output characteristic curve. After verifying the reliability of the DC voltage control system, it is necessary to verify the following characteristics of the MGP grid-integration system when the photovoltaic power output characteristics are changed.

Experimental steps:

1) Start the PV simulator and turn on the output. At this

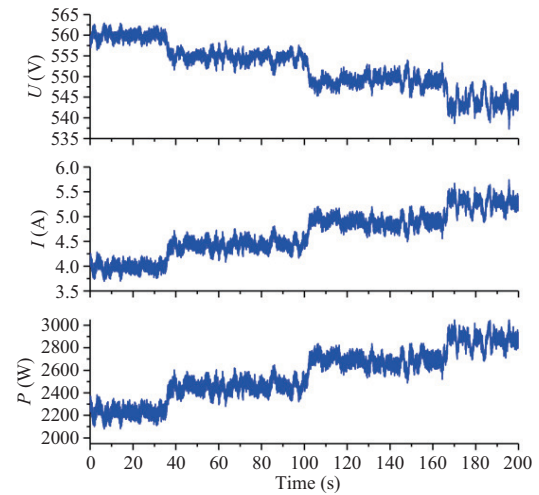


Fig. 14. Results of voltage regulation experiments.



Fig. 15. Control panel for photovoltaic simulator output characteristics.

time, the PV simulator runs at the far right of the P-V curve. After the photovoltaic simulator outputs the current, the DC side of the inverter is charged and the inverter starts.

2) Add excitation to the two synchronous machines, start the inverter, and pull the synchronous motor to the synchronous speed. When the synchronous generator is in compliance with the grid integration conditions, the synchronous generator is integrated into the grid.

3) Turn on the PLC control board, adjust the DC side voltage, fix the DC voltage at 530 V, and then change the PV output characteristic curve about every 40 s. This is equivalent to an increase in light intensity and ambient temperature every 40 s. The P-V relationship, of the five photovoltaic characteristic curves, is shown in Fig. 16. Finally, measure the output power of the photovoltaic simulator and the generator output power.

The experimental results are shown in Fig. 17. During the experiment, the DC voltage can be kept as the command value; it fluctuates slightly when the illumination characteristics change. When adjusting the illumination characteristic curve, the output power of the photovoltaic simulator also changes, according to the P-V curve. The output power of the generator will also change, and its change is synchronized with the change of the output power of the photovoltaic simulator. It can be demonstrated that the MGP can effectively follow the output of the photovoltaic simulator.

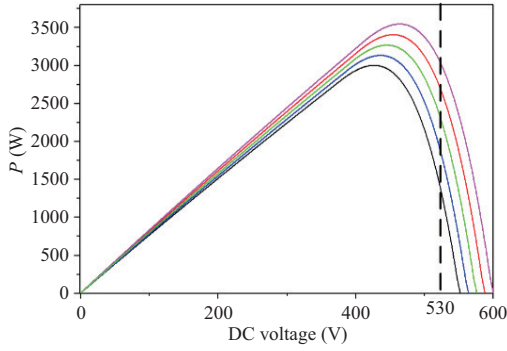


Fig. 16. Pre-set light characteristic curves in the PV simulator.

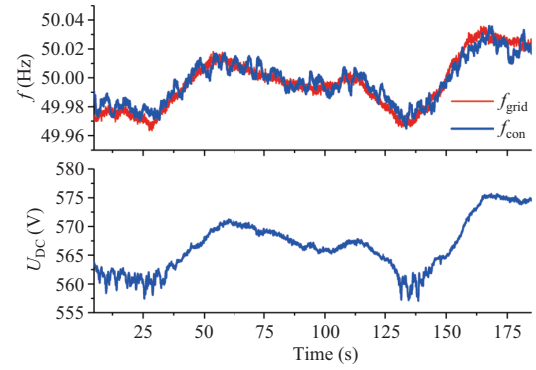


Fig. 18. Self-synchronization characteristic experimental result of PV-MGP.

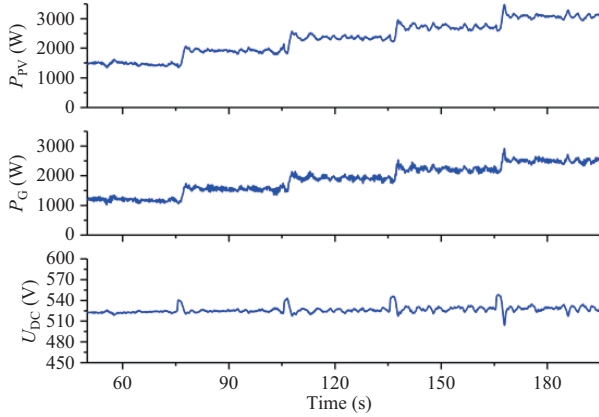


Fig. 17. Experimental results of photovoltaic simulator output for different curves.

V. SELF-SYNCHRONIZATION CHARACTERISTIC FOR PHOTOVOLTAIC POWER WITH THE MGP

The above experimental results show that by controlling the voltage on the DC side of the inverter, the entire system can be controlled, including the output power of the photovoltaic panel, the output power of the inverter, and the transmission power of the MGP system. In the control system, the frequency calculation of the MGP motor drive system is realized by the DC voltage feedback control system, and the grid voltage signal does not need to be measured.

In comparison between the experimental results of the inverter output voltage frequency and the grid frequency, the grid-integrated process of the MGP system can be analyzed. The experimental process refers to experiment 1, but the reference value of the DC voltage is not changed, so that the photovoltaic simulator is integrated into the grid through the MGP system and runs smoothly for 200 s. During the experiment, the inverter output voltage frequency, grid voltage frequency, and DC voltage of the inverter are recorded. The results are shown in Fig. 18.

As shown in this figure, f_{grid} is the grid voltage frequency, f_{con} is the frequency of the inverter output voltage, and U_{DC} is the voltage on the DC side of the inverter. The experiment is performed for 200 s. During the experiment, f_{grid} continued to fluctuate, and, f_{con} followed the f_{grid} fluctuations; the overall trend of both is consistent. At the same time, the trend of U_{DC} is also consistent with the grid frequency.

Throughout the experiment, the control system did not actually collect f_{grid} , which was achieved by its own control, and f_{con} was followed by f_{grid} , which was determined by the power angle characteristics of the MGP system mentioned in Section II. When the grid voltage fluctuates, the transmission power of the MGP system also fluctuates.

In order to study the self-synchronization process of the photovoltaic system through MGP grid integration, increasing grid frequency can be used as an example for analysis:

1) When f_{grid} increases, if f_{con} fails to follow the increase of f_{grid} , the frequency of the MGP system is different on the source side and the grid side. Since the grid-side frequency is greater than the source-side frequency, the transmission power of the MGP system is decreased.

2) At this time, the output power of the inverter decreases, and, at the same time, the discharge current of the DC capacitor of the inverter decreases.

3) At the same time, since the output of the photovoltaic panel has not been affected, its output power remains stable, and the charging current of the DC capacitor does not change.

4) Due to the change of the charging and discharging current, the charging and discharging process of the DC capacitor is unbalanced, the charging current is greater than the discharge current, and U_{DC} is increased.

5) At this time, the DC feedback control system shown in Fig. 9 starts to function and regulates the DC voltage. As U_{DC} increases, the feedback system will increase the f_{con} reference value; then f_{con} increases (i.e., f_{con} gradually follows the increasing trend of f_{grid}).

6) After several cycles of the above feedback process, f_{con} will be implemented for f_{grid} .

VI. CONCLUSION

This paper first analyzes the DC voltage fluctuation characteristics of the grid-integration inverter. Then, based on the MGP's power angle characteristic control method and the operating characteristics of the photovoltaic panel, a DC voltage feedback control method is proposed. In the experimental system, the PV system was integrated into the grid through the MGP. The main conclusions of this paper are as follows:

1) Based on the operating characteristics of each unit in the photovoltaic grid-integration system, a control method for adjusting the output voltage frequency of the inverter and

adjusting the DC-side voltage to allow the MGP to track the photovoltaic output power is proposed. Through experiments, the proposed control method is verified and the feasibility of the control method is demonstrated.

2) The self-synchronization characteristics of the PV using the MGP are realized when it is integrated into the grid and implemented. It is concluded that when using MGP to integrate into the grid, the PV can work normally without detecting the grid frequency signal. This characteristic reduces the dependence of the grid voltage reference value when the PV is integrated to the grid.

In summary: The DC feedback control method proposed in this paper can give photovoltaics self-synchronization characteristics when they are integrated into the grid through the MGP system. Therefore, the control of the photovoltaic grid-integration system can be prevented from being affected by the grid frequency, and it strengthens the power-grid adjustment capability.

Finally, we emphasize that the MGP is still in the research stage and has not yet entered the stage of large-scale application. It is necessary to first apply it on a small scale in the microgrid, and study its contribution to the stability of the grid through small-scale demonstration projects. Based on the results of the small-scale research, the feasibility of its large-scale application can be examined.

REFERENCES

- [1] J. A. Taylor, S. V. Dhople, and D. S. Callaway, "Power systems without fuel," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 1322–1336, May 2016.
- [2] M. Vilathgamuwa, D. Nayanasinghe, and S. Gamini, "Power electronics for photovoltaic power systems," *Synthesis Lectures on Power Electronics*, vol. 5, no. 2, pp. 1–131, Aug. 2015.
- [3] B. Kroposki, B. Johnson, Y. C. Zhang, V. Gevorgian, P. Denholm, B. M. Hodge, and B. Hannegan, "Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy," *IEEE Power and Energy Magazine*, vol. 15, no. 2, pp. 61–73, Mar./Apr. 2017.
- [4] X. Yang, Y. H. Song, G. H. Wang, and W. S. Wang, "A comprehensive review on the development of sustainable energy strategy and implementation in China," *IEEE Transactions on Sustainable Energy*, vol. 1, no. 2, pp. 57–65, Jul. 2010.
- [5] S. C. Wang, "Current Status of PV in China and Its Future Forecast," *CSEE Journal of Power and Energy Systems*, vol. 6, no. 1, pp. 72–82, Mar. 2020.
- [6] N. A. Masood, R. F. Yan, T. K. Saha, and S. Bartlett, "Post-retirement utilisation of synchronous generators to enhance security performances in a wind dominated power system," *IET Generation, Transmission & Distribution*, vol. 10, no. 13, pp. 3314–3321, Oct. 2016.
- [7] P. Kundur, N. J. Balu, and M. G. Lauby, *Power System Stability and Control*, New York: McGraw-Hill, 1994.
- [8] P. Kundur, M. Klein, G. J. Rogers, and M. S. Zywno, "Application of power system stabilizers for enhancement of overall system stability," *IEEE Transactions on Power Systems*, vol. 4, no. 2, pp. 614–626, May 1989.
- [9] S. M. Kaviri, M. Pahlevani, P. Jain, and A. Bakhshai, "A review of AC microgrid control methods," in *2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2017, pp. 1–8.
- [10] A. Khosravi, M. Jazaeri, and S. A. Mousavi, "Transient stability evaluation of power systems with large amounts of distributed generation," in *45th International Universities Power Engineering Conference UPEC2010*, 2010, pp. 1–5.
- [11] Q. C. Zhong, W. L. Ming, and Y. Zeng, "Self-synchronized universal droop controller," *IEEE Access*, vol. 4, pp. 7145–7153, Oct. 2016.
- [12] A. A. Edris, "Proposed terms and definitions for flexible AC transmission system (FACTS)," *IEEE Transactions on Power Delivery*, vol. 12, no. 4, pp. 1848–1853, Oct. 1997.
- [13] H. P. Beck and R. Hesse, "Virtual synchronous machine," in *2007 9th International Conference on Electrical Power Quality and Utilisation*, 2007, pp. 1–6.
- [14] K. Visscher and S. W. H. De Haan, "Virtual synchronous machines (VSG's) for frequency stabilisation in future grids with a significant share of decentralized generation," in *CIGRE Seminar 2008: SmartGrids for Distribution*, 2008, pp. 1–4.
- [15] Q. C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.
- [16] S. M. Wei, Y. K. Zhou, S. Li, and Y. Z. Huang, "A possible configuration with motor-generator pair for renewable energy integration," *CSEE Journal of Power and Energy Systems*, vol. 3, no. 1, pp. 93–100, Mar. 2017.
- [17] Y. K. Zhou, G. R. Xu, and Y. Z. Huang, "Experiment analysis on motor-generator pair system for providing inertia of renewable energy," in *2018 21st International Conference on Electrical Machines and Systems (ICEMS)*, 2018, pp. 1041–1045.
- [18] S. M. Wei, Y. K. Zhou, and Y. Z. Huang, "Synchronous motor-generator pair to enhance small signal and transient stability of power system with high penetration of renewable energy," *IEEE Access*, vol. 5, pp. 11505–11512, Jun. 2017.
- [19] S. M. Wei, Y. K. Zhou, G. R. Xu, and Y. Z. Huang, "Motor-generator pair: a novel solution to provide inertia and damping for power system with high penetration of renewable energy," *IET Generation, Transmission & Distribution*, vol. 11, no. 7, pp. 1839–1847, May 2017.
- [20] Y. K. Zhou, G. R. Xu, S. M. Wei, and Y. Z. Huang, "Techno-economic analysis of motor-generator pair system and virtual synchronous generator for providing inertia of power system," *International Journal of Energy and Power Engineering*, vol. 11, no. 6, pp. 665–669, Apr. 2017.
- [21] Y. K. Zhou, G. R. Xu, S. M. Wei, X. Zhang, and Y. Z. Huang, "Experiment study on the control method of motor-generator pair system," *IEEE Access*, vol. 6, pp. 925–936, Nov. 2017.



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