Effects of motor–generator pair system on improving inertial response and primary frequency regulation capability of renewable energy

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Abstract
The increasing penetration of renewable energy leads to the decrease of inertia and damping for replacing conventional power plants. The motor–generator pair (MGP) is proposed to improve inertial response and frequency regulation capability for the renewable energy. First, the mathematical model of the MGP and the control method of DC-link voltage are given. Then, the inertial characteristics of the MGP are analysed, and a mass block is designed by analysing the key factor affecting the moment of inertia. The transient processes in two machines are discussed by comparing the variations of the voltage and current vectors. It turns out that the electromagnetic–mechanical coupling is the key to realise the primary frequency regulation without frequency acquisition. The photovoltaic (PV) is chosen to illustrate the mechanism of achieving a better primary frequency response with DC-link voltage control methods based on the de-loading and additional frequency deviation strategies. A grid-scale simulation model is built to verify the effectiveness of the proposed scheme. Furthermore, six groups of experiments are designed and performed on an experimental bench. The simulation and experimental results demonstrate that the inertial response and primary frequency response of PV can be improved effectively by adopting MGP for grid connection.

1 | INTRODUCTION

The proportion of renewable energy (RE) in the power system has increased rapidly in recent years, even exceeding the capacity of conventional power generation units in some regional power grids. However, the frequency stability of the power system is decreasing accordingly. This problem is mainly attributed to the fact that the RE generation units do not have the inertial response (IR) and primary frequency response (PFR) similar to those of conventional thermal power plants [1]. On one hand, photovoltaic (PV) does not have IR for the missing of rotating equipment. Although there is a lot of kinetic energy stored in the blades and the shafting, the speed of the wind turbine generators (WTGs) is decoupled from the grid frequency because the grid-connected converter adopts vector control based on the grid frequency [2]. Therefore, PV and WTGs cannot provide inertial support in response to the change of the grid frequency. On the other hand, there is no reserved capacity available for the frequency regulation because of the maximum power point tracking (MPPT) control method. Especially, in the cases of the remote regional grid with high penetration of RE and the islanding grid, it is urgent for the RE to have required IR and PFR according to the regulations [3].

The control method based on \( \frac{df}{dt} \) and frequency deviation is originally proposed in [4], which can provide IR and PFR by releasing the rotational kinetic energy of the WTGs and increasing the active power output proportional to the frequency deviation. However, the disadvantage of this control method is that the WTGs need to absorb active power to restore the initial operating states after a short response, which is not
due to the restoration of the grid frequency. Afterwards, the pitch angle control of the WTGs that mitigates the effect of the inertia reduction caused by the increasing penetration of RE is proposed in [5], and the power reserve control methods by operating at an excessive speed and on the right half plane of the PV curve are proposed in [6] and [7]. The above methods can make use of the adjustable power to realise the emulated IR and PFR. However, the lack of inertia in the power grid for the rapid growth of RE has already resulted in more fluctuations and oscillations of the grid frequency. To solve this problem, an oscillation damping controller [8], synchronous power controllers [9], and a multi-model adaptive control strategy [10] are proposed to dampen the frequency oscillation caused by short-term load changes. However, there are still some problems that the above methods cannot fully solve, such as inertia loss of the PV system, limitations for the amount of the reserved power and improper parameter selections of the controllers in the real operation. Therefore, an additional energy storage device can play an important role in emulating inertia and participating in the frequency regulation [11, 12]. In addition, the mentioned control methods based on the $\frac{df}{dt}$ and frequency deviation use phase-locked loop (PLL) to collect grid frequency, but the introduction of PLL will reduce the stability of the control system and the measurement accuracy is often weakened in the weak grids. Therefore, the technology of virtual synchronous machine is introduced in the control system of the RE converter with energy storage devices [13, 14]. This control method can achieve the IR, PFR and the damping effects similar to the synchronous generator (SG) without PLL, but the control performance largely depends on the selection of control parameters, making it less effective in practical applications.

Due to the characteristics similar to the conventional thermal power unit, the motor–generator pair (MGP) proposed in [15] can be a prospective method to improve the stability of power system with high penetration of RE. In [16], the grid connection of RE via the MGP can enhance the transient stability of power system with analysis of small-signal stability. The source-grid difference control method for the MGP system is investigated and the stability of the control system analysed in [17]. Besides, the MGP system can realise fault ride-through of RE for its functions of the fault isolation and reactive power support [18]. This paper mainly discusses the IR and PFR of RE adopting the MGP system for grid connection.

There are six sections in this paper. The mathematical model of the MGP system and DC-link voltage control method are given in Section 2. In Section 3, the inertial characteristics of the MGP system are illustrated in detail, and a novel mass block design is proposed to increase the inertia of the MGP system effectively. In Section 4, the transient process of the MGP system during the change of grid frequency is discussed by analysing the variations of the voltage and current vectors on both sides of the MGP system. Moreover, the PV is taken as an example to illustrate the effects of the RE on providing the power support for the frequency change, and then, the DC-link voltage control for PV is improved by considering the power reserve and frequency deviation. In Section 5, a three-machine nine-node system is built in PSCAD to demonstrate the IR and PFR of grid-connected PV via MGP. In Section 6, the experimental bench is built, on which six groups of experiments are designed and performed. The experimental results show that the mass block can effectively improve the IR of the MGP system, and the PV adopting the MGP system for grid connection can achieve much better PFR than the PV alone and has a good frequency regulation capability no matter the rate of change of frequency (RoCoF) is fast or slow.

2 | MATHEMATICAL MODEL AND CONTROL METHOD OF MGP

2.1 | Mathematical model of MGP

The MGP system is composed of two coaxially connected synchronous machines equipped with independent excitations. The synchronous motor (SM) is driven by the converter and the SG is the grid-connected unit, as shown in Figure 1. If the connection modes of the stator windings in two machines are the same, the two magnetic fields will rotate in opposite direction because the two machines are placed in the opposite direction. Therefore, the phase sequence of the SG should be opposite to that of the SM to realise stable operation of the MGP system.

Based on the above analysis, the two machines should adopt their own conventions to define the positive direction when establishing the mathematical model of the MGP in order to obtain the motion equation of the MGP system. Since the large-capacity synchronous machines with a non-salient pole are widely used, the mathematical model of the MGP system in the vector form of in the $dq$-axis coordinate system is established based on the mathematical model of this machine [19]

\[
\begin{bmatrix}
U_M \\
U_G
\end{bmatrix} =
\begin{bmatrix}
R_M & 0 \\
0 & R_G
\end{bmatrix}
\begin{bmatrix}
I_M \\
I_G
\end{bmatrix} + \left(\omega_A \hat{\psi}_M - \omega_L \hat{\psi}_G\right) + \begin{bmatrix}
\omega_A I_M \\
\omega_A I_G
\end{bmatrix}
\]

(1)

\[
\begin{bmatrix}
\hat{\psi}_M \\
\hat{\psi}_G
\end{bmatrix} =
\begin{bmatrix}
0 & L_G \\
L_M & 0
\end{bmatrix}
\begin{bmatrix}
\dot{I}_M \\
\dot{I}_G
\end{bmatrix}
\]

(2)
where $U_M$ and $U_G$ are the voltage vectors of the SM and SG, respectively; $I_M$ and $I_G$ are the current vectors of the SM and SG, respectively; $R_M$, $L_M$, $R_G$ and $L_G$ are the resistance and inductance matrices of the SM and SG, respectively; $T_{eM}$, $T_{eG}$, $T_{mM}$ and $T_{mG}$ are electromagnetic torques and mechanical torques of the SM and SG, respectively; $\omega_{eM}$, $\omega_{eG}$ and $\omega_r$ are electrical angular velocity of the of the SM and SG and the mechanical angular velocity of the shafting, respectively; $H_{MGP}$ is the inertia constant of the MGP system; $K_{DM}$ and $K_{DG}$ are the damping coefficients of the SM and SG, respectively; and $\mathcal{A}$ is the coefficient matrix of the rotating magnetic flux.

The electromagnetic vectors of the SM and SG are independent because of the shafting isolation, so are the resistance and inductance parameters. According to (3), any change on one side will cause a corresponding change on the other side through the electromagnetic–mechanical coupling. The rate of the change is influenced by the inertia and damping level of the MGP system that partly depend on the parameters such as $H_{MGP}$, $K_{DM}$ and $K_{DG}$.

### 2.2 DC-link voltage control for the MGP system

According to [17], the transmitted active power of the MGP system is proportional to the phase difference between $U_M$ and $U_G$, which is the theoretical basis for the control of the MGP system. Since direct-drive permanent magnet wind generator (DPMWG) and PV have the same grid-connection structure that is DC link and inverter, they both can be used to drive the MGP system for grid connection by adopting the DC-link voltage control method [18].

The control process can be introduced briefly as follows. First, maximum active power $P_{\text{max}}$ can be obtained from the MPPT algorithm, and then, the DC-link voltage reference $U_{\text{ref}}$ is available by looking up the PV curve of the RE based on $P_{\text{max}}$. Second, the frequency reference $f_{\text{ref}}$ can be obtained by the calculation of the proportional-integral (PI) controller with the difference between $U_{\text{ref}}$ and the measured DC-link voltage $U_{\text{dc}}$. One outstanding advantage of this control method is the self-synchronisation that means keeping pace with the grid frequency without measuring module like PLL for the electromagnetic–mechanical coupling of two machines. When the grid frequency changes, the phase of $U_G$ will change accordingly because the SG is directly connected to the grid. Once the phase difference between $U_M$ and $U_G$ changes, there will be a power imbalance on both sides of the DC link caused by the change of the transmitted active power of the MGP system. Under the adjustment of the DC-link voltage control, $U_{\text{dc}}$ will be continuously approaching $U_{\text{ref}}$, which can ensure the operation stability of the MGP system.

### 2.3 Applicability analysis of the MGP system

As introduced above, the scheme of the MGP system used for RE grid connection is feasible both in the structure and in the control method. However, the potential costs, additional losses and maintenance of the MGP system are the limitations for its practical application. The estimated potential costs mainly include the equipment cost, converter transformation cost, installation cost, civil engineering cost and construction cost, as listed in Table 1.

The losses of the MGP system can refer to that of the SG. In this way, the efficiency of a 200-MW MGP system is about 96.6% according to the efficiency of a 200-MW SG [20]. The maintenance of the MGP system mainly focuses on some parts, such as bearing, carbon brush, damping windings and insulation, referring to the regulations of Harbin Electric Machinery Works of China. The maintenance cost of two 350-MVA SGs is about 2.2 million CNY per year based on the real cost of one thermal power plant in Luoyang City, Henan Province, China. This only accounts for about 1% of the potential costs of a 350-MVA MGP, which mainly owes to the maturity and reliability of the synchronous machine.

Although the cost of the MGP system can be an obstacle for its application, the grid-connected RE via MGP can cope with different fault levels for the advantages of MGP on the real inertia, good insulation level, strong endurance of over-voltage and over-current, reactive power support and electrical–mechanical isolation. Therefore, this novel grid-connection mode of RE can be used in both high-voltage power grid and distribution network. Compared with other methods like energy storage, high operation reliability of synchronous machines can reduce the possibility of some unforeseen failures of MGP and improve the stability of the power grid with high penetration of RE. Besides, the inverter with fast switching frequency can respond to all

| Item                        | Amount (million CNY) | Pricing basis                                      |
|-----------------------------|----------------------|----------------------------------------------------|
| Equipment cost              | 250                  | Consult Harbin Electric Machinery Works of China   |
| Converter transformation cost| 24                   | Refer to the real cost of LVRT transformation of the wind farm in China |
| Installation cost           | 50                   | Calculated by 20% of the equipment cost             |
| Civil engineering cost      | 10                   | Calculated by 20% of the installation cost          |
| Construction cost           | 2                    | Calculated by 4000 m² (500 CNY/m²)                 |
| Total cost                  | 336                  |                                                    |
kinds of load changes within 10 ms for the electrical–mechanical coupling and fast switching frequency, which is very helpful to mitigate the impact of load change on the grid frequency stability.

3 | INERTIAL CHARACTERISTICS OF MGP

The MGP system can mitigate the impact of reduced inertia caused by grid connection of the RE for its real inertial. When the grid frequency decreases due to the load increase, an angular velocity difference will occur between the stator and rotor windings of the SG. Due to the electromagnetic–mechanical coupling, the MGP system can provide IR by releasing the stored rotational kinetic energy as soon as the grid frequency changes. This is one of the biggest advantages over the current emulated inertia control methods applied in the RE by the means of detecting the grid frequency. The inertia of the MGP system also plays a key role in reducing RoCoF and the maximum frequency deviation $\Delta f_{\text{max}}$. Besides, the IR of the MGP system is smooth and relatively constant and outperforms that of the inertia emulation methods in case of any grid frequency change.

Based on the above analysis, the MGP system can play a very important role in improving the IR in the power grid with a high penetration of the RE. Therefore, it is necessary to further study the magnitude and associated factors of the inertia of the MGP system. Similarly to the combined inertia of the steam turbine and the generator, the inertia of the MGP system consists of those of two synchronous machines and their excitation systems. The rotational kinetic energy $E_{\text{MGP}}$ and inertia constant $H_{\text{MGP}}$ of the MGP system can be expressed as

$$E_{\text{MGP}} = \frac{1}{2}j_{\text{MGP}} \omega_{\text{MGP}}^2$$

$$H_{\text{MGP}} = \frac{E_{\text{MGP}}}{j_{\text{MGP},N}}$$

where $j_{\text{MGP}}$ is the moment of inertia of the MGP system, $\omega_{\text{MGP}}$ is the rated mechanical angular velocity of the MGP system and $j_{\text{MGP},N}$ is the rated capacity of the MGP system.

Because the MGP consists of two synchronous machines, the applicability estimation of the MGP system can refer to the operation and management of conventional SGs. The shafting of a 555-MVA thermal power unit includes several mass blocks, such as low-/high-pressure cylinders, exciter and generator, whose total moment of inertia can reach 27547.8 kg·m² and the inertia constant is about 2.5–10 [19]. The moments of inertia of all mass blocks with the capacity of 600 MVA are shown in Table 2 [21]. In comparison, the shafting of MGP includes two sets of exciters and generators.

| Mass block       | Low pressure cylinder | High pressure cylinder | generator | exciter |
|------------------|-----------------------|------------------------|-----------|---------|
| $J_{\text{total}}$/kg·m² | 13112.7               | 2106.3                 | 7435.8    | 58.4    |

4 | PFR AND IMPROVED DC VOLTAGE CONTROL METHODS OF RE-ADOPTING THE MGP SYSTEM

4.1 | Primary frequency response

At the moment of the increase of the power load, the grid frequency decreases and the output voltage frequency of the inverter stays unchanged. Meanwhile, the speed of the shafting slows down immediately to release the stored kinetic energy. As a result, the power angle of the SG increases from $\delta_{G0}$ to $\delta_{G1}$, and the magnitude of the SG current vector IG increased from $I_{G0}$ to $I_{G1}$, as shown in Figure 3. Therefore, the electromagnetic torque on the shaft increases. Because two synchronous machines are coaxially connected, the output torque of the SM increases accordingly, which will accelerate the discharge speed of the DC-link capacitor and lower the DC-link voltage. Then, the magnitude of the SM current vector $I_M$ increases from $I_{M0}$ to $I_{M1}$ with the increase of the discharged...
energy from the DC-link capacitor. As a result, the active power output of the MGP system increases. This increased active power comes from not only the electrical energy stored in the capacitor, but also the rotational kinetic energy of the shaft. Figure 3 shows the phase relationship between the voltage and current of the MGP system before and after the change of grid frequency as the grid voltage vector is used as a reference.

According to the DC voltage control, the output frequency of the inverter can be defined as

\[ f_{\text{ref}} = K_p \Delta U_{\text{dc}} + K_i \int \Delta U_{\text{dc}} dt \]  

(8)

where \( K_p \) and \( K_i \) are PI parameters of the DC-link voltage control. The approximate active power output of the MGP system, \( P_G \), can be expressed as [17]

\[ P_G = K_{\text{MGP}} (\delta_M + \delta_G + \delta_0) \]  

(9)

where \( \delta_0 \) is the phase difference between electromotive force of the SM and SG, and \( K_{\text{MGP}} \) is the power coefficient of the MGP system. The power angles of SM and SG can be expressed as

\[
\begin{align*}
\delta_M &= 2\pi f_{\text{ref}} t - \omega_r t + \delta_0 \\
\delta_G &= \omega_r t - 2\pi f_{\text{g}t} + \delta_0
\end{align*}
\]  

(10)

Therefore, from (9) and (10), the relationship between the differential of \( P_G \) and grid frequency \( f_g \) can be expressed as

\[
\frac{dP_G}{dt} = 2\pi K_{\text{MGP}} (K_p \Delta U_{\text{dc}} + K_i \int \Delta U_{\text{dc}} dt - f_g).
\]  

(11)

It can be concluded from (11) that the change rate of \( P_G \) is inversely proportional to the change of the grid frequency \( f_g \), so the active power output of the MGP system can respond to the change of the grid frequency. The DC-link voltage control does not function since the difference of the DC-link voltage \( \Delta U_{\text{dc}} \) is small at the beginning of the frequency change. Therefore, the stored kinetic energy of the MGP system is released to provide IR as analysed in Section 3.

The above analysis does not consider the damping of the MGP system because the damping coefficients are neglected in (11). The damping of the MGP system influences the frequency recovery speed and accelerates the attenuation rate of the frequency oscillation, which helps keep the frequency stable during the change of the power load.

The DC-link voltage control starts to provide PFR with the increasing of \( \Delta U_{\text{dc}} \). When \( U_{\text{dc}} \) is less than \( U_{\text{ref}} \), the output frequency of the inverter decreases under the DC-link voltage control. Besides, the PI parameters also play an important role in the transient process of the recovery since they determine the adjustment speed of the DC-link voltage control according to (11). Therefore, the DC-link voltage control works a little longer than the inertia of the MGP system, and the length of its adjustment depends on the \( K_p \) and \( K_i \).

However, the speed of the shaft will be stabilised at a new value below the rated, and the DC-link voltage will gradually recover to the reference value after a while. As a result, more energy is needed for the recovery of the speed of the shafting and DC-link voltage. In addition, the active power output on both sides of the MGP system oscillates with large peaks in the first cycle of the frequency decrease due to the effects of the frequency change and DC-link voltage control.

4.2 De-loading strategy of the PV generation system

Whether the power reserve strategy chooses operations at an excessive speed or on the right half plane of the PV curve, the grid connections for the DPMWG and PV via MGP are both based on the same DC-link voltage control method. Therefore, PV system is taken as an example to illustrate the following
strategies. To simplify the expression, PV + MGP is chosen to be short for the grid connection of the PV system via MGP system. Then, the load increase is taken as an example to analyse the PFR of the PV + MGP as follows. Moreover, it can be assumed that the PV curve remains unchanged for its relatively long power fluctuation period.

Since the stored kinetic energy and electric power are only functioning in the first few periods, more energy is needed for the recovery of the grid frequency. Therefore, the control system of the PV + MGP is required to have the similar PFR ability of the governor. In order to realise this goal, the PV generation system should adopt the de-loading strategy to have some active power reservations to provide a better PFR, as shown in Figure 4.

The five sets of curves are the operating curves of PV under different light intensities and temperature conditions. The red curve represents the set of the operating points with the active power reservation. The shaded area enclosed by the blue curve and dotted line indicates the stable operating area of the PV generation system under the blue curve. The blue curve in Figure 5 is taken as an example to explain how to determine the de-loading operating point. Point A is the maximum active power operation point, and point B is selected as the sub-maximum active power operation point. Therefore, the PV operating point moves up along curve AB when the grid frequency decreases, and the active power output of the PV + MGP increases accordingly. In order to make sure that the PV + MGP has required PFR ability, the de-loading capacity needs to be determined. With reference to the definition of the static adjustment coefficient of the steam turbine generator, the load reduction rate LR% of the PV generation unit can be defined as

\[
LR\% = \frac{P_{MPPT} - P_{LR}}{P_{MPPT}} \times 100\% = \frac{|\Delta f|}{f_{\text{max}} \sigma f} \times 100\% \tag{12}
\]

where \(P_{MPPT}\) and \(P_{LR}\) are the active power outputs with MPPT and de-loading method, respectively; \(\Delta f\) and \(f_{\text{max}}\) are the frequency deviation and the maximum frequency, respectively; \(\sigma f\) is the adjustment coefficient of the steam turbine generator.

According to the power system operation regulations of the State Grid Corporation of China, the absolute frequency deviation should not exceed 0.5 Hz, and the range of \(\sigma f\) is generally from 0.03–0.05. Then, it can be calculated from (11) that the range of LR% is 20–33.3%. However, the active power loss of the MGP system needs to be given in LR%. The efficiency of the SG with large capacity is generally more than 98% [19], so the efficiency of MGP is about 96%. In order to meet the requirements of the primary frequency adjustment, the LR% of the PV + MGP is selected as 35% according to the upper limit selection principle. On this basis, an improved DC-bus voltage control based on the de-loading strategy is proposed, as shown in Figure 5.

The improved control method only adds load reduction module without changing the IR and PFR of the PV + MGP, which fully takes the advantage of the IR of the MGP system and the frequency adjustment capability based on DC-link voltage control. However, no extra active power can be provided under the DC-link voltage control during the frequency recovery. In order to solve the above problem, an additional frequency deviation calculation module is added, as shown in Figure 6.

The additional frequency change calculation module can increase the steady-state output of the MGP system, which is helpful for the restoration of the grid frequency. But the effects of this strategy on the PFR of the PV + MGP are limited by the measuring accuracy of the frequency detecting device and the selection of the proportional coefficient \(k_f\).

5 | SIMULATION

A three-machine nine-node system is built in PSCAD to study the IR and PFR capability of grid-connected PV via MGP with the proposed control strategies. The structure of the simulation model is shown in Figure 7.
The parameters of the simulation are shown in Table 3.

In order to test the IR of grid-connected PV via MGP, three groups of simulations are conducted under different inertia constants based on the analysis in Section 3. A 90-MW load increase is set on bus 8. The simulation results are shown in Figure 8.

As revealed in Figure 8(a), the stored rotational energy in the MGP system helps to reduce the RoCoF and maximum deviation of the grid frequency in case of load increase. The IR of MGP can also be reflected by the increasing rate of the output active power at the beginning of load increase. It can be concluded that the rate of change and maximum deviation of the grid frequency are proportional to that of the inertial constant increase.

Next, the primary frequency regulation capability of grid-connected PV via MGP is studied by comparing different load increase. Three groups of load increase are set on bus 8. The results are shown in Figure 9.

As the change of load increases by equal difference (15 MW), the maximum output active power of grid-connected PV via MGP also increases by equal difference approximately. From Figure 9(b), the change of maximum deviation and recovery time of grid frequency becomes smaller and shorter under the same load change increment. It demonstrates that the grid-connected PV via MGP has a good primary frequency regulation capability and perform well under different load change.

Finally, four groups of simulations with different proportional coefficients are conducted to illustrate their effects on the frequency response of the grid-connected PV via MGP. The values of \( k_f \) are 0.16, 0.32, 0.48 and 0.64, respectively. The same 90-MW load increase is set on bus 8, and the results are shown in Figure 10.

As can be seen from Figure 10, the output power of grid-connected PV via MGP increases with the increase of \( k_f \). As a result, the maximum deviation, oscillation amplitude and recovery time of grid frequency becomes smaller and shorter under the same load increase. This verifies that the proposed control strategy can be helpful to improve the frequency stability by increasing \( k_f \) at a reasonable range.

### EXPERIMENT DESIGN AND RESULTS ANALYSIS

In order to verify the above theory and proposed control strategy of the PV + MGP, an experimental bench is set up in the laboratory, as shown in Figure 11.

The bench mainly includes a 10-kW PV emulator, a 5.5-kW MGP system (including two STC-5.5 synchronous machines), and a 5-kW three-machine series system (including two STC-5 synchronous machines, a 7.5-kW DC motor and a set of mass block adjustment modules), one control cabinet (including a 30-kW converter and a DC-link voltage controller), a 33.33-kW programmable AC load, a 45-kW grid emulator, a 12-kW
HUawei PV inverter and a 30-kW DC motor speed controller. Other parameters of the experimental bench are shown in Table 4.

Based on the above experimental bench, the following six experimental groups are performed to verify the inertia and PFR characteristics of the PV + MGP. The single-phase values of the voltage and current are measured by using a Yokogawa scope corder, and the frequency and power results are calculated in the Simulink with the measured data. Therefore, the experimental results below are single-phase values.

6.1 Load change experiments of the MGP system

In order to test the frequency response of the MGP system, the inverter adopts the constant $V/F$ control instead of DC-link voltage control to eliminate the impact of the control system. First, start the converter to drive the 5-kW three-machine series system to the synchronous speed and close K2 and K3. Then, start the load and the three-phase active power of the load is set as 300 W. After the experimental system is stabilised, the active powers of the load are set as 600, 900 and 1200 W, respectively. The frequency of the point of common coupling ($f_{\text{PCC}}$) under different load changes is shown in Figure 12.

The RoCoF and intersection points at the first cycle under different load changes are the same, and the change of frequency has a linear relationship with the change of the load. The frequency attenuation under different load changes is similar under the damping of the MGP system. It is mainly because the inertia and damping coefficient of the MGP system is unchanged in the experiment. All these results illustrate that the MGP system has good droop characteristics like the steam turbine generator. Of course, the $V/F$ control causes the decrease of the steady-state value of the frequency with the increase of power load, indicating that the MGP system has a good IR but not the frequency regulation ability.
6.2 Different inertia contrast experiments

In order to test the effect of the mass block, two experiments are performed with and without the mass block on the shaft, respectively. The experimental steps are similar to that in Section 6.1. The active power increase of the load is set from 300 to 600 W, and the converter also adopts V/F control. The frequency results with different inertia are shown in Figure 13. The enlarged part of the frequency demonstrates that the frequency of the group without the mass block decreases faster and deeper than that with the mass block under the same load change. The frequency deviations of the two groups are about 0.278 and 0.215 Hz with a reduction of 22.7% by using the mass block. The above analysis verifies that the mass block installed on the shafting can effectively improve the IR of the MGP system by enlarging the equivalent radius. However, the oscillation and attenuation process of the frequency in two groups after the first few cycles are similar because the damping coefficient of the MGP system is unchanged.

6.3 PFR comparisons of the PV and PV + MGP

For further studying the IR and PFR of the PV + MGP, two experiments with same load change are performed with PV and PV + MGP, respectively. The three-phase active power of the load increase from 2.1 to 2.4 kW, and the maximum active power of the PV emulator is 1.65 kW. Since the main difference between the two groups is whether the PV connects to the PCC via MGP, so the comparisons are reliable.

First, start the DC motor speed controller to drive SG to the synchronous speed. Second, close K1 and K3 and set the initial value of the load. Then, close K5 and the PV inverter operates according to the MPPT control algorithm. When the output of the PV inverter is stable, set the load change and record the experimental data. After the first group is finished, switch off the PV inverter and open K5. Start the converter and choose the DC-link voltage control with the de-loading strategy. The LR% is selected as 40% for the bigger power loss of the experimental machines. When reaching the synchronous speed, K4 is closed by the synchronisation device in the control cabinet. When the output of the MGP system is stable, set the load change and record the experimental data. The experimental results are shown in Figure 14.

As shown in Figure 14, the maximum frequency deviation of the PV + MGP group is approximately 0.11 Hz, which is almost only half of that in the PV group. This means that the MGP system can greatly improve IR of PV. The active power output of the PV + MGP is smaller than that of PV before the load changes because of the de-loading strategy. When the load changes, the active power output of the PV inverter stays unchanged under the control of the MPPT algorithm. In contrast, the active power output of PV + MGP increases rapidly, as mentioned in Section 3, and the change rate of the active power output has a linear relationship to that of the frequency in the first half circle. The active power output of the PV + MGP decreases gradually under the DC-link voltage control based on the de-loading strategy, and its decreasing speed is influenced by the charging and discharging speed of the capacitor and the performance of the control system. The above analysis demonstrates that the output characteristics of the PV + MGP are similar to the characteristics of the conventional generator with droop control, which are very important for improving the IR and PFR of the PV generation system.

6.4 Contrast experiments of the PV + MGP under changing DC-link voltage references manually

Since the sampling time of the frequency acquisition in the laboratory cannot meet the requirement of controller’s real-time calculation, it is difficult to achieve real-time frequency acquisition in the experiment. In order to verify the effectiveness of the DC-link voltage control based on the de-loading and additional frequency change strategy, $U_{ref}$ is manually changed at the moment of load change. The active power of load increases
from 900 to 1200 W. Other steps are the same as those in the second group in Section 6.3. The experimental results are shown in Figure 15.

As can be seen from Figure 15, since the load change amount is reduced compared to that in Section 6.2, the fluctuations of the frequency and active power output of the PV + MGP are relatively small. By manually reducing $U_{ref}$, the DC-link voltage and the active power output of the PV + MGP can be restored more quickly under the improved control strategy. Moreover, the active power output of the PV + MGP increases by nearly 36% compared to that before the load change, which can provide more active power support and is more conducive to the improvement of frequency stability.

6.5 Contrast experiments of the PV + MGP under different load changes

In order to test the PFR of the PV + MGP under different load changes, two groups of load increasing experiments are performed. The three-phase active power of the load increases from 900 W to 1500 and 1800 W, respectively. The other settings and experimental steps are the same as those in Section 6.4. The experimental results are shown in Figure 16.

As can be seen from Figure 16, the frequency deviation and RoCoF increase as the load change increases. Moreover, there is a positive proportional relationship among the deviations of frequency, active power offset and DC-link voltage, which is consistent with the experimental results in Section 6.4. These differences are enlarged with the increase of the power load. However, the recovery speed of the frequency and active power output of the PV + MGP are nearly the same, and the recovering time of the frequency is much longer than the decreasing

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**TABLE 4** System parameters

| Parameters                              | Value     |
|-----------------------------------------|-----------|
| Nominal line voltage of the AC system (V) | 380       |
| Frequency (Hz)                          | 50        |
| Capacitance (F)                         | $50 \times 10^{-6}$ |
| Weight of mass block (kg)               | 20        |
| PI of the PI controller                 | (-8, 20)  |

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One under different changes of the power load. This is mainly because the inertia of the MGP system works at the beginning of the change of the load, and the control parameters determine the recovery speed. The optimisation of the system structure and parameters can further improve the frequency stability.

6.6 PFR experiment of the PV + MGP under fast RoCoF

The grid emulator is chosen for its fast RoCoF to test the PFR of the PV + MGP in this case. First, start the converter and choose the de-loading strategy. Second, start the power grid simulator. After frequency is stabilised at 50 Hz, close K6. When reaching the synchronous speed, K4 is closed by the synchronisation device in the control cabinet. When the output of the PV + MGP reaches the steady state, the output frequency of the grid emulator is programmed manually. The experimental results are shown in Figure 17.

There are large fluctuations in the PV + MGP with during the drop and recovery of the frequency because the maximum deviation and change rate of the frequency are much greater than those in the above experiments. The transient processes are caused by large transient components that appear in the stator and rotor windings on both sides of the MGP for the conservation of flux linkages in the synchronous machines. The active power output of the PV + MGP can still maintain stability under the DC-link voltage control and damping of the MGP system in addition to extra active power support for the grid. The above analysis shows that the PV + MGP can still have relatively good PFR under the condition of rapid frequency change.
7 | CONCLUSION

This paper discusses the IR of the MGP system and analyses the effects of the electromagnetic–mechanical coupling of the MGP system and DC-link voltage control on the frequency regulation of the RE. Some conclusions are drawn from the theoretical analysis, simulation and experimental results as follows.

(i) The IR of the PV can be improved by adopting the MGP system, and the inertia can be increased by enlarging the equivalent radius of the shaft, which are verified by the first two experimental groups.

(ii) The DC-link voltage control can response as soon as the grid frequency changes without measuring the frequency for the electromagnetic–mechanical coupling of the MGP system. With this advantage, the improved control methods based on the de-loading and additional frequency deviation strategy are proposed to improve the PFR of the RE.

(iii) The simulation results illustrate that the grid-connected PV via MGP can perform well on both IR and FPR in case of load increase on a grid scale. Besides, the last simulation results verify that the proposed control strategy can be helpful to improve the frequency stability by increasing $k_f$ at a reasonable range.

(iv) The experimental results of the third group demonstrate that the PFR of the PV + MGP is similar to that of the conventional generator with droop control, and the results of the fourth group illustrate the transient process of the recovery and frequency regulation capability can be improved by using the novel control strategy.

(v) The last two experiments show that the PV + MGP with the improved control can perform well regardless of whether the RoCoF is fast or slow. Besides, the damping of the MGP system helps improve frequency stability of the PV + MGP.

ACKNOWLEDGEMENTS

This work was supported in part by the Natural Science Foundation of China under Grant 51977077, in part by the Natural Science Foundations of Jiangsu Province of China under Grant BK20180283 and in part by the Cooperative Training Project of North China Electric Power University Scholarship Fund under Grant XM1906825.

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How to cite this article: Gu Y, et al. Effects of motor–generator pair system on improving inertial response and primary frequency regulation capability of renewable energy. IET Renew Power Gener. 2021;15:313–325. https://doi.org/10.1049/tpg2.12025