ABSTRACT With the increase of renewable energy sources (RES) in power systems, the number of traditional synchronous generators (SGs) declines gradually, which leads to a decrease in total inertia and frequency instability in extreme situations. The synchronous motor-generator pair (MGP) system was proposed as a new grid-connection method to improve the inertial response and frequency stability of grids. To study the effects of the MGP on the frequency stability and penetration rate of RES in power grids, first the frequency response equations of a single MGP in a single-machine infinite bus system are derived; then, the system frequency response (SFR) model for a multi-machine system with the MGP integrated is built. By comparing key critical indices of the frequency response after step disturbance with this model, we discover that the MGP system can increase the upper limit penetration rate of RES by quite a percentage. Furthermore, time domain simulations are used to compare the frequency characteristics of RES penetration rates of 25%, 50% and 75% with and without MGP. Finally, the MGP test bench is built for relevant experimental verification.

INDEX TERMS Renewable energy sources (RES), motor-generator pair (MGP), inertial response, dynamic frequency response characteristics, upper limit penetration rate of RES.

NOMENCLATURE

A. ACRONYMS

RES Renewable energy sources
SG Synchronous generator
MGP Motor-generator pair
SFR System frequency response
DFIGs Doubly-fed induction generators
PMSGs Permanent magnet synchronous generators
PV Photovoltaic
VSG Virtual synchronous generator
SM Synchronous motor
HVRT High voltage ride through
LVRT Low voltage ride through

B. VARIABLES

J Moment of inertia
r Radius of rotation
m Mass of rigid body
H Inertia constant
ω₀ Synchronous speed
SB Rated capacity
HC Inertial constant of PV capacitor
C Capacitance of DC side of the inverter
UC Capacitor voltage
SN Rated installed capacity of renewable energy
Due to insufficient system inertia and primary frequency regulation, a large-scale power outage occurred in the United Kingdom on August 9, 2019, with a loss of approximately 3.2% of the load [1]. The maximum power point tracking curve is widely used to extract the maximum energy from variable renewable energy sources (RES). The output electromagnetic powers of RES, including doubly-fed induction generators (DFIGs), permanent magnet synchronous generators (PMSGs) and photovoltaic (PV), cannot allocate disturbance power automatically. There is no bearing of RES extraction with respect to frequency changes of the system [2]. In the power system with high penetration of RES, where a large number of traditional synchronous generators (SGs) are replaced, the moment of inertia is relatively reduced, which speeds up the frequency deviation under disturbance. In addition, the low tolerance of disturbance of RES may further increase unbalanced powers and seriously deteriorate the frequency stability of the grids.

In order to improve the inertial response, most of the previous studies controlled the converters to improve the frequency adjustment capabilities. To achieve the virtual inertial response, an additional control link for active power control of wind turbines was added in [3]. By optimizing the short-term overproduction response of variable-speed wind turbines, the synthetic inertia provision was realized in [4]. Additionally, frequency-droop control imitated the self-regulation capability of SGs to control the power regulation of RES [5]. The droop control through active power was presented in [6] for the primary frequency regulation of RES. Virtual inertia control and droop control were combined to improve the response characteristics of wind turbines to frequency changes of systems in [7] and [8]. The deviation and rate of change of frequency were introduced into the active power control loop of wind turbines to realize the comprehensive inertia control [9]. To mimic the inertial response and damping characteristics of SGs, virtual synchronous generator (VSG) technology was proposed in [10], [11], and [12]. Working with about 10% output margin, the load reduction scheme of wind turbines proposed in [13] can provide inertia response and primary frequency regulation, whereas the scheme cannot work when the output of wind farms is low [14].

However, the existing methods through control of inverters to improve frequency stability have certain limitations. For instance, the inertial response from the kinetic energy of wind turbine’s rotor can be of short duration and cause the second frequency drop. Because of the constraints of the extreme values for the rotor speed of wind turbines, the adjustment ability is limited. Besides, the setting of control parameters
is complicated and subject to external influence. How to set
the control parameters scientifically and accurately is still
challenging in practice. In addition, the remaining SGs have
to share more disturbance power with some SGs replaced
by RES, and this leads to an increase in the rate of change
of frequency. Because of the current source characteristics
of virtual inertia and droop control [15], RES cannot able
to instantaneously allocate disturbance power according to
the synchronous power coefficient in such a control mode
[16]. Theoretically, VSG technology can share power distur-
bance instantaneously, but the large instantaneous unbalanced
torque affects the stable operation of RES and there are still
control delays in the VSG control.

In contrast, traditional SGs can distribute the distur-
bance power instantaneously according to their synchroniz-
ing power coefficients [17]. Besides, the rotating rotors
have reliable inertial response and can respond to the power
deviation of the system to support the power balance and
restrains the frequency deviation [18], [19]. Therefore, based
on the theory of SGs, the MGP was proposed as a possi-
ble grid-connection approach to improve the stability of
high proportion RES systems [20]. Based on this idea, first
the oscillation mode was studied and compared through its
small signal model, which demonstrated the improvements
of MGP on stability region and damping ratio over tra-
ditional grid-connected inverters [21], [22], and then time
domain simulation results during the faults verified that MGP
can effectively improve the transient stability of grids [23].
In addition, the fault isolation capability of RES can be
enhanced significantly by MGP [24]. Though the frequency
stability improvement were studied in different scenarios, the
effects of the MGP on the critical penetration rate of RES and
quantitative calculations have not been investigated. Thus,
How the integration of MGP affects the penetration rate of
RES deserves further study.

To fulfill this gap and as a part of the continuous research,
the main goal of this study is to illustrate the role of MGP
system in stability enhancement with different penetration of
RES in multi-machine systems and try to find their critical
penetration rate. This paper is organized as follows. Section II
presents the operating principle of MGP. In Section III,
the frequency response of a single MGP is derived for a
single MGP experimental setup and multi-machine exper-
imental bench, including PV and MGP, are established to
validate the enhanced influence of MGP on the frequency
response.

II. CONCEPTUAL STUDY OF THE MGP
A. STRUCTURE OF THE MGP
Fig.1 illustrates the layout of MGP and its application
scheme. The MGP consists of an SM and SG, where their
rotors are connected to the same mechanical shaft. The elec-
tricity generated by RES is used to drive the SM to convert
electrical energy into mechanical energy. The SM drives the
SG through a mechanical shaft, and the SG converts mech-
anical energy into electrical energy. Two machines rotate at
the same speed on steady state. The excitation systems and
control system adjust the power transmitted by the MGP
system.

The useful features of the MGP system can be easily
predicted based on its structure. For example, it has real
inertia, it electrically isolates the RES and the grid, it can
withstand overvoltage and overcurrent, it provides reactive
power support to the grid, etc. However, the power con-
sumption of rotation machines and additional investment cost
may limit the application of MGP at low level penetration
RES. Based on a 5.5 kW MGP experimental test bench, the
measured efficiency is 91.7%. With the expansion of capacity,
the efficiency of the whole system is significantly improved.
The additional costs of MGP mainly include the costs of two
SGs, a converter, installation, and civil engineering. MGP can
provide sufficient reactive power support and realize high
voltage ride through (HVRT) and low voltage ride through
(LVRT) [24], [25]. Reactive power compensation devices
and converter modification of HVRT and LVRT for RES
stations can be avoided. Besides, as more and more existing
conventional units are replaced by RES, the potential costs of
machines will be reduced if decommissioned thermal units
can be reused.

From a systematic point of view, the MGP can increase the
stability of the grid at the RES ends, where the strength is
usually weak. Hopefully, the MGP may be one of the most
effective grid-connection methods for the future grid with an
ultra-high proportion of RES [26].

B. INERTIA OF MGP
The MGP system can increase inertial response of power
grids. The inertia of a power system is a resistance to
frequency deviation caused by external disturbances.
The moment of inertia \( J \) is a physical quantity that characterizes the rotational inertia of a rigid body, which can be estimated with the mass block as in (1).

\[
J = \int r^2 \, dm
\]  

(1)

Based on the mass parameters of a thermal generator, the moment of inertia of an MGP with the same capacity is estimated. For a conventional thermal power generator, the rotational part is composed of the exciter, SG, low-pressure cylinder, and high-pressure cylinder. The MGP system consists of two synchronous machines and two sets of excitation systems. Thus, the moment of inertia of the MGP is about 65\% that of a thermal generator with the same capacity, as shown in Appendix A [27].

The moment of inertia \( J \) can be expressed by the inertia constant \( H \), as shown in (2).

\[
H = \frac{1}{2} J \omega_0^2
\]  

(2)

For example, suppose that the inertia constant \( H \) of a 600MW turbogenerator is 6.636s. Then, similarly, \( H \) of a MGP with the same capacity can be calculated as 4.38s.

The virtual inertia of PV is entirely derived from the energy storage of the capacitor on the DC side of the inverter. The inertial constant of PV capacitor \( H_C \) is in (3).

\[
H_C = \frac{1}{2} C U_C^2 S_N
\]  

(3)

Taking \( U_C \) as 625V and \( C \) as 0.1F in (3), the inertial constant \( H_C \) of 600MW PV can be calculated as 0.01659s. Therefore, the inertia of the MGP is about 400 times that of an inverter with the same capacity.

C. POWER ANGLE CHARACTERISTICS OF MGP

An equivalent electrical circuit with the classical model for MGP is shown in Fig.2. The shafts of the two machines of the MGP are coupled, therefore, the angular speeds of two machines rotors are the same if the torsional stiffness of the shafts is ignored. Then, \( E'_M \) and \( E'_G \) rotate synchronously at the synchronous speed \( \omega_0 \).

\[
\Delta P_M = \frac{|U_{BM}| |E'_M|}{x_{dM}} \cos \delta_{M0} \Delta \delta_M
\]  

(4)

\[
\Delta P_G = \frac{|U_{BG}| |E'_G|}{x_{dG}} \cos \delta_{G0} \Delta \delta_G
\]  

(5)

According to (4) and (5), \( \Delta P_M \) and \( \Delta P_G \) have the same changing trend as \( \Delta \delta_M \) and \( \Delta \delta_G \). To measure the phase disturbance of MGP when the power fluctuates, we define the deviation of power angle of MGP, \( \Delta \delta_{MG} \), as shown in (6) and Fig.3. In dynamic disturbance analysis, \( \Delta \delta_{MG} \) can be used as the state variable to measure the power angle change of MGP.

\[
\Delta \delta_{MG} = \Delta \delta_M + \Delta \delta_G
\]  

(6)

III. FREQUENCY RESPONSE CHARACTERISTIC OF A SINGLE MGP

A. CLASSIC SECOND-ORDER MATHEMATICAL MODEL OF MGP

Fig.4 illustrates the scheme of a MGP connected to an infinite bus.

\[
\Delta T_{EM} = K_{SM} \Delta \delta_M = \frac{|E'_M| |U_{BM}|}{x_{dM}} \cos \delta_{M0} \Delta \delta_M
\]  

(7)
\[
\Delta T_E = K_{DG} \Delta \delta_G = \frac{|E'_G|}{x'_{DG}} |U_{BG}| \cos \delta_{DG} \Delta \delta_G \quad (8)
\]

Considering the MGP as a whole mass block, the SM’s mechanical torque \(T_{mM}\) and the angular speed \(\omega_M\) are equal to the SG’s mechanical torque \(T_{mG}\) and the angular speed \(\omega_G\), respectively. The inertia constants \(H\) of two machines are equal. The inertial constant of MGP, \(H_{MGP}\), is \(2H\). The motion equations of the two machines are given by (9) and (10).

\[
\begin{align*}
\dot{s} \Delta \omega_M &= \frac{1}{2H} (\Delta T_{eM} - \Delta T_{mM} - K_{DM} \Delta \omega_M) \\
\dot{s} \Delta \delta_M &= \omega_0 \Delta \omega_M \\
\dot{s} \Delta \omega_G &= \frac{1}{2H} (\Delta T_{mG} - \Delta T_{eG} - K_{DG} \Delta \omega_G) \\
\dot{s} \Delta \delta_G &= \omega_0 \Delta \omega_G
\end{align*}
\quad (9)
\]

\[
\dot{s} \omega_M = \frac{1}{2H} (\Delta T_{eM} - \Delta T_{mM} - K_{DM} \omega_M) \\
\dot{s} \delta_M = \omega_0 \Delta \omega_M \\
\dot{s} \omega_G = \frac{1}{2H} (\Delta T_{mG} - \Delta T_{eG} - K_{DG} \omega_G) \\
\dot{s} \delta_G = \omega_0 \Delta \omega_G
\quad (10)
\]

The damping terms, \(K_{DM} \Delta \omega_M\) and \(K_{DG} \Delta \omega_G\), of those two machines are the same due to the same rotor angular speed. The frequency differences between the stator and the rotor of the SM and the SG are also usually equal. Then we define that \(\omega_{MGP} = \omega_M = \omega_G\) where \(\omega_{MGP}\) is the rotor speed of MGP. Hence, the speed in (9) and (10) can be added directly. Combining the definition of deviation of power angle of the MGP, \(\Delta \delta_{MG}\), the motion equation of the MGP described by \(\Delta \omega_{MGP}\) and \(\Delta \delta_{MG}\) can be expressed as (11).

\[
\begin{align*}
\dot{s} \omega_{MGP} &= \frac{1}{2H_{MGP}} [\Delta T_{eM} - \frac{K_M K_{DG}}{(K_M + K_{DG})} \Delta \delta_{MG}] \\
\dot{s} \delta_{MG} &= \frac{K_M + K_{DG}}{K_M} \omega_0 \Delta \omega_{MGP}
\end{align*}
\quad (11)
\]

\[
\begin{bmatrix}
\Delta \omega_{MGP} \\
\Delta \delta_{MG}
\end{bmatrix} = \begin{bmatrix}
-K_{DM} K_{DG} & -1 & 0 \\
2H_{MGP} & 2H_{MGP} & 2H_{MGP} \\
K_M & K_M & 1
\end{bmatrix} \begin{bmatrix}
\Delta \omega_{MGP} \\
\Delta \delta_{MG}
\end{bmatrix} + \begin{bmatrix}
\Delta y
\end{bmatrix}
\quad (12)
\]

The closed-loop transfer function \(G_{MGP}(s)\) from the disturbance variable \(\Delta T_{eM}\) to the output \(\Delta \omega_{MGP}\) is given in (13).

\[
\frac{\Delta y}{\Delta u} = G_{MGP}(s) = \frac{\Delta \omega_{MGP}}{\Delta T_{eM}} = C_{sys} (sI - A_{sys})^{-1} B_{sys} + D_{sys}
\quad (13)
\]

where \(I\) is the identity matrix, the transfer function \(G_{MGP}(s)\) represents the frequency response characteristic of the system over the full frequency band, \(C_{sys} = [c_{31} c_{32}] = [10], D_{sys} = d_{33} = 0\). \(A_{sys}, B_{sys}\) are calculated as follows.

\[
A_{sys} = \begin{bmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{bmatrix}
\quad (14)
\]

\[
B_{sys} = \begin{bmatrix}
b_{13} \\
b_{23}
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2H_{MGP}} \\
0
\end{bmatrix}
\quad (15)
\]

The Bode diagrams of the closed-loop transfer function of a single SG and a single MGP under the same parameters is shown as in Fig.5(a), and the time-domain response of frequency under the same disturbance are shown in Fig.5(b). It can be seen that the MGP and SG have similar frequency curves, and the MGP has stronger frequency disturbance suppression ability than a single generator, mainly because of its larger inertia and damping parameters with the same capacity.

\[\text{IV. THE PROMOTION EFFECT OF MGP ON THE UPPER LIMIT PENETRATION RATE OF RES} \]

\[\text{A. SFR MODEL OF MULTI-MACHINE SYSTEMS IN WHICH RES IS CONNECTED TO THE GRID VIA MGP} \]

The SFR model averages the dynamic behavior of machines in a large system into an equivalent single machine without considering the specific governor control, turbine model, limiting and other nonlinear links with the secondary frequency regulation, it is often used to describe the average system frequency response after a disturbance in power systems [29], [30]. Thus, the SFR model is established to quantify the effects of MGP on the frequency response of in a system.

For power systems with high penetration of RES, it is necessary to introduce a parameter to characterize the penetration rate of RES. The proportion of RES can be defined as (16).

\[
K = \frac{\text{Power output of RES}}{\text{Load power of system}}
\quad (16)
\]
FIGURE 5. Frequency characteristic of a single MGP and a single SG. (a) Bode diagrams of closed-loop transfer functions of a single SG and a single MGP. (b) Time-domain frequency response of a single SG and a single MGP under the same disturbance.

Based on the traditional vector control, the inertial support of RES is completely provided by MGP. The inertial characteristic of MGP in Section II shows that the moment of inertia of MGP is about 65% of the traditional generator unit with the same capacity, i.e., \( H_{\text{MGP}} = 0.65H_G \), where \( H_{\text{MGP}} \) is the inertial constant of MGP and \( H_G \) is the inertia constant of the traditional generator unit with the same capacity. Assuming that all RES are connected to grids with MGP, the \( K \) ratio RES with MGP can provide additional inertia of 0.65\( K \cdot H_G \). Combined with (11), \( K \) ratio RES with MGP can provide additional damping 2\( K \cdot D \). Also, the goal of this paper is to study the overall frequency characteristics of the system integrated with MGP, so the frequency dispersion, power angle stability issues, and uncertainty of the RES are not considered with the SFR model. Therefore, the simplified aggregated SFR model of the power system with the \( K \) proportion of RES connected to grids via MGP can be obtained as shown in Fig.6, where \( D \) is the damping factor, \( R \) is the governor regulator coefficient, \( T_R \) is the reheater time constant, \( F_H \) is the fraction of total power generated by the high-pressure turbine, \( \Delta P_L \) is the load power deviation, \( \Delta P_m \) is the mechanical power deviation of generator units, and \( \Delta P_e \) is the electromagnetic power deviation of generator units.

![SFR model of the power system with the K proportion of RES connected to grids through MGP.](image)

The open-loop transfer function of the system in Fig.6 relating the output \( \Delta \omega_t \) and the input \( \omega_{\text{ref}} \) can be deduced as (17).

\[
H(s) = \frac{1 - K + F_H T_R s}{R + T_R s} \times \frac{1}{(1 - K)(2H_Gs + D) + 0.65K(2H_Gs) + 2KD}
\]

The closed-loop of frequency response with a given power disturbance can be deduced as (18).

\[
G(s) = \frac{\Delta \omega_t}{\Delta P_L} = \frac{1}{1 + H(s)} \frac{s + \frac{1}{F_H T_R s}}{1 + T_R s} \frac{R \omega_n^2}{DKR + DR + (1 - K) s^2 + 2\zeta \omega_n s + \omega_n^2}
\]

where the natural oscillation frequency \( \omega_n \) and the damping ratio \( \zeta \) are given by (19) and (20).

\[
\omega_n^2 = \frac{DKR + DR + (1 - K)}{2H_G R T_R - 0.7H_G KT_R} \quad (19)
\]

\[
\zeta = \frac{1}{2} \frac{2H_G R - 0.7H_G K + 0.65K + 0.65K + (1 - K)F_H T_R}{DKR + DR + (1 - K)} \quad (20)
\]

In the Laplace domain, per unit frequency can be computed for \( \Delta P_L \) in the form of a step function amplitude \( P_{\text{step}} \) of the system as shown in (21).

\[
\Delta \omega_t(s) = \frac{R \omega_n^2}{DKR + DR + (1 - K)} \left( \frac{1 + T_R s}{s(s^2 + 2\zeta \omega_n s + \omega_n^2)} \right) P_{\text{step}}
\]

Consequently, the frequency deviation in the time domain \( \Delta \omega_t(t) \) is given by as in (22), shown at the bottom of the next page, where the coefficients \( \alpha \), the damped frequency \( \omega_{\text{fr}} \), and \( \phi \) are calculated as follows.

\[
\alpha = \sqrt{1 - 2T_R \zeta \omega_n + T_R \omega_n^2} \quad (23)
\]

\[
\omega_{\text{fr}} = \omega_n \sqrt{1 - \zeta^2} \quad (24)
\]

\[
\phi = \tan^{-1}\left( \frac{\omega_n T_R}{1 - \zeta \omega_n T_R} \right) - \tan^{-1}\left( \frac{\sqrt{1 - \zeta^2}}{-\zeta} \right) \quad (25)
\]

According to the Laplace domain and time domain solutions of frequency response of the system after a load disturbance in the form of a step function, the relationship between key dynamic frequency indices and the proportion of RES connected to grids via MGP can be obtained. The key dynamic frequency indices include the initial rate of change of frequency (RoCoF), the steady-state deviation of frequency response (\( \Delta f_{\text{nadirMGP}} \)) and the maximum frequency deviation (\( \Delta f_{\text{nadirMGP}} \)) for power systems whose RES is with MGP.

Corresponding to the condition \( t = 0 \) in (22), the RoCoF for power systems whose RES is with MGP \( R oC oF_{\text{MGP}} \) is
For the typical parameter scenario ($R = 5\%$, $H_G = 12.0$s, $T_R = 6$s, $F_H = 0.333$, $D = 0.01$ p.u. power/p.u. speed deviation) [30], the key dynamic frequency indices of RES connected to grids with and without MGP are calculated. The results are listed in Table 1, and the key indices with typical values of $K$ and the critical penetration rate of RES are calculated in Table 2. It can be concluded that.

1) RoCoF is inversely proportional to the inertia constant of the system, and MGP can significantly reduce the RoCoF. Also, the frequency nadir is improved with MGP. While the steady-state frequency is less sensitive.

2) The constraint of the critical penetration rate of RES is that the frequency response after a 0.1 p.u. load disturbance does not exceed 0.02 p.u. Constrained by $Δf_{ss}$, the critical rate of RES without MGP is 75%, and is 75.9% with MGP, under typical parameters.

3) Constrained by $Δf_{nadir}$, the critical penetration of RES without MGP is 52%, and is 66.7% with MGP.

### Table 1: Key dynamic frequency indices of the system frequency response based on the SFR model.

| Key indices | RES | RES+MGP |
|-------------|-----|---------|
| RoCoF$\Delta f_{ss}$ | 1/24(1−K) | 1/24(1−MGP) |
| Steady-state deviation $Δf_{ss}$ | 0.05%(0.0005+0.05%) | 0.05%(0.0005+0.05%) |
| Maximum deviation $Δf_{nadir}$ | 0.05%×1.25×$e^{-0.005\delta}$ | 0.05%×1.25×$e^{-0.005\delta}$ |

### B. TIME-DOMAIN ANALYSIS FOR SYSTEM FREQUENCY RESPONSE OF MULTI-MACHINE SYSTEMS WITH HIGH PENETRATION OF RES

Two simulation models are built in PSCAD/EMTDC to analyze the frequency characteristics of high-penetrated RES systems with and without MGP. As shown in Fig.7, in model I, the PV is directly connected to grids, and in model II, the PV is connected to grids through the MGP system. Regardless
of the frequency regulating effect of PV, the frequency responses of the two models under different penetration rates of PV are compared to study the frequency stability. The specific parameters of simulation models are presented in Appendix C. The detailed control diagram of PV and MGP adopted in simulation model I and model II are shown in Appendix D.

In the three scenarios, the proportion of PV is 25%, 50% and 75%, while the load power is increased by a step of 10% respectively. The active powers transmitted by thermal power units and PV units under different proportions are shown in Fig.8.

From Fig.8, it can be seen that there are two roles for the inertial response of the MGP: 1) providing the instantaneous active power support at the moment of load disturbance. 2) improved with the increased power transmission of PV.

Fig.9 shows the frequency-time responses in the two models under the three scenarios. From Fig.9, the key dynamic frequency indices of PV connected to grids with and without MGP are listed in Table 3.

We can conclude that:
1) The dynamic change of the system frequency worsens as the penetration of PV increases.
2) Under the same proportion of PV, for simulation model II in which PV is connected to grids through the MGP, the RoCoF is lower, the maximum frequency deviation becomes smaller obviously, and the steady-state deviation \( \Delta f_{\text{nadir}} \) becomes smaller compared with model I.
3) After a 10% increase in load power with a step change, the \( \Delta f_{\text{nadir}} \) of model I under 75% penetration ratio of PV is 1.14 Hz and the \( \Delta f_{\text{nadir}} \) of model II under 75% penetration ratio of PV with MGP is 1.10 Hz; the \( \Delta f_{\text{nadir}} \) of model I

| Key indices/penetrations | RES | RES+MGP |
|--------------------------|-----|---------|
| RoCoF                    | 0.056 | 0.051 | 0.064 | 0.088 |
| \( \Delta f_{\text{nadir}} \) | 0.067 | 0.167 | 0.067 | 0.19 |
| \( \Delta f_{\text{nadir}} \) | 1.27  | 0.19  | 0.18  | 0.256 |

| Critical penetration rate (\( \Delta f_{\text{nadir}} \)) | 75% | 75.9% |
|----------------------------------------------------------|-----|------|
| Critical penetration rate (\( \Delta f_{\text{nadir}} \)) | 52% | 66.7% |
TABLE 3. Key dynamic frequency indices of PV connected to grids with and without MGP.

| Key indices                                      | RoCoF (Hz/s) | Maximum deviation $\Delta f_{\text{damp}}$ (Hz) | Steady-state deviation $\Delta f_{\text{s}}$ (Hz) |
|------------------------------------------------|--------------|-----------------------------------------------|-----------------------------------------------|
| 25% PV connected to grids via MGP               | 0.0815       | 0.57                                          | 0.17                                          |
| 25% PV connected to grids directly              | 0.126        | 0.65                                          | 0.21                                          |
| 50% PV connected to grids via MGP               | 0.148        | 0.93                                          | 0.35                                          |
| 50% PV connected to grids directly              | 0.259        | 1.11                                          | 0.39                                          |
| 75% PV connected to grids via MGP               | 0.372        | 3.64                                          | 1.10                                          |
| 75% PV connected to grids directly              | 1.172        | 5.57                                          | 1.14                                          |

under 50% penetration ratio of PV is 1.11 Hz and the $\Delta f_{\text{damp}}$ of model II under 50% penetration ratio of PV with MGP is 0.93 Hz. According to the constraint that frequency response after a 10% p.u. load disturbance does not exceed 0.02 p.u., the simulations agree with the predicted results in Table 1.

4) The MGP system clearly improves frequency stability based on the three key indices of dynamic frequency response.

V. EXPERIMENTAL VERIFICATION OF ENHANCED INFLUENCE OF MGP ON TIME DOMAIN FREQUENCY CURVES

In order to validate the enhanced influence of MGP on the time domain frequency response and the system frequency dynamic response of power systems with RES connected to the grid via MGP, experimental analysis is carried out in this section.

A. TESTING ON TIME DOMAIN FREQUENCY RESPONSE OF A SINGLE MGP

An experimental MGP test bench is established, as shown in Fig.10, where one of the tasks is to test the frequency characteristic of the MGP.

In this test bench, a PV simulator is used to simulate the real renewable power generation, and the MGP system consists of two 5.5 kW synchronous machines. The RES is connected to the programable load via the MGP when switches k1, k2 are closed and k4 is open. The electrical quantities transducer measures the power transmission through the MGP system, and the programmable logic controller (PLC) controls the power tracking of PV and power output of the MGP system.

The test bench can be also used to emulate a SG for comparison study while switches k1 and k2 are open and switch k4 is closed. A 5.5 kW DC machine is connected mechanically with the SG, and the DC speed governor drives the DC machine and SG to mimic the SG unit. With switch k3 closed, the SG is connected to the programmable load. The specific parameters of the above machines are shown in Appendix E. Load disturbances are set in the programmable load, and frequency response in the two experimental settings under load disturbances can be recorded.

FIGURE 10. 5.5 kW experimental bench.

The frequency response results of the 5.5 kW MGP and the 5.5 kW SG under load changes from 0 to 1200 W and from 1200 W to 3000 W are shown in Fig.11. It can be seen that the MGP and a single SG have similar frequency response under the same disturbance, and the MGP system has stronger frequency disturbance suppression ability than a single SG with the same capacity.

FIGURE 11. Frequency response of two experimental settings. (a) Load disturbance from 0 to 1200 W. (b) Load disturbance from 1200 W to 3000 W.

B. EXPERIMENTAL ANALYSIS FOR SYSTEM FREQUENCY RESPONSE OF MULTI-MACHINE SYSTEMS WITH MGP

To analyze the frequency characteristics of multi-machine system with and without MGP, the experimental system is built according to the structure of Fig. 7. As shown in Fig.12, the PV simulator and traditional SG are connected to the load with switches k1, k2 and k3 closed at the same time, similar to the structure of model I, in which PV is connected to grids directly. In addition, closing all the switches k1, k2, k3 and k4 in Fig.10 can simulate the structure of model II, in which the PV is connected to grids through MGP.

In the two experimental models, the output of PV is set to 1500W and 2100W respectively to imitate different
proportions of PV, and the remaining active output is borne by the SG. The load is set to suddenly increase from 2100W to 3000W, measuring the output curves of PV and SG in the two experimental models, as shown in Fig.13.

In the model I of Fig.12, the initial power of load is 2100 and the power of SG is 600W with the output of PV set 1500W. When the load power increased suddenly from 2100W to 3000W, the inertial and primary frequency of SG complement the power shortage of load, as shown in Fig.13(a). In the experimental model II, the initial power of PV with MGP is 600W when the output of PV is set 1500W because of the loss of MGP. When the load power increased suddenly from 2100W to 3000W, the inertial and primary frequency of SG and the inertial response of MGP complement the power shortage of load simultaneously, as shown in Fig.13(b). When the photovoltaic power is set to 2100, the power curves of model I and model II are shown in Fig.13(c) and (d) respectively.

The frequency response curves of two models with different power outputs of PV are shown in Fig.14. By comparing the RoCoF and the frequency nadir, the dynamic change of system frequency response becomes worse with the increased power from PV.

From Fig.13 and Fig.14, it can be seen that PV with MGP can provide instantaneous active power support because of the inertial response of MGP at the moment of load disturbance. And the inertial support provided by MGP can improve the dynamic index of system frequency response.

VI. CONCLUSION

Considering the frequency instability caused by the lack of inertial response in the power grid with high penetration of RES, a renewable grid-connection method of MGP is proposed. This paper compares the frequency responses of high penetration of RES with and without the MGP, mainly considering the difference caused by the inertia effect. The following are the main conclusions:

1) The frequency response characteristic of MGP is derived in a single-machine infinite bus system, and the response characteristic is validated by an example.

2) The SFR model for the MGP is built, and three key indices (RoCoF, steady-state frequency deviation, and maximum frequency deviation) are analyzed and calculated. The results show that the inertial response of the MGP increases the upper limit penetration rate of RES connected to the grid.

3) A simulation model is built to compare the time-domain of the frequency response curves of the PV connected to the grid under 25%, 50%, and 75% penetration ratios, with and without MGP. The simulation result verified the theoretical analysis.

4) Experimental analysis of a single MGP experimental setup and a multi-machine experimental bench validates the enhanced influence of MGP on the frequency response.
APPENDIX A
See Tables 4 and 5.

### TABLE 4. Inertia moment of 600 MVA thermal power unit.

| Mass composition   | Inertia moment (kg m²) | Total moment of inertia (kg m²) |
|--------------------|------------------------|---------------------------------|
| Exciter            | 58.36                  |                                 |
| Generator          | 7435.81                |                                 |
| Low pressure cylinder | 13112.76              | 22713.22                        |
| High pressure cylinder | 2106.29               |                                 |

### TABLE 5. Inertia moment of 600 MVA MGP.

| Mass composition     | Inertia moment (kg m²) | Total moment of inertia (kg m²) |
|----------------------|------------------------|---------------------------------|
| Exciter of the SM    | 58.36                  |                                 |
| Rotor of the SM      | 7435.81                |                                 |
| Exciter of the SG    | 58.36                  | 14988.34                        |
| Rotor of the SG      | 7435.81                |                                 |

APPENDIX B
The simplified aggregate SFR model of the power system with K proportion of RES is shown as in Fig. 15.

![Fig. 15. SFR model of the power system with K proportion of RES.](image)

The open-loop transfer function of the system shown in Fig. 15 is given by (33).

\[
H(s) = \frac{1 - K + F_H T_R s}{R + T_R s} \left( 1 - K \right) \left( 2 H_G s + D \right) (33)
\]

The closed-loop of frequency response with a given power disturbance can be deduced as follows.

\[
G(s) = \frac{\Delta \omega_r}{\Delta P_L} = \frac{1}{1 + H(s)} \cdot \frac{1}{\left( 1 - K \right) \left( 2 H_G s + D \right)} (34)
\]

\[
\omega_n^2 = \frac{DR + 1 - K}{H_G R T_R (1 - K)} \omega_n (35)
\]

\[
\omega_n = \frac{H_G R (1 - K) + (DR + F_H (1 - K)) T_R}{2 \left( DR + 1 - K \right)} \omega_n (36)
\]

In the Laplace domain, the frequency response after a load disturbance in the form of a step function amplitude \(P_{step}\) is derived as (37).

\[
\Delta \omega_r(s) = \frac{R \omega_n^2}{DR + 1 - K} \left( \frac{1 + T_R s}{s^2 + 2 \xi \omega_n s + \omega_n^2} \right) P_{step} (37)
\]

The corresponding time domain analytical solution is determined as in (38), shown at the top of the next page.

APPENDIX C
See Tables 6 and 7.

### TABLE 6. The parameters of simulation model I.

| Basic data | 25% PV | 50% PV | 75% PV |
|------------|--------|--------|--------|
| Load power (MW) | 80     | 80     | 80     |
| Installed capacity of thermal power unit (MVA) | 75     | 50     | 75     |
| Installed capacity of PV (MVA) | 25     | 50     | 25     |
| Inertia constant of thermal power unit (s) | 12.45  | 8.31   | 4.15   |
| Inertia constant of PV (s) | 0      | 0      | 0      |
| Inertia constant of the system (s) | 12.45  | 8.31   | 4.15   |

### TABLE 7. The parameters of simulation model II.

| Basic data | 25% PV | 50% PV | 75% PV |
|------------|--------|--------|--------|
| Load power (MW) | 80     | 80     | 80     |
| Installed capacity of thermal power unit (MVA) | 75     | 50     | 75     |
| Installed capacity of PV with MGP (MVA) | 25     | 50     | 25     |
| Inertia constant of thermal power unit (s) | 12.45  | 8.31   | 4.15   |
| Inertia constant of PV with MGP (s) | 2.7    | 5.4    | 8.1    |
| Inertia constant of the system (s) | 15.15  | 13.71  | 12.24  |

APPENDIX D
See Figs. 16 and 17.

![Fig. 16. The detailed control diagram of PV in model I.](image)

APPENDIX E
See Table 8.
\[ \Delta \omega_f(t) = \frac{R P_{\text{Step}}[1 \pm \left( \frac{\omega_0 \sqrt{\gamma^2 - 1} e^{-\gamma \omega_0 t}}{\omega_0 \sqrt{\gamma^2 - 1}} \right) \cos \left( \omega_0 \sqrt{\gamma^2 - 1} \right) e^{-\gamma \omega_0 t}]}{(D R + 1 - K)} \]

\[ = \frac{R P_{\text{Step}}[1 \pm \alpha e^{-\gamma \omega_0 t} \sin (\omega_0 t + \phi)]}{(D R + 1 - K)} \]  

(38)

**FIGURE 17.** The detailed control diagram of MGP in model II.

**TABLE 8.** Equipment parameters of experimental system.

| Equipment                  | Model number | Main parameters                      |
|---------------------------|--------------|--------------------------------------|
| SM / SG                   | TF(D)21/10   | Rated power (kW) 5.5                 |
|                           | .5-4         | Rated voltage (V) 230                |
|                           |              | Rated current (A) 9                  |
|                           |              | Rated frequency (Hz) 50              |
|                           |              | Rated power factor 0.8               |
|                           |              | Rated speed (RPM) 1500              |
|                           |              | Field current (A) 3.9                |
|                           |              | Rated power (kW) 5.5                 |
|                           |              | Rated voltage (V) 220                |
|                           |              | Rated current (A) 41.1               |
|                           |              | Excitation voltage (V) 220           |
|                           |              | Excitation current (A) 1.18          |
|                           |              | Excitation mode separately           |
| DC machine                | Z2-52        | Rated speed (RPM) 1500              |
| PV emulator               | 62100H-600S | Rated power (kW) 10                 |
|                           |              | Output-voltage (V) 6−600             |
|                           |              | Output-current (A) 0−17              |
| Inverter                  | BNSG10KS     | Rated power (kW) 10                 |
|                           |              | DC voltage (Vdc) 400−780             |
|                           |              | AC voltage (Vac) 310−450             |
| Frequency converter       | ZY-PR900F-5.5K-3B | Rated input voltage (V) 380       |
|                           |              | Rated frequency (Hz) 50/60           |
|                           |              | Rated output current (A) 17         |
| PLC control panel Speed governor | ACLT-3803H-programmable load | CPU224XP/FX1N-20MR-4AD |
|                           |              | Frequency (Hz) 50                     |
|                           |              | Input voltage (V) 400                |
| AC load                   |              | Rated resistive power (kW) 33.33     |
|                           |              | Rated inductive power (kVar) 33.33   |
|                           |              | Rated capacitive power (kVar) 33.33  |

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