Vector control strategy for motor-generator pair drive inverters in parallel operation

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Abstract
In view of the weak moment of inertia for power system with high penetration of renewable energy and limited transient voltage support of power electronics, a synchronous motor-generator pair (MGP) is proposed as a possible solution for renewable energy integration to improve grid stability. In order to realize the large-scale renewable energy integration, parallel inverters drive MGP is an ideal control scheme. Firstly, the working principle and mathematical model of MGP are introduced. Then based on a comparative analysis of control of parallel inverters and torque control of synchronous motors, the decoupling vector control method of MGP is proposed. Considering the linear relation between q-axis current and the active power in the rotor flux-oriented mode, the strategy of parallel drive for MGP with vector control is established. Different control loop for off-grid and grid-connected operation is designed, and effectiveness of this control strategy is verified by simulation. Finally, a 5 kW MGP experimental platform with dual inverters is built, the parameters are selected to test stability of the system, and power distribution and efficiency are studied. The results indicate that the parallel operation of MGP is stable under dynamic conditions, the strategy can realize the independent control of each inverter.

1 | INTRODUCTION

By the end of 2019, installed renewable energy capacity was enough to provide an estimated 27.3% of global electrical generation, maintaining the more than 8% average growth rate over the previous five years [1]. A high proportion of renewable energy integration will become an important feature of the future power grid. As a result of the limitations of their control mode and capacity, conventional renewable resources, such as wind and solar energy, cannot provide enough moment of inertia and the ability of frequency regulation for the power grid [2, 3]. Also, the lack of reactive power reserve and short-circuit capacity make it impossible to provide effective voltage support [4, 5]. Thus, the frequency and voltage reference of power grid with high penetration rate of renewable energy is not so stable as before [6]. For that, different solutions have been put forward by scholars, such as the additional damping link, droop control and virtual synchronous generator (VSG) [7–9]. VSG is one of the most representative methods which can emulate the transient characteristics of synchronous generators (SGs) in some way, so the inertia and damping can be both achieved [7, 8]. The algorithm-based VSG may be conveniently performed on the existing grid-connected converters and the parameters can be controlled in real time to enhance its flexibility and applicability [10, 11]. Though the advantages are obvious by emulating the nature of SGs, the improvements are realized through the energy interaction between renewable energy and power grid. The additional energy storage system in these methods will make the equipment investment increase, also the transient condition tolerance of the inverter-based generating units is much less than the real SGs [11]. In addition, the more complete the imitation of the equations of SGs is, the more complex the algorithm is, then unreliability of the control is inevitable. The improvements have a very limited effect on inertia and damping, it may not meet the requirements of a higher rates of renewable energy integration in the future.

Then a synchronous motor-generator pair (MGP) system for renewable energy integration is proposed in [12, 13] to improve
the grid stability, and some research has been done. In [13, 14], the small-signal model of MGP is systematically established and the damping characteristics is analysed, which demonstrate that the damping ratio is higher than that of the traditional units and MGP can effectively enhance frequency response and damp oscillation. And in [15], the power angle stability of MGP system is studied through simulation and the results show MGP has a longer critical fault-clearing time than traditional units. Additionally, the experimental results of fault ride-through during grid voltage sag, overvoltage and multiple voltage sags of MGP in [16] demonstrate that MGP can provide strong reactive power support to the power grid and has the nature of voltage isolation between the renewable energy and grid.

For wind turbines and photovoltaics, the point of common coupling (PCC) is limited to the low-voltage grid. For large capacity wind turbines, power can be transmitted to the grid by parallel operation of grid side back-to-back inverters [17]. For photovoltaics, a large power generation unit is usually formed by the series of basic PV panels, and the grid side inverters are connected to the grid in parallel [18]. Thus, for grid integration of large-scale renewable energy, the existing control method of MGP with a single inverter cannot meet the requirements in terms of its capacity and reliability. And considering the investment cost, it is uneconomical to build a full power inverter for power integration. Therefore, in order to facilitate the convergence and the coordinated operation of different renewable energy sources, the mode of driving MGP with parallel inverters is an inevitable choice.

The current research of MGP only focuses on the mode of driving with a single inverter. In [12], the phase relationship between the terminal voltage and the excitation electromotive force of the two machines is analysed, and the method of regulating the phase difference between the motor and generator is proposed to control the active power. In other words, the output frequency of the inverter is adjusted by active power feedback of the generator, so that the power angle of MGP can be regulated. But when MGP is driven by multiple inverters, it is impossible to allocate the frequency references reasonably to the parallel inverters. Therefore, it is necessary to study the control method which is suitable for driving MGP with parallel inverters.

At present, the research on the parallel operation of inverters can be divided into two types according to their applications: grid-connection and motor drive. The parallel operation of grid-connected inverters can be divided into control modes with or without interconnection lines [19]. The modes with interconnection lines mainly include central control, master-slave control, average control and 3C control [20]. The control methods with interconnection lines require communication between power modules, and the complex structure is not suitable for parallel operation of distributed power generation units. The droop control is a typical control method without interconnection lines, which enables parallel inverters to share active and reactive power through voltage and frequency droop control [21–24]. In the application of motor drive, the control methods of inverters driving high-power induction motor with the parallel operation are studied in [25, 26], the circulating current can be suppressed by tracking current reference and centralized current sharing control. In [27], the control method of a single PMSM driven by parallel voltage source inverters (VSI) based on FOC and DTC technology is studied, the proposed control strategy can suppress the harmonic peaks of all switching frequencies. The existing research on inverters with parallel operation is limited to the grid-connected inverters and the drive of a single motor, the output power of the inverters is generally controlled by controlling the output current, so the operation characteristics of the motor is not required to be considered in this control mode. When the inverter is used to drive the motor, the outer loop of the control link is often the speed loop. As MGP is such a motor device that is used for grid integration, basic control principles of parallel operation of the inverters and motor drive is necessary to be combined to study the control strategy of inverters for driving MGP in parallel.

In this paper, decoupling vector control method of MGP is proposed firstly based on a comparative analysis of the traditional control of parallel inverters and the power angle characteristics of MGP. Then the strategy of driving MGP with parallel inverters without interconnection lines is established, in which the common inner q-axis current loop is used for controlling the active power, and outer control loop is designed for off-grid and grid-connected operation respectively, also the stability of the control system is analysed in detail. Then the proposed strategy is tested under dynamic conditions by simulation model. Finally, 5 kW MGP experimental platform with dual inverters is built, the experimental results indicate that the parallel operation of MGP can have a stable operation under each stage, and independent control and power distribution of each inverter can be realized.

This paper is organized as follows. In Section 2, the working principle and mathematical model of MGP is presented. In Section 3, the control method based on traditional grid-connected and motor drive inverters in parallel operation is analysed and compared, then the vector control strategy for MGP drive inverters in parallel operation without interconnection lines is proposed. Based on the strategy, the simulation results and its verification are presented in Section 4. In Section 5, the experimental study including stability analysis and parameter selection of control system, detailed experiment results are introduced, followed by the conclusions in Section 6.

2 | THE WORKING PRINCIPLE AND MATHEMATICAL MODEL OF MGP

The structure of MGP system is shown in Figure 1. The MGP system consists of two motors which are typically the synchronous motor (SM) and synchronous generator (SG), and the shafts of two machines are coupled so that they can rotate in the same direction and speed. The energy generated by renewable resources is converted into power frequency by inverters and integrated into the power grid via MGP. It can be seen from the overall structure that the motor replaces the traditional steam turbine or hydro turbine as the prime mover, so renewable resources have some characteristics of the traditional synchronous units. In this way, renewable resources are mainly
responsible for providing electric energy, while MGP is mainly responsible for grid-connection and providing certain voltage and frequency support for power grid.

For a clear comparison with grid-connected power electronic converters, the main advantages and disadvantages of MGP are discussed. MGP plays a positive role in the aspects of voltage and frequency stability just as presented in Table 1, so its application scenarios are clear.

For frequency stability, the main disadvantage is that the moment of inertia and damping cannot be regulated flexibly. But we need to know the variable damping and inertia are designed for stable operation of power electronic converters with low inertia and damping level. Then the decreased efficiency and increased cost for the additional equipment are indeed the disadvantages for its application. Though the investment cost is one of the important factors need to be considered, but the stability issue is also a real problem for power grid with a high penetration rates of renewable energy or even with a higher penetration. Fortunately, the additional cost can be reduced through substituting for some reactive power compensation equipment used for voltage ride-through and energy storage equipment used for frequency support. And the improvements in frequency and voltage stability result in the increase in penetration rate of renewable energy, also the income from the power generation will make MGP more economic or feasible in application.

**TABLE 1** Advantages and disadvantages of MGP

| Features  | Advantages                              | Disadvantages                          |
|-----------|-----------------------------------------|----------------------------------------|
| Frequency | Real moment of inertia                  | Invariable moment of inertia and damping|
|           | Damping windings                        |                                        |
|           | Higher frequency tolerance              |                                        |
| Voltage   | Higher overload capacity                 | —                                      |
|           | LVRT/HVRT (0.2 pu/1.3 pu, >1s)          |                                        |
|           | Voltage isolation                       |                                        |
| Response  | Spontaneous response to ΔV/Δf (in ms)   | —                                      |
| Operation | Easier control                          | Lower efficiency                       |
|           | Easier maintenance                      |                                        |
| Cost      | Reduced investment of reactive power compensation and energy storage equipment | Extra cost of SM and SG |

MGP system is composed of two synchronous machines, and the electrical models of synchronous motor and generator are the same except that the positive direction of specific electrical quantities is different [28]. The motion equation can be established by the relationship between the rotors of the two machines, as shown in Equation (1). The power transmission of MGP is realized by the imbalance of electromagnetic torque of SM and SG.

\[ 2(H_M + H_G) \frac{d\omega_m^*}{dt} = |T_eM^*| - |T_eG^*| - (K_{DG} + K_{DM})\Delta\omega_m^* \tag{1} \]

In which, the inertia time constants of the motor and generator are \(H_M\) and \(H_G\) respectively, the electromagnetic torque are \(T_{eG}\) and \(T_{eM}\), the rotor angle are \(\delta_G\) and \(\delta_M\), and the damping coefficient are \(K_{DG}\) and \(K_{DM}\) respectively.

For SM and SG, the transmission equation of active power can be simplified into Equations (2) and (3) respectively. And the stator voltage can be represented by Equations (4) and (5) respectively.

\[ P_M = -\frac{U_M^2}{X_M} \sin \delta_M \tag{2} \]
\[ P_G = \frac{U_G^2}{X_G} \sin \delta_G \tag{3} \]
\[ U_M = E_M + R_{SM}i_{SM} + jL_{SM}i_{SM} \tag{4} \]
\[ U_G = E_G - R_{SG}i_{SG} - jL_{SG}i_{SG} \tag{5} \]

In which, \(U_M\) and \(U_G\) are stator voltage, \(\delta_M\) and \(\delta_G\) are rotor angle, \(X_M\) and \(X_G\) are d-axis reactance of stator, \(E_M\) and \(E_G\) are internal voltages, \(R_{SM}\) and \(R_{SG}\) are equivalent resistance, \(L_{SM}\) and \(L_{SG}\) are equivalent inductor, \(i_{SM}\) and \(i_{SG}\) are stator current of SM and SG respectively.

The rotor angle relationship of MGP system is shown in Figure 2. Combined with the simplified power equation of
synchronous machine, when the phase of stator voltage between SM and SG increases, the power angle of both machines increase, and the power angle $\delta_{MG}$ increases, then the active power transmitted by MGP system increases [14]. When the voltage vector of SG is taken as a reference, the phase of stator voltage which can be changed by stator current can cause the change of power angle, thus affecting the power transmission of MGP. And it is the characteristic of power angle of MGP.

### 3 | THE CONTROL METHOD OF DRIVING MGP WITH PARALLEL INVERTERS

In order to achieve the universality and flexibility of the parallel drive of MGP, it is necessary to consider both the control characteristics of grid-connected inverters and the synchronous motor.

#### 3.1 | Parallel mode analysis and LC filter modelling

For parallel drive of MGP, it is hoped that each inverter can keep good independence and the parallel modules can be expanded flexibly under the control. There is only an AC bus connection between different power modules in non-interconnected control mode, and the inverters can be controlled only by detecting the local information. Therefore, the control mode based on non-interconnection lines is adopted.

A series filter is often needed at the output of inverters to filter high order harmonics. For MGP, the form of LC filter is chosen, and in order to realize the decoupling of power, the form in $dq$ coordinate system is usually used. When only the resistance and reactance parameters of the filter are taken into account, voltage and current loop equations can be presented as Equations (6), (7).

\[
\begin{align*}
U_{ld} &= U_{md} + R_{Ld} i_{ld} + L_{d} \frac{d i_{ld}}{dt} - \omega L_{q} i_{Lq} \\
U_{Lq} &= U_{mq} + R_{Lq} i_{Lq} + L_{q} \frac{d i_{Lq}}{dt} + \omega L_{d} i_{Ld} \\
I_{ld} &= I_{md} + C \frac{d u_{md}}{dt} - \omega C u_{Lq} \\
I_{Lq} &= I_{mq} + C \frac{d u_{mq}}{dt} + \omega C u_{Ld}
\end{align*}
\]  

Equations (6), (7).

The voltage and current double closed-loop controller can be established based on the Equations (6) and (7), in which the voltage loop is the outer loop, the current loop is the inner loop. The voltage loop includes the cross-decoupling term of current and the feed-forward compensation term of voltage in the current loop, which makes the system have good performance on dynamic response. When the reactance of the LC filter is much larger than the equivalent resistance, the resistance effect can be ignored.

#### 3.2 | Comprehensive analysis of operation characteristics of SM

Based on the power angle characteristics of MGP, the power angle can be controlled by current vector. For the synchronous motor, vector control is adopted and consistent with voltage and current double closed-loop expressed in Equation (6), (7), and more effective torque control can be got compared with V/F control.

The torque expression of SM in $dq$ coordinate can be expressed in Equation (8) [28].

\[
T_{em} = 3/2 \cdot n_p (\psi_{md} i_{mq} - \psi_{mq} i_{md})
\]  

(8)

If the rotor flux linkage of SM has only the direct axis component in $dq$ coordinate, the electromagnetic torque can be regarded as the sum of excitation torque and reluctance torque. The excitation torque is generated by the interaction of rotor flux link $\psi_f$ and $i_{mq}$; the other one is generated by the interaction of $i_{md}$ and $\psi_f$, so it can be expressed as:

\[
\begin{align*}
T_{em1} &= 3/2 \cdot n_p i_{mq} \psi_f \\
T_{em2} &= 3/2 \cdot n_p (I_{md} - I_{mq}) i_{md} i_{mq}
\end{align*}
\]  

(9)

In the rotor flux-oriented mode, the control with $i_{md} = 0$ is a common control method in vector control, so that the motor torque is electromagnetic torque, and which is linear with $i_{mq}$. The control link can be simplified by using the frame, so that the $d$-axis component of stator flux linkage is completely decoupled from $i_{mq}$, and is only determined by the excitation current. When MGP is connected to power grid, its speed is relatively constant, so its output power can be controlled with $q$-axis current. As $q$-axis current is used for controlling the active power of MGP, the most advantage is that renewable energy is responsible for providing the active power, and the regulation of voltage or reactive power can be realized by the excitation control of synchronous machine. And independent control of active and reactive power can be achieved based on the principle.

#### 3.3 | The vector control strategy for driving MGP with inverters in parallel operation

Based on the analysis in Sections 3.1 and 3.2, the control strategy of controlling the power transmission from the inverters to
the MGP system by controlling the current vector is established in Figure 3. With constant $d$-axis current, the active power of each inverter is essentially determined by respective $I_{qref}$, also the inverters can share different ratio of power by setting corresponding $I_{qref}$. And significantly the combined current injection of two inverters should not exceed the current rating of MGP.

The proposed control strategy is mainly aimed at the active power control of parallel inverters, and the reactive power control can be easily achieved by the excitation control methods such as the constant excitation voltage, automatic voltage regulator (AVR) and power system stabilizer (PSS), the mode of excitation depends on actual operation requirements such as the capacity of machines and the regulation capability of reactive power. The excitation system of SM mainly has effects on the capacity of machines and the regulation capability of reactive power. The excitation system of SM mainly has effects on the renewable energy, and the excitation of SG mainly has effects on the reactive power fed into the power grid. Voltage control has been demonstrated in Sections 2 and 3.2, because it is not the focus of this paper, only the excitation mode and principle are briefly presented.

$I_{qref}$ can be set through external setting which may consider the power rating of MGP, and can be set through speed loop in the off-grid stage or through voltage loop in grid-connected stage. Different setting principles have their own application scenarios: in the off-grid stage, the current reference is controlled by speed variation, and MGP system is accelerated to synchronous speed. And in grid-connected stage, the current reference value can be set directly through external setting or voltage loop in which the typical application such as photovoltaics and other renewable resources with the similar operation characteristics. Then inner current loop is composed of the motor current loop and inductor current loop. The motor current loop is set for accurate current control of the MGP and the inductor current loop is set for accurate current control of parallel inverters, and the reactive power control of parallel inverters, and the reactive power control of parallel inverters, and the reactive power control of parallel inverters, and the reactive power control of parallel inverters, and the reactive power control of parallel inverters, and the reactive power control of parallel inverters.

Figure 3

Control structure of the strategy proposed

In which, $I_{m}$, $I_{m}^*$: Actual value and reference value of phase current of synchronous motor;

$\theta$: Rotor angle of synchronous motor;

$U_{inv}$, $U_m$: Output voltage of inverters and phase voltage of motor;

$L, C$: Inductance and capacitance of the output filter;

$K_{pwm}$: Equivalent gain of PWM inverter;

$R_M, X_M$: Equivalent resistance and reactance of SM. According to the control block diagram above, it can be concluded that the open-loop transfer function $G_o$ is:

$$G_o = \frac{I_m}{I_m^* - I_m} = \frac{s(k_{p1} + k_{i1})}{sL} \times \frac{s(k_{p2} + k_{i2})}{sL} \times K_{pwm} \times \frac{k_{pwm} (s k_{p2} + k_{i2})}{s} \times (1 + sCZ_m) + Z_m + sL(1 + sCZ_m) + 1}{s + 1} \quad (10)$$

And closed loop transfer function is:

$$G = \frac{I_m}{I_m^*} = \frac{s(k_{p1} + k_{i1})}{sL} \times \frac{s(k_{p2} + k_{i2})}{s} \times K_{pwm} \times \frac{k_{pwm} (s k_{p2} + k_{i2})}{s} \times (1 + sCZ_m) + Z_m + sL(1 + sCZ_m) \quad (11)$$

Considering the inner loop of inductance current, the inductance current $I_l^*$ can be expressed as:

$$I_l = \frac{s(k_{p2} + k_{i2})}{s} \times K_{pwm} \times \frac{s(k_{p1} + k_{i1})}{s} \times \frac{1}{sL} \times \frac{I_m^*}{k_{pwm} \times \frac{s(k_{p2} + k_{i2})}{s} + sL} \quad (12)$$

Therefore, the characteristic equation with $k_{p2}$ and $k_{i2}$ is:

$$s^2L + s k_{p2} K_{pwm} + k_{i2} K_{pwm} = 0 \quad (13)$$

Also, the characteristic equation with $k_{p1}$ and $k_{i1}$ is:

$$s^2L + s k_{p1} K_{pwm} + k_{i1} K_{pwm} = 0 \quad (14)$$

Figure 4

Block diagram of the vector control system

In which, $I_{m}$, $I_{m}^*$: Actual value and reference value of inductance current of inverters;

$k_{p1}$, $k_{i1}$, $k_{p2}$, $k_{i2}$: Proportion and integral coefficient of PI regulator of current loop of motor and inductance current loop of inverters;
Based on the transfer function and characteristic equation here, detailed parameter selection and stability analysis are presented in Section 5.

4 SIMULATION AND VERIFICATION OF PARALLEL DRIVE

The simulation model of MGP driven by two inverters in parallel through the electrical and mechanical coupling relationship is established. In the model, rotor angle $\theta$ and angular speed $n$ of MGP need to be measured, and the output voltage and current of two inverters are used as a feedback signal. The output power of the inverter is controlled by the externally given current reference or speed loop. The two control systems have the same function for an independent control. The schematic diagram of the simulation model is presented in Figure 5 and the main parameters are shown in Tables 2 and 3.

### TABLE 2 Simulation parameters

| Simulation parameters | Value |
|-----------------------|-------|
| Step size/μs          | 20    |
| AC side line voltage/V| 380   |
| Frequency/Hz          | 50    |
| Capacity of motor/kW  | 5     |
| Capacity of generator/kW | 5     |
| Filter inductance/mH  | 2     |
| Filter capacitor/μF   | 10    |

Based on the selected parameters above, MGP operated under off-grid and grid-connected stages with dynamic conditions is studied.

The parallel inverters run with a speed loop during off-grid stage, and the simulation results are shown in Figure 6. Because of the long start-up process of MGP, the inertia is reduced here for simulation. In the first 6 s, the power of inverters is increasing for start-up. Then a load change of 1500 W is applied in 10 s, the injection power of inverter increases and the speed of MGP can also remain stable. During the normal operation, the phase difference between stator voltage of SM and SG are changed for power transmission.

Then grid-connected operation with variable frequency ($\pm 0.05$ Hz) of power grid is presented in Figure 7. Initially, the
current reference of the two inverters is both 5 A, and then the current reference of inverter 1 is changed to 8 A at 16 s and the current of inverter 2 is always kept at 5 A. The output power of inverter 1 increases from 1600 to 2100 W with a step change of $i_{q\text{ref}}$, and the active power transmitted to power grid also increases by 500 W. When current reference is changed, the inverter 2 can maintain its output, so independent control can be achieved. Due to the inevitable power loss of machine, the power is smaller than that of inverters.

Because of the constant value of $d$-axis current, the increase of $i_{q\text{ref}}$ makes the current phase of SM changed. Taking the phase of the stator voltage of SG as a reference, the phase difference of voltage between SM and SG increases, and the power angle of MGP increases, so the output power of the generator changes. Despite the frequency fluctuations, MGP can well follow the inverters for the generator absorbs or releases rotational kinetic energy for restraining the fluctuation so effects on inverters are reduced. The parallel drive system under the control can also have a stable operation with variable frequency.

It can be seen from the simulation results that the parallel drive system can both keep a stable operation under off-grid and grid-connected operation. Dynamic response of the system is fast, its power output can quickly follow the reference value $i_{q\text{ref}}$ and the two inverters can maintain good independence. Even with load disturbance and frequency fluctuation, MGP can well follow the inverters and the control system is robust. The detailed considerations and design about the control are discussed in experiment section.

5 | EXPERIMENTAL VERIFICATION OF PARALLEL DRIVE

Based on the control strategy above, an experimental platform for the parallel drive of MGP is established. The platform is shown in Figure 8, it consists of a DC power supply, two inverters, LC filters, a DSP controller and a 5.5 kW MGP. The DSP controller is TMS320F28335, and Chroma 62100H-600S photovoltaic simulator is adopted as the DC power supply, the excitation winding of motor and generator are fed by two independent excitation power supplies are respectively, especially an AVR is used for voltage regulation of the generator. Some parameters of the equipment are shown in Table 4.

The main working principle of the control system is as follows. The controller samples the output current of two inverters and stator voltage and current of SM, also it collects the encoder signal of the mechanical rotor as an angle reference for signal synchronization, then through calculation 12 PWM pulses are input to two inverters respectively. The controller communicates with the host computer through the SCI serial port, and the host computer controls the on/off of the inverters, the grid-connection of MGP, and the power control command. And the combined current injection of two inverters is limited below 10 A according to the power rating of the SM.

Based on the experimental platform, the feasibility of the control strategy is verified through experiment under conditions of off-grid and grid-connected operation.

5.1 | Stability analysis and parameter selection of the control system

Before the experiment, the parameters of the control system need to be set and stability should be analysed in detail.
5.1.1 Analysis of inner loop of inductance current

According to the Equation (13), the expression of the generalized root locus with $k_{p2}$ as the gain is:

$$1 + \frac{k_{p2} \cdot sK_{pwm}}{k_{i2}K_{pwm} + s^2 L} = 0$$

As can be seen in Figure 9(a), when the value of $k_{i2}$ is smaller, the phase margin is bigger. By comparison, it is found that when the integral coefficient is 0.2, the system has a more appropriate stability margin.

When $k_{i2} = 0.2$, it can be seen from the root locus in Figure 9(b) that when $k_{p2} = 0.04$, the system has the best damping ratio, so the parameters of inner loop can be taken as $k_{p2} = 0.04$, $k_{i2} = 0.2$.

5.1.2 Analysis of outer loop of motor current

The generalized root locus equation with $k_{p1}$ as the gain can be obtained from Equation (14):

$$1 + \frac{k_{p1} \cdot sK_{pwm} \cdot sK_{p1}}{K_{pwm} \cdot \frac{sK_{p1} + k_{i1}}{s} \cdot (1 + sCZ_m) + Z_m + sL(1 + sCZ_m)} = 0$$

Then the root locus is shown in Figure 10.

It can be seen that when $k_{p1} < 48.8$, the eigenvalues of the system are in the left half plane, and with the increase of the coefficient, the eigenvalues gradually approach the right half plane. At the same time, when $k_{p1}$ decreases, the damping ratio of the system tends to increase. The Bode diagram of the system with different $k_{p1}$ values is shown in Figure 11, when $k_{p1}$ decreases, the system amplitude stability margin increases, and the stability margin of phase angle decreases. The stability margin of $k_{p1} = 0.5$ is more appropriate.

In this figure, when $k_{p1} = 0.02$, $G_m = 67.8$, $P_m = 44.5$; $k_{p1} = 0.06$, $G_m = 58.2$, $P_m = 46$; $k_{p1} = 0.3$, $G_m = 44.2$, $P_m = 54.9$; $k_{p1} = 0.5$, $G_m = 39.8$, $P_m = 62$)

In order to further determine the more appropriate coefficient, the dynamic response of different coefficient is judged by step response in Figure 12. Combined with the parameters of the inner loop PI controller, $k_{i1} = 0.2$, and the unit step response of the system is 1. When the value of $k_{p1}$ is small, the overshoot of unit step response of the system becomes smaller, but the response time becomes slower. Therefore, $k_{p1} = 0.5$ is selected.

To sum up, the parameters selected for the inverters are $k_{p1} = 0.5$, $k_{i1} = 0.2$, $k_{p2} = 0.04$, and $k_{i2} = 0.2$ to ensure that
the system operates in a stable and stable region, and also can obtain a better dynamic response.

5.2 Experimental study

5.2.1 Off-grid operation

Firstly, off-grid stage of the system is studied, the overall operation in which the inverters drive MGP from zero speed to grid-integration needs to be concerned. Figure 13 includes three operation stages of MGP: I is start-up stage, II is speed adjustment stage and III is grid-connection stage.

For stage I, in order to shorten the start-up process of MGP, the starting current of inverter is set at 5 A. During the first 0.2 s, the motor speed increases rapidly. Then after that, the control command is selected by logic, and the reference value of $q$-axis current is obtained through the outer loop of motor speed whose reference value is set as 1500 r/min.

In stage II, the rotor accelerates until the synchronous speed. As can be seen from Figure 13, the whole acceleration process of MGP takes about 10 s (because the speed of MGP is slightly adjusted after the speed is close to the synchronous speed). Then MGP can have a stable operation at off-grid stage with synchronous speed, also the grid-connected operation can be achieved.

In stage III, the grid-connection operation can be made. When grid-connected conditions are met, the relay is controlled to be closed which completes the grid-connected operation of MGP. In this stage, the inverters no longer need the outer speed loop, as the speed of MGP is coupled with the frequency of the power grid, so the power of MGP is directly controlled by the inner loop of current.

It should be emphasized that off-grid and grid-connected operation of MGP is the focus of the control strategy proposed in this paper, so there is no detailed description of the shutdown stage of MGP. On one hand, in practice even if the power from renewable energy (inverters) is insufficient, MGP can still connect to the power grid and act as the synchronous condenser for supplying reactive power; on the other hand, shutdown for generators is easy to achieve than inverters. In the experiment, the current reference is gradually reduced, and the grid-connected circuit breaker will be disconnected when the specified power of MGP is close to zero.
5.2.2 Grid-connected operation with the same sharing ratio of power

Firstly, the working characteristics of inverters under the condition of equal power sharing is verified. The power transmission ratio of the two inverters is set to be 0.5. Initially, the current reference of the inverters is 4 A, and then the current command value is adjusted to 6 A and 8 A after every 10 s. The output voltage and current of inverters are shown in Figure 14.

It can be seen from Figure 14(a) that under the same sharing ratio of power, with the increase of current command of inverters, the output current of each inverter increases synchronously, the output current of each inverter can follow the given value well, and the current fluctuation is small, and the error is controlled within ±0.2 A.

During the process, the current of SM and SG increases with the output of the inverters which is shown in Figure 14(b). Due to the mechanical and electrical loss of the MGP system, the active power of generator is slightly less than that of the motor. For current control, the voltage drop on the output inductance makes the voltage of the motor increases slightly, but the voltage is also stable near the rated value.

Figure 14(c) is the enlarged diagram of the waveform in Figure 14(b) when the stator current of SM is 4 A. It can be seen that the output current of the inverter has less harmonic content and maintains a better sinusoidal waveform. The mechanical isolation of MGP system makes MGP have a good ability to suppress high-order harmonics.

The control strategy can effectively control the output power of MGP which is shown in Figure 15. The transmission power of the generator increases from 700 to 1500 W and then to 2200 W with the increase of power of inverters, and the phase difference between SM and SG is also increasing, which indicates the power angle of MGP can be controlled by current vector. The voltage control is independent of the control strategy proposed, so AVR is used on the SG and the reactive power exchanged with the power grid is nearly zero. The reactive power control is not the scope of the paper, so not presented in the paper.

5.2.3 Grid-connected operation with different sharing ratio of power

When the current reference of inverters is 4, 6 and 8 A respectively, the operation under the condition of different power sharing is studied. The current reference of the two inverters can be calculated by Equation (17):

\[
\begin{align*}
I_{qref1} &= r \times I_{qref} \\
I_{qref2} &= (1 - r) \times I_{qref}
\end{align*}
\]

(17)

The sharing ratio of power of inverter one is set as \( r = 0.3 \), the output current waveform of inverter is shown in Figure 16(a). The output current of the two inverters is basically distributed according to the given proportion. Because the current of inverter 1 is always smaller, the current of inverter one fluctuates more compared with inverter 2, but it can still be stable near the reference.

When the output power of each inverter increases, the power distribution of the two inverters is also consistent with \( r \), which shows that the output active power of the inverter can be controlled by controlling \( I_{qref} \).
Further, the current and power when $i_{qref} = 6$ A, $r = 0.5$, 0.4, 0.3, 0.2 and 0.1 respectively is shown in Figure 17. It can be seen that the active power of the inverters can better follow the current reference under different $r$ values and the power of MGP remain constant because of the same $i_{qref}$.

Based on the two scenarios above, the distribution of power can well follow the change of the ratio $r$, also with the varied and constant reference value of the current, the system can have stable operations.

### 5.2.4 Efficiency study

The efficiency study under different scenarios of Section 5.2.2 and 5.2.3 is presented here for a clear demonstration on the operating efficiency, and also the impact of operation scenarios on efficiency is analysed.

As presented in Table 5, power from inverters and after MGP are respectively defined as $P_M$ and $P_G$, $P_{loss}$ is the power loss of MGP, and $\eta$ is the operation efficiency under the three scenarios.

The efficiency of the system is not good for the poor performance of the two synchronous machines, which are mainly used for experimental teaching. The rated efficiency of the machines is below 85%, so two mechanically coupled machines work with a 70% efficiency normally. But it is important to know the motor with a higher efficiency is easy to achieve, and for larger capacity
motors, the efficiency can reach 95%. So mainly the impact of operation scenarios on efficiency is discussed.

Comparing scenario 2 with scenario 1, the efficiency is decreased about 4% for unbalanced operation of two inverters, the unbalanced current between inverters makes the loss on filter inductors increase, so parallel inverters with the equal current is the desired operation status. And for scenario 3, with a constant current reference, the power from inverters and after MGP are almost the same as $I_{\text{qref}} = 6$ A in scenario 2, which shows the influence of different degrees of power imbalance of inverters on the transmission efficiency is limited and the efficiency can be guaranteed.

### 6 Conclusion

In this paper, the control strategy of driving MGP by inverters in parallel is proposed based on the vector control and power angle characteristics of MGP, and the following results and conclusions are obtained:

1. Based on the principle of grid-connected inverters and torque control of synchronous machine, the mathematical model of the inverters integrated into the power grid via MGP is established. Combining the cross-decoupling link of voltage feedforward with rotor flux-oriented control, the control strategy where active power is controlled by $q$-axis current is realized.

2. The strategy of driving MGP with parallel inverters without interconnection lines is proposed based on the current vector control of MGP, and different application scenarios and setting principle of $q$-axis current are also discussed.

3. The simulation model of MGP driven by parallel inverters is built, which verifies that the control strategy can realize the off-grid and grid-connected operation of MGP under load disturbance and frequency fluctuation.

4. A 5 kW experimental platform of MGP driven by dual inverters is built, and the stability analysis and parameter selection of the control link is studied. Then off-grid and grid-connected operation are verified through experiment, and the results show that the inverters can have fast response and the operation of each inverter is well independent. The system can operate normally with the same and different sharing ratio of power, and an efficiency study is made to demonstrate operation efficiency of the system and its relationship with operation scenarios.

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### REFERENCES

1. REN21. 2020.: Renewables 2020 Global Status Report. REN21 Secretariat, Paris, pp. 46–47 (2020)
2. Margaris, I.D., et al.: Frequency control in autonomous power systems with high wind power penetration. IEEE Trans. Sustainable Energy 3(2), 189–199 (2012)
3. Jong, K.W., Kim, T., Park, J.W.: Decoupled frequency and voltage control for stand-alone microgrid with high renewable penetration. IEEE Trans. Ind. Electron 55(1), 122–133 (2019)
4. Xie, D., et al.: A comprehensive LVRT control strategy for DFIG wind turbines with enhanced reactive power support. IEEE Trans. Power Syst. 28(3), 3302–3310 (2013)
5. Dong, Y., et al.: A comprehensive droop control strategy for DFIG wind turbines with enhanced reactive power support. IEEE Trans. Power Syst. 28(3), 3302–3310 (2013)
6. Wei, S., et al.: A possible configuration with motor-generator pair for renewable energy integration. CSEE J. Power Energy Syst. 3(1), 93–100 (2017)
7. Beck, H.P., Hesse, R.: Virtual synchronous machine. In: Proceedings of the International Conference on Electrical Power Quality and Utilisation. Barcelona, Spain, pp. 1–6 (2007)
8. Zhong, Q., Weiss, G.: Synchronverters: Inverters that mimic synchronous generators. IEEE Trans. Ind. Electron. 58(4), 1259–1267 (2011)
9. Zhang, Y.C., et al.: Motor-generator pair: A novel solution to provide inertia and damping for power system with high penetration of renewable energy. IEEE Trans. Power Syst. 22(1), 84–92 (2007)
10. Liu, J., Miura, Y., Ise, T.: Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators. IEEE Trans. Power Electron. 31(1), 3600–3611 (2015)
11. Alipour, J., Miura, Y., Ise, T.: Power system stabilization using virtual synchronous generator with alternating moment of inertia. IEEE J. Emerg. Sel. Top. Power Electron. 3(2), 451–458 (2014)
12. Zhou, Y., et al.: Study experiment on the control method of motor-generator pair system. IEEE Trans. Ind. Electron. 62(4), 2026–2036 (2015)
13. Wei, S., et al.: Motor-generator pair: A novel solution to provide inertia and damping for power system with high penetration of renewable energy. IET Gener. Transm. Distrib. 7(11), 1839–1847 (2017)
14. Wu, Q., et al.: Small signal stability of synchronous motor-generator pair for power system with high penetration of renewable energy. IEEE Trans. Power Syst. 31(1), 365–374 (2016)
15. Wei, S., Zhou, Y., Huang, Y.: Synchronous motor-generator pair to enhance small signal and transient stability of power system with high penetration of renewable energy. IET Generation, Transmission & Distribution 8, 13251–13258 (2020)
16. Gu, Y., et al.: Isolation and protection of the motor-generator pair system for fault ride-through of renewable energy generation systems. IEEE Trans. Power Electron. 33(7), 6696–66974 (2020)
17. Li, R., Xu, D.: Parallel operation of full power converters in permanent-magnet direct-drive wind power generation system. IEEE Trans. Ind. Electron. 60(4), 1619–1629 (2013)
18. Kim, K., et al.: Parallel operation of photovoltaic power conditioning system modules for large-scale photovoltaic power generation. IET Power Electron. 7(2), 406–417 (2014)
19. De Brabandere, K., et al.: A voltage and frequency droop control method for parallel inverters. IEEE Trans. Power Electron. 22(4), 1107–1115 (2007)
20. Guerrero, J.M., Hang, L., Uceda, J.: Control of distributed uninterruptible power supply systems. IEEE Trans. Ind. Electron. 55(8), 2845–2859 (2008)

21. Barklund, E., et al.: Energy management in autonomous microgrid using stability-constrained droop control of inverters. IEEE Trans. Power Electron. 23(5), 2346–2352 (2008)

22. Mohamed, Y.A.I., Elsaadany, E.F.: Adaptive decentralized droop controller to preserve power sharing stability of paralleled inverters in distributed generation microgrids. IEEE Trans. Power Electron. 23(6), 2806–2816 (2008)

23. Zhong, Q.: Robust droop controller for accurate proportional load sharing among inverters operated in parallel. IEEE Trans. Ind. Electron. 60(4), 1281–1290 (2013)

24. Hua, M., et al.: Multilayer control for inverters in parallel operation without inter-communications. IEEE Trans. Power Electron. 27(8), 3651–3663 (2012)

25. Wei, Y., Zhang, X., Qiao, M.: Parallel technique of multiple inverters for motor drive system. Electr. Mach. Control 14(2), 36–40 (2010)

26. Wei, Y., et al.: Parallel control study of multiple inverters for ship electric propulsion. In: Proceedings of International Conference on Electrical Machines and Systems. Beijing, China, pp. 1–4 (2011)

27. Wang, Z., et al.: Field-oriented control and direct torque control for paralleled VSIs fed PMSM drives with variable switching frequencies. IEEE Trans. Power Electron. 31(3), 2417–2428 (2016)

28. Kundur, P.: Power System Stability and Control. McGraw-Hill, New York (1994)