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Adaptive power sharing scheme for parallel-connected hybrid inverters in microgrid

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Abstract
This paper presents an adaptive power sharing control method of parallel-connected hybrid inverters in microgrid. Normally the AC microgrid is composed of hybrid inverters, other power generation equipment and some loads in parallel. Droop control or virtual synchronous generator is usually adopted to control parallel inverters, so the output power ratio between each inverter is fixed by droop parameters. The input of hybrid inverter is PV panel and battery, so the power output ability of each hybrid inverter is different because of the different PV panel capacity, illumination condition, battery capacity and battery state of charge. Hence, the output power of some hybrid inverters is short or redundant sometimes, which makes microgrid unstable or causes power generation restraints. It is necessary to recognize the actual power capacity of each inverter and control the output power reasonably. This paper analyzes the characteristics of parallel-connected hybrid inverters with droop control in microgrid. An adaptive power sharing method is developed to identify the unbalanced between the each inverter on DC bus. By adjusting the droop parameters, the output power of each inverter is regulated where the controlled parameters are defined in system transfer function with an optimal target. Experimental tests are executed following the numerical simulation. The results show that the output power of each inverter can be adjusted adaptively according to the practical needs. The excessive power from one inverter can be absorbed by the others. Therefore, the stability and the power capability in the system are both ensured by adopting the proposed methods. The outcomes of the study provide a reference to the development of the adaptive inverter in microgrid.

1 | INTRODUCTION

Driven by economic, environmental and energy shortage reasons, the renewable energy industries grow rapidly. A large number of photovoltaic (PV) power stations have been built and are generating power now. Grid-connected inverters [1] are used in these stations. However, PV power fluctuates with time, weather and illumination condition. Energy storage system is necessary to regulate power for charging and discharging management. A hybrid inverter [2, 3] comprises a PV controller, a battery controller and a DC–AC converter is proposed which can work in both grid-connected and standalone conditions. Following more and more distributed generation units being installed, the microgrid composed of PV inverters, hybrid inverters and other generation equipment in parallel has been formed. The control of parallel inverters and energy management [4] of microgrid are getting complicated. There are many studies on microgrid systems [5–8] aiming at developing microgrid architectures, switching strategy between on-grid and off-grid condition, power sharing method and so on. Some of these studies focus on the control strategy of parallel-connected inverters, including wired control methods [9, 10] and wireless ones [11, 12]. The common control methods of parallel inverters are droop control and VSG (virtual synchronous generator) [13]. [14] analyzes and designs the stability of parallel inverter in which droop control with virtual impedance is adopted. [15–21] present a droop control by combing with promising technologies, including sliding mode, adaptive virtual impedance, self-synchronizing and decoupling loop to improve control stability, load immunity and power sharing accuracy. [22, 23] present the droop control with...
Virtual impedance and external impedance to suppress circulating current.

The output power ratio between each parallel inverter is fixed by the constant droop parameters when conventional droop control is adopted. However, the power output ability of each hybrid inverter is different and fluctuant because of the different PV panel capacity, illumination condition, battery capacity and battery state of charge (SOC), which will lead to the output power of some hybrid inverters being scarce or redundant. As a result, the microgrid will be unstable or the generated power will be limited. It is necessary to share power reasonably between parallel inverters based on actual power output ability. [9, 15, 17, 18] present current or power sharing methods. However, these methods focus on different line impedance and control stability issues. [24, 25] investigate power balance by using droop control in relation to the above issues, but they don’t present optimal solutions for these issues.

To override aforementioned problem, an adaptive power sharing control scheme is developed in this paper. A small-scale microgrid and corresponding control strategies are introduced in this paper. The topologies of the hybrid inverters with control strategies and seamless switching operation between on-grid and off-grid are presented in Section 2. Then, the adaptive power sharing method subject to standalone condition is proposed in Section 3. The power unbalance states of each inverter can be regulated based on the inverter actual power output ability, which improves the stability of parallel inverters and power generating utilization of microgrid. (The stable running time and the generation utilization rate are increased by about 20% in some conditions.) Finally, detailed experiments following the simulation by MATLAB verify the effectiveness of the proposed scheme and the conclusions are drawn in Section 4.

2 CHARACTERISTICS AND GENERAL CONTROL OF PARALLEL HYBRID INVERTERS IN MICROGRID

A small-scale microgrid is established, shown in Figure 1, which is composed of hybrid inverters, other inverters, diesel generator (DG), distributed loads, and so on. The microgrid is connected to utility grid by a controlled switch (S1). The AC terminals, such as inverters and DG, are connected together to an AC bus. The hybrid inverter converts PV power and battery storage power into AC power. The batteries can be charged by power from either the PV or the AC bus, and other different power (e.g. PV power, small wind power) are connected into AC bus by other inverters. An energy management system (EMS) controller detects and regulates the state of every component in the microgrid. When the utility grid is abnormal and the power sources in microgrid cannot supply enough power to the loads, DG is started by a controlled switch (S2).

The EMS controller plays an important role in microgrid, and its flowchart is shown in Figure 2, where $M_{soc}$ and $M_{power}$ are the thresholds of SOC and power margin in line with DG operation. There are two seamless-switching operation modes, that is, grid-connected mode and standalone mode. AC bus power is uninterrupted while switching between the two modes. When the utility works normally, the microgrid is connected to the utility grid via S1 without DG operation. The batteries are charged when the PV has excessive power. In opposites, the batteries are discharged if no enough power for the loads.

If the utility grid works in abnormal, the microgrid disconnects from the utility grid by S1, and works in the standalone mode. The PV and batteries supply power to the loads, while the excess power of PV is absorbed by the batteries. DG starts running when the PV and batteries have insufficient power to the loads or when the battery SOC is too low, and then, DG stops running when PV and battery power can supply loads and the SOC rises to a required threshold. When power margin
or SOC gradually becomes lower than a minimal threshold, DG starts running and the inverters run continuously. The AC bus voltage is uninterrupted at this condition. Once an overload demand suddenly appears, all the inverters would stop immediately that makes AC bus power interrupted for a short time.

P/Q control [20] is commonly used for inverter output control in grid-connected mode, and active and reactive power can be controlled by only current control loop. The P/Q control expression can be shown as

\[ i_p^* = \frac{P_{ref}}{E_g}, \quad (1) \]

\[ i_{q2}^* = \frac{Q_{ref}}{E_g}, \quad (2) \]

\[ i_{grid}^* = \sqrt{2} i_p^* \sin \theta_g - \sqrt{2} i_{q2}^* \cos \theta_g, \quad (3) \]

where \( E_g, \theta_g \) are the amplitude and angle of grid voltage; \( P_{ref}, Q_{ref} \) are the references of active and reactive output power; \( i_p, i_{q2} \) are the current references of active and reactive power; and \( i_{grid} \) is the total current reference of one inverter.

In the standalone mode, droop control or VSG are widely used for parallel inverter control. Conventional droop control is adopted here. Two parallel-connected inverters are taken as an example for common parallel inverter situations. An equivalent circuit is shown in Figure 3. \( E \angle \phi \) is the AC bus voltage, and \( E_1 \angle \phi_1 \) and \( E_2 \angle \phi_2 \) are the output voltage of the two parallel inverters. \( \phi_i \) is the phase angle difference between the inverter output voltage and AC bus voltage. \( R_s \) is the sum of output and line resistance, whereas \( X_i \) is the sum of output and line inductive impedance. \( i \) is the \( i \)-th inverter in microgrid.

The active and reactive output power of the \( i \)-th inverter can be represented as

\[ P_i = \frac{(UE_i \cos \phi_i - U^2) \cos \theta_i + UE_i \sin \phi_i \sin \theta_i}{|Z_i|}, \quad (4) \]

\[ Q_i = \frac{(UE_i \cos \phi_i - U^2) \sin \theta_i - UE_i \sin \phi_i \cos \theta_i}{|Z_i|}, \quad (5) \]

where \( |Z_i| \) is the output impedance amplitude of the \( i \)-th inverter, \( |Z_i| = \sqrt{R_s^2 + X_i^2} \), and \( \theta_i \) is the angle of output impedance \( Z_i \).

Assuming that the impedance is inductive (\( Z_i = jX_i \)), \( P_i \) and \( Q_i \) can be derived as shown:

\[ P_i = \frac{U E_i \sin \phi_i}{X_i} \approx \frac{U E_i \phi_i}{X_i}, \quad (6) \]

\[ Q_i = \frac{U E_i \cos \phi_i - U^2}{X_i} \approx \frac{U (E_i - U)}{X_i}. \quad (7) \]

Therefore, active power could be controlled by angular \( \phi_i \) and reactive power could be controlled by voltage amplitude \( E_i \), and then the droop control expression can be obtained as

\[ \omega^*_{\text{droop}} = \omega_0 - m(P - P_0), \quad (8) \]

\[ E_{\text{droop}}^* = E_0 - n(Q - Q_0), \quad (9) \]

where \( \omega_{\text{droop}}^* \) and \( E_{\text{droop}}^* \) are the references of angular frequency and voltage amplitude of every inverter. \( \omega_0 \) and \( E_0 \) are the nominal angular frequency and voltage amplitude. \( P_0 \) and \( Q_0 \) are the initial output active power and reactive power, whereas \( P \) and \( Q \) are the actual counterparts. \( m \) and \( n \) are the active and reactive power droop coefficient, respectively.

When switching from the standalone mode to the grid-connected mode, the current spike will appear if there are phase and amplitude differences between AC bus voltage and the grid voltage. The AC bus should be pre-synchronized to the grid before switching for eliminating those differences. This paper adopts a pre-synchronization strategy proposed in [26, 27]:

\[ \Delta \omega_{\text{syn}}^* = \frac{k_{\omega}}{s} (\theta_0 - \theta), \quad (10) \]

\[ \Delta E_{\text{syn}}^* = \frac{k_E}{s} (E_0 - E), \quad (11) \]

\[ \omega^* = \omega^*_{\text{droop}} + \Delta \omega_{\text{syn}}^* \quad (12) \]

\[ E^* = E_{\text{droop}}^* + \Delta E_{\text{syn}}^* \quad (13) \]

where \( \Delta E_{\text{syn}}^* \) and \( \Delta E_{\text{syn}}^* \) are the regulated variables for pre-synchronization; \( k_{\omega} \) and \( k_E \) are the coefficients of the integral controller; \( \theta \) and \( E \) are the angle and amplitude of the inverter output voltage; \( \omega^* \) and \( E^* \) are the revised references of angular frequency and voltage amplitude.

A single-phase hybrid inverter is taken as an example for the parallel scheme research, as shown in Figure 4, which has a PV DC/DC converter, a battery DC/DC converter, a DC/AC inverter, and an LC filter (\( L_s, C_s \)).

In the standalone mode, the DC bus voltage of the hybrid inverter is controlled by the battery DC/DC converter. The PV voltage is controlled by the PV DC/DC converter, and the maximum power point tracking (MPPT) is performed by adjusting the PV voltage reference. The AC output voltage is controlled by the DC/AC converter, and its closed-loop control structure.
FIGURE 4 Topology of the single-phase hybrid inverter

FIGURE 5 Closed-loop control structure of hybrid inverter DC/AC in Figure 4 consists of an inner current loop and an outer voltage loop, as shown in Figure 5 \((L = \text{sum of } L_1 \text{ and } L_n)\). \(v^*\) and \(v_o\) are the reference and actual value of the inverter output voltage, whereas \(i^*_L\) and \(i_L\) are those of inverter inductor current. \(i_o\) is the inverter output current and used as feedforward to improve the dynamic response performance.

Based on the above analysis, the system control scheme of the parallel hybrid inverter in microgrid is illustrated in Figure 6, which consists of three control modules, that is, grid-connected mode, standalone mode and their switching. \(\theta^*\) is an angle reference of the inverter output voltage. \(i^*\) is reference of the current loop which is selected by the operational mode; \(i^*\) is equal to \(i^*_{\text{grid}}\) under the grid-connected mode; \(i^*\) is equal to \(i^*_{L}\) under the standalone mode. To make the transient output current and voltage smooth, the output current reference is given to each other as initial current reference between P/Q and droop control when switching operation mode, and the utility voltage is given as an initial reference of droop control when switching from the grid-connected to standalone mode.

3 ADAPTIVE POWER SHARING CONTROL METHOD BASED ON DC BUS VOLTAGE

When employing the conventional droop control at standalone mode, the output power ratio of these parallel inverters is fixed, which is determined by droop constants \(P_0, Q_0, \omega_0, E_0, m\) and \(n\). However, the capability of each inverter is different and varied due to the different PV panel, different batteries, varied illumination variation and SOC. Meanwhile the load may change quickly. When the power of a certain inverter cannot meet demands of load consumption, the output current will distort and the related inverter will soon stop, which makes the microgrid collapse if other inverters have no enough power to the load. However, when the power generation of partial inverters is higher than load consumption, the inverters will be limited, which makes some PV power lost, and the abovementioned situation should be handled to improve the microgrid stability and power generating efficiency.

Based on the hybrid inverter control system analysis in Section 2, DC bus voltage is very sensitive to the power between PV, battery, and AC load. The DC bus voltage should drop below the normal when the PV and battery power is less than that to the load, and rises above the normal when the power is redundant. The PV power should be limited when the DC bus voltage rises to too high a level. So, the power balance state can be identified based on the DC bus voltage. The inverter output power could be changed by adjusting output angular frequency as in Equation (8). The DC bus voltage could also be controlled by regulating \(\omega^\ast_{\text{droop}}\), so as to regulate the output power.

Hence, an adaptive power sharing scheme is proposed for parallel hybrid inverters, as shown in Figure 7, that is, to increase output frequency when the DC bus voltage is too high, and to decrease output frequency when the DC bus voltage is too low. The reference \(U^\ast_{\text{busL}}\) is one of the DC bus voltage references, and sets lower than normal voltage reference, whereas the reference \(U^\ast_{\text{busH}}\) sets higher than normal voltage reference. The normal reference of DC bus voltage is controlled by the
batteries, whereas the lower and higher references are controlled by adjusting the output frequency reference. A PID controller is used to eliminate the voltage static error while keeping control loop stable. \( \Delta \omega^*_{bus} \) is the sum of \( U^*_{busL} \) and \( U^*_{busH} \) in a closed-loop control where \( U^*_{busL} \) and \( U^*_{busH} \) refer to the minimum limitation and the maximum limitation of the PID output. They are set as zero to avoid disturbing the DC bus normal control. The initial value of the PID output is also set as zero. The revised frequency reference \( \omega^* \) can be represented as:

\[
\omega^* = \omega^*_{drop} - \Delta \omega^*_{bus}. \quad (14)
\]

Based on diagrams of Figures 5–7, the closed-loop control structure of parallel hybrid inverter with adaptive power sharing is derived, as shown in Figure 8. \( U^*_{bus} \) represents \( U^*_{busL} \) and \( U^*_{busH} \), respectively, but does not represent the normal voltage reference. \( P_{in} \) represents the power from PV and batteries to DC bus. \( v_{load} \) is real-time load voltage, equal to AC bus voltage.

Then the DC bus voltage in a closed-loop control structure \( U^*_{bus} \) is extracted from Figure 8, as shown in Figure 9.

Considering that the parasitic resistance \( R_{bus} \) of DC bus capacitor \( C_{bus} \) is obvious, the transfer function and its small signal expression can be represented as:

\[
P = P_{in} - \frac{C_{bus} U^*_{bus} s}{R_{bus} C_{bus} + s + 1} U_{bus}, \quad (15)
\]

\[
\Delta P = - \frac{C_{bus} U^*_{bus} s}{R_{bus} C_{bus} + 1} \Delta U_{bus}, \quad (16)
\]

Considering that the control speed of DC bus voltage loop is very low, the dual output voltage closed-loop of hybrid inverter can be approximately equal to 1. The control object can be deduced as shown:

\[
G_{obj}(s) = \frac{UE(R_{bus} C_{bus} s + 1)}{C_{bus} U_{bus} X s^2}, \quad (18)
\]

where \( X \) represents \( X_j \); \( U \) is the voltage amplitude of the load or the AC bus.

Quasi differential is adopted in the PID controller and the transfer function is shown as:

\[
G_{pid}(s) = k_{bp} + \frac{k_{bi}}{s} + \frac{k_{bd}}{T_d s} + 1, \quad (19)
\]

where \( k_{bp}, k_{bi} \) and \( k_{bd} \) are the proportional, integral and differential gains, respectively. \( T_d \) is the filter coefficient for quasi differential.

Open-loop transfer function of DC bus voltage control can be deduced from Equations (18) and (19), as shown in Equation (20).

\[
G_{bus}(s) = \frac{UE((k_{bp} + k_{bi} T_d)^2 + (k_{bp} + k_{bi} T_d)s + k_{bi})}{C_{bus} U_{bus} X^2 (T_d s + 1)}, \quad (20)
\]

where \( H_{delay} \) represents the delay caused by PWM switching period and its expression is shown as:

\[
H_{delay} = e^{-T_s}, \quad (21)
\]

where \( T_s \) is the switching period of the control loop and PWM.

The voltage controller is designed with bode plot, mainly involving the stability, static error and dynamic performance.
### TABLE 1 Parameters of hybrid inverter and controller

| Parameters                        | Values       |
|-----------------------------------|--------------|
| Max PV input power                | 6000 W       |
| Max Bat charge/discharge power    | 3000 W       |
| Max AC output power               | 5000 W       |
| Normal DC bus voltage             | 360 V        |
| Nominal output voltage            | 230 V/50 Hz  |
| DC bus capacitor \(C_{bus}\)      | 1200 µF/80 mΩ|
| Inverter inductor \((L_{i} + L_{o})\) | 1000 H/10 mΩ |
| Inverter capacitor \(C_{o}\)      | 13.2 µF      |
| Output line inductor \((L_{low})^a\) | 5 H         |
| Output line resistor \((R_{low})^a\) | 20 mΩ    |
| PWM switching period \((T_{j})\)  | 62.5 s       |
| DC bus proportional gain \((k_{pp})\) | 0.0008     |
| DC bus integral gain \((k_{pi})\)  | 0.0015       |
| DC bus differential gain \((k_{pd})\) | 0.0003    |
| Differential filter coefficient \((T_{d})\) | 0.0005 |

*\(L_{low}\) and \(R_{low}\) are the parasitic inductance and resistance of the inverter.

The parameters of the parallel inverter and the designed parameters of the controller are listed in Table 1. A bode plot of the DC bus voltage control system is shown in Figure 10. The system is stable with phase margin of 84°.

To improve the EMS performance of microgrid in the standalone mode, the output power of hybrid inverter needs to be controlled to a reference or a scope. For example, the inverter with higher SOC battery should release more power, whereas the lower one should release less power. The output power can be controlled by adjusting \(\omega^*_{\text{droop}}\), as shown in Figure 11. Switch \(S_p\) means this controller is optional, and \(-\Delta \omega^*_{\text{power}}\) is frequency reference from power control, and then, the closed-loop control of inverter output power can be derived as in Figure 12, and open loop transfer function can be written as Equation (22).

\[
G_{\text{power}}(s) = \frac{EU(k_{pp} + k_{pi})}{Xs^2},
\]  

where \(k_{pp}\) and \(k_{pi}\) are the proportional and integral gains, respectively.

The full control of angular frequency based on Equation (10) and Figures 7 and 11 is rebuilt as shown in Figure 13. The operation priority of DC bus voltage controller is higher than the one of output power controller because the micro-grid stability is more important than EMS demand. Hence, the biggest one between \(\Delta \omega_{bus}^*\) and \(-\Delta \omega^*_{\text{power}}\) is selected to be frequency adjustment value when \(\Delta \omega_{bus}^*\) is higher than 0, whereas the smallest one is selected when \(\Delta \omega_{bus}^*\) is lower than 0. The pre-synchronization controller is triggered by switch \(S_p\) as switching from standalone mode to grid-connected mode.

## 4 EXPERIMENTS

In this section, two prototypes of 5 kW hybrid inverter have been developed to verify the parallel-connected inverter control system with the proposed scheme, where the parameters of the inverter and the controller are shown in Table 1.
The test rig of a small-scale microgrid with maximum power 30 kW is shown in Figure 14 which is composed of two hybrid inverters, two batteries, two PV simulators, one DG, one load box, one meter and some switches. Part of the test rig is used for the experiments and its schematic diagram is shown in Figure 15. The two parallel hybrid inverters run at standalone mode. The PV simulators and batteries of each inverter are expected to be regulated to the fixed power in Table 2. The load power is changed in experiment process to verify the proposed method, and the output current is used to represent output power of each inverter in this paper.

At first, the load power is raised from 4.5 kW to 8.0 kW, then returns to 4.5 kW. The waveforms of DC bus voltage, output current and load voltage are shown in Figure 16.

**TABLE 2** PV and battery power capacity of both hybrid inverters

| Parameters                  | Values  |
|-----------------------------|---------|
| The 1st PV panel\(^a^\) power capacity | 4770 W  |
| The 1st battery\(^a^\) charge/discharge power capacity | 3000 W  |
| The 2nd PV panel\(^a^\) power capacity | 0 W     |
| The 2nd battery\(^a^\) charge/discharge power capacity | 3000 W  |

\(^a^\)The 1st PV panel and the 1st battery are connected to the 1st inverter. The 2nd PV panel and the 2nd battery are connected to the 2nd inverter.
When the load is 4.5 kW, the 1st and 2nd inverters supply the same power 2.25 kW, and the output current of each inverter is 9.78 A in root mean square (RMS) value, as shown in Figure 16(a). The rest power 2.52 kW (4.77–2.25 kW) from the 1st PV is automatically charged to the 1st battery. The power capacity of every inverter could meet equal sharing of load power and the parallel system is stable.

When the load changes into 8 kW, the 2nd inverter supplies full power 3 kW (13.04 A in RMS value), and the 1st inverter supplies power 5 kW (4.77 kW from the 1st PV and 0.23 kW from the 1st battery, 21.74 A in RMS value), as shown in Figure 16(b). In this situation, the DC bus voltage of the 2nd inverter falls about 20 V and then keeps unchanged. The insufficient power 1 kW of the 2nd inverter is automatically compensated by the 1st inverter. It shows that the proposed scheme is running and keeps the parallel system stable when the power of one inverter is insufficient for power equal sharing.

In above experiments, the DC bus voltage and output power of the 2nd inverter are controlled timely and smoothly when the load power rises and returns suddenly, as shown in Figure 16(c,d).

After that, the load power is reduced from 5.5 kW to 1 kW, then back to 5.5 kW. The waveforms are shown in Figure 17.

When the load is 5.5 kW, each inverter supplies the same power 2.75 kW (11.96 A in RMS value), as shown in Figure 17(a). The rest power 2.02 kW (4.77–2.75 kW) from the 1st PV is charged the 1st battery. The power capacity of every inverter is not redundant for power equal sharing, so the PV capacity is not limited.

When the load changes into 1 kW, the 1st inverter supplies 1.77 kW (7.70 A in RMS value) which is the rest power from the 1st PV besides the power 3 kW charged 1st battery, and the 2nd inverter absorbs 0.77 kW (3.35 A in RMS value) to charge the 2nd battery, as shown in Figure 17(b). In this situation, the DC bus voltage of the 1st inverter rises about 10 V and then keeps unchanged. The excess power 0.77 kW of the 1st inverter is absorbed by the 2nd inverter. It shows that the proposed scheme is running and makes the PV capacity unlimited when the power of one inverter is excess for power equal sharing.

In the above experiments, the DC bus voltage and output power of the 1st inverter are controlled timely and smoothly when the load power reduces and returns suddenly, as shown in Figure 17(c,d).

In addition, the proposed scheme could also be verified by changing PV or batteries power. The power system responds to the change in a swift way which verifies the system performs in a desirable manner.

5 CONCLUSION

The characteristics of a microgrid with several parallel-connected hybrid inverters have been analyzed in this paper. Based on the built system, an adaptive power sharing scheme associated with the inverters is proposed, and the output power of parallel hybrid inverters is equal once the power meets the

FIGURE 17 Experimental results: (a) load power 5.5 kW; (b) load power 1.0 kW; (c) Dynamic response as the load power switches from 5.5 to 1.0 kW; (d) Dynamic response as the load power switches from 1.0 to 5.5 kW.
load demand, where the power of each inverter is adaptively shared when the power of some inverters cannot meet the load demand. Based on the scheme proposed in Section 3, the dynamic response of the inverters can follow the load changes in a stable and swift way, and the results show that the method is effective for microgrid system subject to power balance control and the efficiency improvement of power generation. In addition, the proposed power sharing scheme can also be combined with other promising technologies (such as VSG and other schemes) besides droop control, and the output power of inverter is also regulated by adjusting the frequency reference of output voltage. The outcomes of the study will encourage the uptake of renewable-based microgrid that works in a stable and efficient manner, which also provide a reference to other parallel system control study, such as parallel UPS and DC microgrid.

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**REFERENCES**

1. Wu, J., et al.: Resonance Characteristics Analysis of Grid-connected Inverter Systems based on Sensitivity Theory.” J. Power Electron. 18(3), 746–756 (2018).
2. Ortjohann, E., et al.: Grid-forming three-phase inverters for unbalanced loads in hybrid power systems. In: Proceeding of the IEEE 4th World Conference on Photovoltaic Energy Conversion, Waikoloa, HI, 2006, pp. 2396–2399.
3. Do, T.D., et al.: An adaptive voltage control strategy of three-phase inverter for stand-alone distributed generation systems. IEEE Trans. Ind. Electron. 60(12), 5660–5672, (2013).
4. Alramlawi, M., Mohagheghi, E., Li, P.: Predictive active-reactive optimal power dispatch in PV-battery-diesel microgrid considering reactive power and battery lifetime costs. Sol. Energy 193, 529–544 (2019).
5. Tiwari, S.K., Singh, B., Goel, P.K.: Design and control of microgrid fed by renewable energy generating sources. IEEE Trans. Ind. Appl. 54(3), 2041–2050, (2018).
6. Rezkallah, M., et al.: Comprehensive controller implementation for wind-PV-diesel based standalone microgrid. IEEE Trans. Ind. Appl. 55(5), 5416–5428, (2019).
7. Guerrero, J.M., et al.: Control strategy for flexible microgrid based on parallel line-interactive UPS systems. IEEE Trans. Ind. Electron. 56(3), 726–736, (2009).
8. Shi, R.L., et al.: Operation control strategy for multi-energy complementary isolated microgrid based on virtual synchronous generator. Automation of Electric Power Systems 40(18), 32–40, (2016). (in Chinese)
9. Roslan, A.M., et al.: Improved instantaneous average current-sharing control scheme for parallel-connected inverter considering line impedance impact in microgrid networks. IEEE Trans. Power Electron. 26(3), 702–716, (2011).
10. Chen, X., et al.: Distributed cooperative control of multiple hybrid energy storage systems in a DC microgrid using consensus protocol. IEEE Trans. Ind. Electron. 67(3), 1968–1979, (2020).
11. Huang, X., et al.: Decentralized control of multi-parallel grid-forming DGs in islanded microgrids for enhanced transient performance. IEEE Access 7, 17958–17968, (2019).
12. Sharma, R., Suhag, S.: Virtual impedance based phase locked loop for control of parallel inverters connected to islanded microgrid. Computers and Electrical Engineering 73, 58–70, (2019).
13. Wang, Y.W., et al.: Research on transient characteristic optimization of virtual synchronization generator control strategy. Proc. CSEE 39(20), 5885–5893, (2019). (in Chinese)
14. Ma, W.T., Wang, J.M., Wang, Y.Q.: Analysis of the influence of virtual impedance on the stability of parallel voltage inverters with different voltage levels. Electric Power, network launch (2020). (in Chinese)
15. Mohamed, Y.A.I., El-Saadany, E.F.: Adaptive decentralized droop controller to preserve power sharing stability of parallel inverters in distributed generation microgrids. IEEE Trans. Power Electron. 23(6), 2806–2816, (2008).
16. Sofia, M.A., Gharibpetian, G.B.: Dynamic performance enhancement of microgrids by advanced sliding mode controller. Int. J. Electric Power Energy Syst. 33(1), 1–7, (2011).
17. Zhang, Q.J., et al.: Parallel operation of microgrid inverters based on adaptive sliding-mode and wireless load-sharing controls. J. Power Electron. 15(3), 741–752, (2015).
18. Guerrero, J.M., et al.: Output impedance design of parallel-connected UPS inverter with wireless load-sharing control. IEEE Trans. Ind. Electron. 52(4), 1126–1135, (2005).
19. He, J.W., Li, Y.W.: Analysis, design, and implementation of virtual impedance for power electronics interfaced distributed generation. IEEE Trans. Ind. Appl. 47(6), 2525–2538, (2011).
20. Zhang, Q.H., et al.: A control strategy for parallel operation of multi-inverters in microgrid. Proc. CSEE 32(25), 126–132, (2012). (in Chinese)
21. Wu, W.P., Cui, Y., Yan, X.W.: Operation strategy of parallel self-synchronizing voltage sources in a distributed microgrid. Power System Protection and Control 48(12), 107–117, (2020).
22. Zhang, M.R., et al.: Control strategy design and parameter selection for suppressing circulating current among SSTs in parallel. IEEE Trans. Smart Grid 6(4), 1602–1609, (2015).
23. Zhang, M.R., Du, Z.C., Wang, S.B.: Research on droop control strategy and parameters selection of microgrids. Trans. of China Electrotechnical Society 29(2), 136–144, (2014).
24. Zhang, E.G., Kang, J.S.: A power sharing control method of parallel hybrid inverters to preserve microgrid stability. In: Proceedings of the 22nd International Conference on Electrical Machines and Systems, Harbin, China, 1–4 (2019).
25. A.E.M. Bouzid, et al.: A novel Decoupled Trigonometric Saturated droop controller for power sharing in islanded low-voltage microgrids. Electr. Power Syst. Res. 168, 146–161, (2019)
26. Shi, R.L., et al.: Seamless switching control strategy for microgrid operation modes based on virtual synchronous generator. Autom. Electr. Power Syst. 40(10), 16–23 (2016). (in Chinese)
27. Hao, X.X., et al.: Research on switch of microgrid between grid-tied and islanded operation modes based on virtual synchronous generator. Electric Drive 46(1), 50–54, (2016). (in Chinese)

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