Maximum Power Output Control Method of Photovoltaic for Parallel Inverter System Based on Droop Control

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Abstract. Generally, the output power of photovoltaic (PV) inverter will match the load requirement. And at the beginning of the design the load power is less than the maximum output power of PV cells to ensure the system operation stable when the PV inverter operates in islanded mode. However, it causes the energy waste of PV cells. Therefore, more and more PV cells are combined with other energy sources to form the microgrid system in order to reasonably plan the power output of each energy source. Droop control is usually used to achieve the power distribution of parallel inverter in microgrid system. However, the traditional methods of adjusting the droop coefficients or adding virtual impedance cannot automatically achieve the maximum utilization of output energy of PV cells. Thus, a novel droop control method has been proposed to achieve the maximum power output of PV (MPO-PV) unit in this paper, where the PV units of parallel system always operate at the maximum power and the other inverters make up the remaining power required by the load, with effective improvement of the utilization rate of renewable energy sources (RESs). Meanwhile, the control parameters of the improved droop loop have been designed by the small signal modeling and system stability analysis. Finally, the validity of the proposed method has been verified by experimental results.

Keywords: PV cells · Parallel inverter · Droop control · MPO-PV · Small signal modeling

1 Introduction

Distributed generation (DG) has been developed rapidly in recent years due to the advantages of low environmental pollution, high energy utilization, flexible installation and low transmission power loss [1]. Compared with traditional generators, DG units have a high degree of controllability and operability, which makes micro-grid system based on DGs play an important role in maintaining the stability of power grid [2]. Although the power demand of micro-grid is increasing, the rated power of inverter switching devices is often limited by technical or economic factors. Therefore, multi-inverter parallel operation is usually adopted to improve the system capacity [3].

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Droop control [4, 5] can solve the problem of voltage frequency regulation and power distribution between inverters without the interactive communication line, which has been widely used in the application of island parallel mode [8, 9] and grid-connected mode [14, 15] for PV inverter. In the PV inverter control methods based on droop control, the PV cells are generally assumed as constant voltage dc power supply with an infinite capacity by most scholars. However, the PV power is often fluctuant due to the intermittency and weather factors. Thus, this assumption ignores some problems in practical operation of PV inverters.

Therefore, several studies have been started to solve the problems mentioned above in grid-connected mode and island mode. To ensure the system connect with the grid at maximum power constantly and maintain the dc link voltage stable, the improved droop control schemes have been proposed in [8], which enhance the controllability of system power. To ensure that, [11] depends on predictive control algorithm for PV inverter to realize fast and accurate control of active power, and to alleviate the power grid frequency contingency without energy storage device. In addition, many issues may occur in island mode for the PV system based on traditional droop control, such as the voltage limit violation, fluctuations of PV input power, deviation of voltage/frequency and power oscillation. To solve the problem that the transient stress of energy storage converter current increases due to the large sudden change of load in the island mode of PV/storage microgrid system, a PV/storage coordinated control strategy has been proposed to suppress the transient power fluctuation of power conversion system (PCS) for energy storage and avoid the overcurrent fault [12]. However, this method lacks expansibility due to the utilization of high-speed communication line. The traditional droop scheme may not work well when its demanded power cannot be met by some renewable sources due to intermittency without storage. Therefore, an enhanced dual droop scheme has been proposed to improve the ability to resist the influence of the natural environment for two-stage PV system [14]. It has been proposed about a novel three-stage robust inverter-based voltage/var control (TRI-VVC) approach for high PV-penetrated distribution networks to reduce energy loss and mitigate voltage deviation [15]. To enable the maximum utilization of the voltage/current (V/A) rating of the interfacing inverter, an adaptive droop control has been proposed in a PV/battery hybrid system [19].

In the above studies, an auxiliary energy storage system is required to maximize the output power of PV inverter [19]. It is an urgent problem to be solved concerning how to achieve the MPO-PV units based on droop control in the parallel system without energy storage devices. Therefore, an improved droop method has been proposed here.

2 Issues Existing Traditional Droop Control

The configuration of paralleled inverter system is shown in Fig. 1. The system is composed of two single-stage full-bridge inverters in parallel, where the inverter 1 connects with the PV cells and inverter 2 connects with an equivalent dc power supply which may be a dc-link bus from other converter or source (non-renewable energy sources (NRESs), such as energy storage converter, diesel generator, et al.); Lacn are the filter inductors; Cacn are the filter capacitors; Rln and Lln are the resistive and inductive component of line impendences, respectively; Rloadn are the local loads.

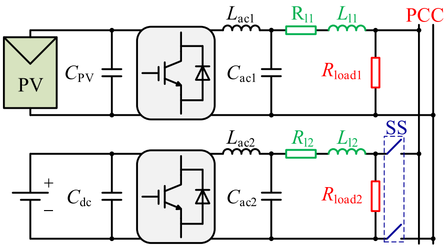


Fig. 1. Structure block diagram of parallel inverter system.

The inverter 2 is connected with the point of common coupling (PCC) by the static switch (SS).

The typical R/X ratio of a low voltage (LV) line has been given as 7.7 [2], that is, the line impedance is mainly resistive. Thus, the output power can be obtained:

$$P_{acn} = \frac{EV_{acn}}{R_{ln}} \cos \delta_n - \frac{E^2}{R_{ln}} \tag{1}$$

$$Q_{acn} = -\frac{EV_{acn}}{R_{ln}} \sin \delta_n \tag{2}$$

where, Vacn and E are the output voltage amplitudes of inverters and PCC; □n is the power angle difference between output voltage of inverters and voltage of PCC; Pacn and Qacn are the output active power and reactive power, respectively.

Thus, the resistive droop equations can be represented by (3) and (4):

$$V_{acrefn} = V_0 n - k_{pn}(P_{acn} - P_{0n}) \tag{3}$$

$$\omega_{acrefn} = \omega_{0n} + k_{qn}(Q_{acn} - Q_{0n}) \tag{4}$$

where, V_{acrefn} and ω_{acrefn} are the reference amplitude and reference angular frequency of inverter output voltage; k_{pn} and k_{qn} are their droop coefficients of active and reactive power; V_{0n} and ω_{0n} are their rated amplitude and angular frequency; P_{0n} and Q_{0n} are their rated active and reactive power, respectively.

It is shown in Fig. 2 about the control block diagram of single inverter based on traditional droop control. Firstly, the output voltages v_{acn} and currents i_{acn} should be measured to calculate P_{acn} and Q_{acn}. Then, the reference v_{acrefn} of output voltage can be generated by the droop control and can be tracked by the dual loop control. For simplicity, the two inverters are assumed as equally rated ($P_{01} = P_{02} = P_0$) and the total power required by the loads is also assumed to be more than the rated power of a single inverter and less than two times of its rating ($P_0 < P_{Load} < 2P_0$). Generally, the droop coefficients are set to be the same ($k_{p1} = k_{p2}$, $k_{q1} = k_{q2}$) for power sharing. Therefore, the droop line of active power is shown in Fig. 3. Before parallel operation, the two inverters supply power to their local loads, respectively. At this point, the inverter 1 and 2 operate at a_1 and a_2 with the output active P_{1a} and P_{2a}, respectively. The inverters operate in parallel mode when SS is closed. The operating point of inverter 1 moves from a_1 to b_1 and inverter 2 moves from a_2 to b_2 due to the droop characteristic. Then, the inverters share the power of loads at steady state (P_{Load} = 2 P_b = 2P_{ac1} = 2P_{ac2}). Since the maximum output power point of PV cells is c_1, the traditional droop control cannot make PV cells operate at the maximum power point (MPP), which will inevitably cause the waste of PV power. If the inverter 1 outputs the maximum power (P_{ac1} = $P_{PV\max1}$) without changing the droop line and the inverter 2 supplies the remained power of the loads (P_{ac2} < $P_{PV\max1}$), the circular current will be generated because the amplitude of output voltages are different, which endangers the safe operation of the system.

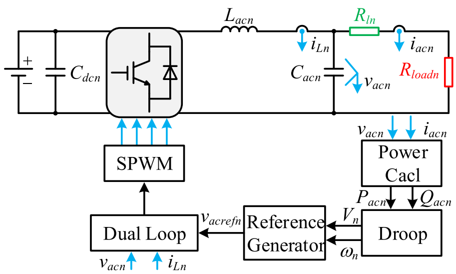


Fig. 2. Traditional control block diagram of single inverter.

The virtual impedance is usually used in the application of parallel inverter to balance the impedance between inverters and achieve power sharing. Similarly, the virtual impedance can also be added to distribute output power in proportion. If the added virtual impedance is resistive and define Zvir = Rv, the equivalent reference of output voltage can be expressed as:

$$v_{ref} = v_{acref} + v_{vir} = v_{acref} + i_o \cdot R_v \tag{5}$$

The equivalent voltage vvir generated by virtual impedance can make the droop line of inverter 1 translate ΔV. If vvir = ΔV = ΔV1, inverter 1 can operate at the MPP c1 and inverter 2 supplies the remained power, which achieves maximum utilization of PV power. Nevertheless, the method based on virtual impedance to achieve maximum power output of PV has the following shortcomings:

- Even if the complete information of PV curve is known, the value of virtual impedance needs to be repeatedly adjusted to make the inverter work at the MPP.
- Under the influence of natural factors such as weather, the MPP on the PV curve will change accordingly, and the local load may also fluctuate. Therefore, necessary to change the value of virtual impedance in real time to adapt to the normal operation of the system, with increasing the difficulty of actual assembly.

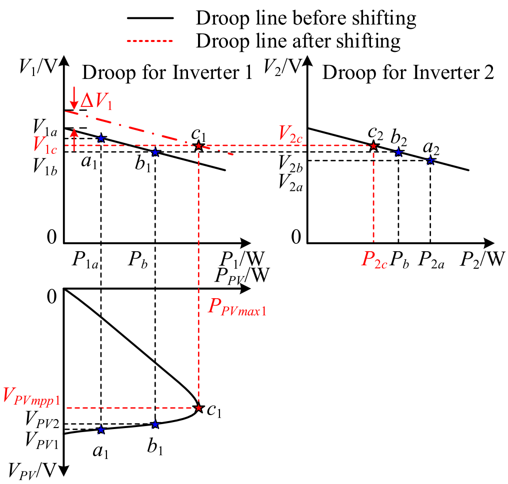


Fig. 3. Relation diagram of resistive P-V droop curve and PV power curve.

3 Novel Droop Control Method to Achieve MPO-PV for Parallel Inverter System

3.1 Design of Translation ΔV

The method to shift the droop line of PV inverter can be used to improve the energy utilization of PV cells when inverters are in parallel operation. If the droop line of inverter 1 can be raised by ΔV_1 as shown in Fig. 3, the operation point a_1 of inverter 1 can move to the MPP c_1 of PV cells, which achieves the MPO-PV.

The problem is how to determine the value of ΔV_1, where the simplest way has been proposed here. The power imbalance, i.e., the difference between the value $P_{PV\max1}$ of MPO-PV and output power of PV inverter 1, can be fed to a PI controller of power loop, and then output of the PI controller can be used as ΔV_1, which will always enforce a zero-power imbalance in the steady state. ΔV_1 can be obtained by (4):

$$\Delta V_1 = \left(k_{PVp1} + \frac{k_{PVi1}}{s}\right)(P_{PV\max1} - P_{ac1}) > 0 \tag{6}$$

where, $P_{PV\max1}$ can be tracked by some common MPP tracking methods; k_{PVp1} and k_{PVi1} are the proportional and integral gains of the PI controller of power loop, respectively.

Hence, according to (4), the droop equation of active power for PV inverter can be expressed as:

$$V_{ac1} = V_01 - k_{p1}(P_{ac1} - P_{01}) + \left(k_{PVp1} + \frac{k_{PVi1}}{s}\right)(P_{PV\max1} - P_{ac1}) \tag{7}$$

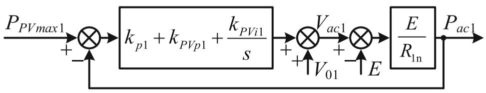


Fig. 4. Block diagram of active power closed loop control.

3.2 Analysis for Active Power

It is assumed that the rated output power of the inverter is the same as the maximum output power of the PV cells, i.e., $P_{01} = P_{PV\max1}$, and (5) can be further reduced to:

$$V_{ac1} = V_0 1 + \left(k_{p1} + k_{PVp1} + \frac{k_{PVi1}}{s}\right)(P_{PV\max1} - P_{ac1}) \tag{8}$$

Due to the fact that power angle δ is usually small, sin $\delta \approx \delta$ and cos $\delta \approx 1$ can be used for simplification. Then, the closed-loop control block diagram of output active power is shown in Fig. 4.

According to the superposition theorem, the closed-loop transfer function of the output active power is:

$$\begin{aligned} P_{ac1}(s) = & \frac{\left[\left(k_{p1} + k_{PVp1}\right)s + k_{PVi1}\right]E}{\left[\left(k_{p1} + k_{PVp1}\right)E + R_{l1}\right]s + k_{PVi1}E} \frac{P_{PV\max1}}{s} \\ & + \frac{Es}{\left[\left(k_{p1} + k_{PVp1}\right)E + R_{l1}\right]s + k_{PVi1}E} \frac{V_{01} - E}{s} \end{aligned} \tag{9}$$

According to the final value theorem, the final steady state value of the output active power can be obtained as:

$$\lim_{t \to \infty} P_{ac1}(t) = \lim_{s \to 0} sP_{ac1}(s) = P_{PV\max1} \tag{10}$$

According to (8), it can be inferred that the output power P_{ac1} of inverter can track the maximum output power $P_{PV\max1}$ of the PV cells with zero steady state error by proposed method. Moreover, the proposed method is not affected by the voltage of PCC and the impedance of transmission line.

3.3 Implementation of the Novel Droop Mehtod to Achieve MPO-PV for Parallel Inverter System

Since the maximum active power output of photovoltaic cells will not affect the reactive power of the inverter, the reactive power Eq. (2) can remain unchanged. According to (2) and (6), it is shown in Fig. 5 about the control strategy of the overall parallel inverter system. Figure 5(a) shows the proposed control method to achieve MPO-PV for PV inverters and Fig. 5(b) shows the traditional resistive droop control adopted by the NRESs inverters.

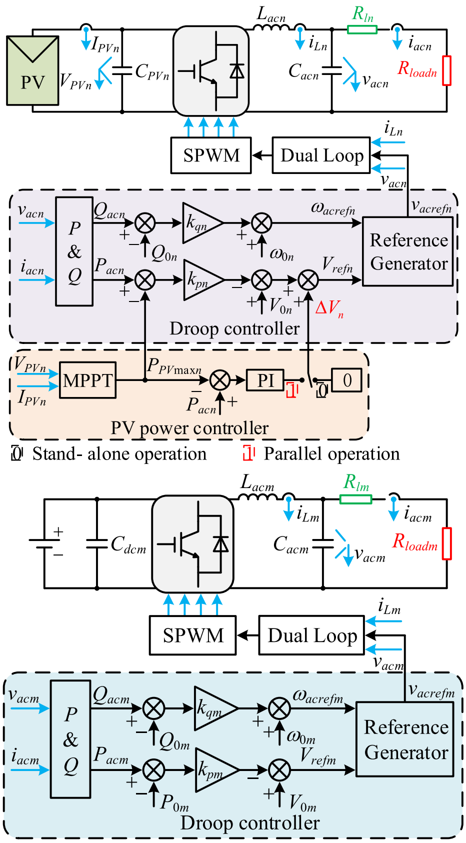


Fig. 5. Control strategy of the overall parallel inverter system: (a) novel resistive droop control method to achieve MPO-PV for PV inverters, (b) traditional resistive droop control for NRESs inverters.

For the PV inverter n, when connected with NREs inverter m in parallel mode, the measured output voltage V_{PVn} and current I_{PVn} of PV cells can be fed to the MPP block to obtain the maximum output power point (V_{PVmppn}, $P_{PV\max n}$) of the PV cells. In addition, the measured output voltage v_{acn} and current i_{acn} can be used to calculate the output active power P_{acn} of inverter. The input to the PI controller of PV power loop is the difference between $P_{PV\max n}$ and P_{acn}. The output ΔV_n of PI controller can be fed to active droop equation, and then the reference voltage of inner loop can be generated.

Finally, the generated reference v_{acrefn} can be tracked by the dual-loop quasi-proportional-resonant (qPR) controller shown in (11) which is insensitive to the resonance frequency drift compared to the proportional-resonant (PR) controller.

$$G_{qPR}(s) = k_p + \frac{2k_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \tag{11}$$

where, k_p is the proportional gain, and k_r is the resonant control gain, ω_0 and ω_c are the fundamental frequency of output voltage and cutoff frequency, respectively.

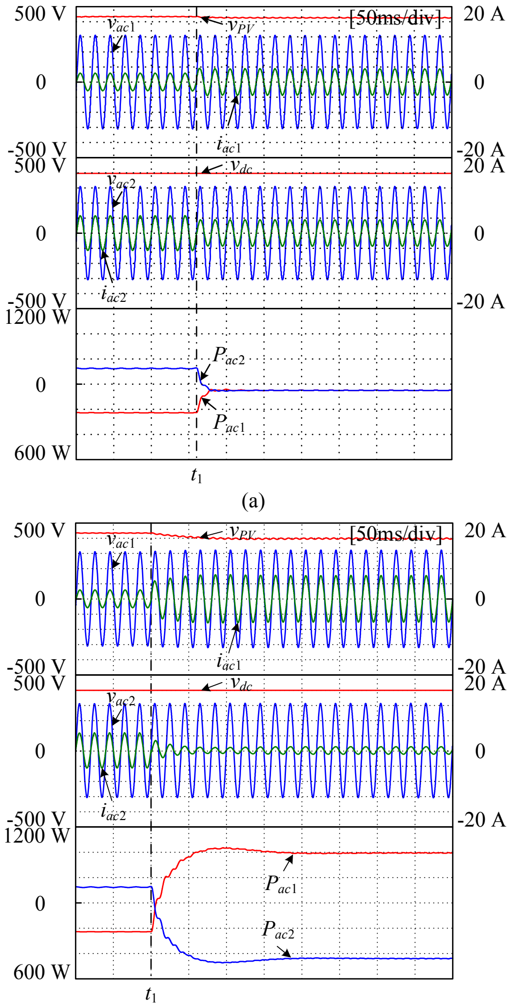
For the NRESs inverter m, the measured output voltage v_{acm} and current i_{acm} can be used to calculate the output power P_{acm} and Q_{acm}. Then, the generated P_{acm} and Q_{acm} are fed to the traditional resistive droop Eqs. (1) and (2) to obtain the output voltage reference v_{acrefm}. Finally, the similar dual-loop control is also used to track the voltage reference.

As for the inductive transmission line, the similar control method can be used to achieve the same control target: to change the resistive droop control to the inductive one. And the generated ΔV_n should be added in the inductive active power equation. Similarly, the reactive power equation can remain unchanged.

4 Simulation Results

Simulations have been performed with two similarly rated inverter systems in PLECS. The main purpose of the simulations is to verify the anticipated MPO-PV for parallel inverter system.

Figure 6 shows the comparison simulation results between the proposed control and traditional droop control, and the inverters supply power to the loads (P_{ac1} = 370 W, P_{ac2} = 726 W) alone before t_1. When the SS is closed at t_1, the PV inverter adopting the traditional droop control shares power (P_{ac1} = P_{ac2} = 548 W) with the NRESs inverter as shown in Fig. 6(a), which causes the energy waste of PV cells. When using the proposed control method shown in Fig. 5(a), the PV inverter can achieve the maximum power output and the NREs inverter makes up the remained power of the load automatically as shown in Fig. 6(b).



(b)

Fig. 6. Comparison simulation results: (a) proposed control method to achieve MPO-PV for PV inverters, (b) the traditional droop control.

5 Conclusion

To solve the problem of the maximum power output for PV cells in parallel inverter system, a novel droop control method has been proposed in this paper to achieve MPO-PV for parallel inverter system, and the energy utilization ratio of PV inverter has been improved. Finally, the simulation results have varied the validity and robustness of the proposed method.

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