An Improved Decentralized Control of Grid-Connected Cascaded Inverters with Different Power Capacities

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Abstract—The existing decentralized control for modular cascaded inverters is based on the assumption that all inverter modules have same capacities. However, available source power capacities of cascaded inverters may be different in practical distributed generation systems. To address this issue, this letter proposes an improved decentralized control scheme, in which the voltage amplitudes vary according to their individual available powers. Moreover, a power factor consistency control is proposed to achieve autonomous voltage phase synchronization. The steady-state analysis and synchronization mechanism of cascaded inverters are illustrated. In addition, the proposed strategy offers other advantages, including adjustable grid power factor and immunity to grid voltage faults. The effectiveness of the proposed control is tested by experiments.

Index Terms—Cascaded micro-converters, decentralized control, grid-connected, microgrid, renewable generation.

I. INTRODUCTION

Cascaded H-bridge converters are widely applied in modular inverter systems [1], [2] and cascaded distributed generation systems [3]-[6]. Generally, cascaded inverters are used in two operation modes: islanded mode for feeding a load and grid-connected mode for connecting to utility grid.

In the islanded mode, decentralized control has been gradually studied for modular converters due to the advantages of full modularity, communication-free and high reliability. In [7], a compound decentralized control strategy was early proposed for input-series-output-series dc/dc converters to maintain autonomous voltage and power balances. Then, some improved decentralized control methods were proposed to eliminate the input voltage sensors [8] and enhance dynamic voltage regulation [9]. A frequency self-synchronization control for cascaded dc/ac inverters was firstly proposed to achieve decentralized power balance in [10]. However, system stability of islanded operation highly relies on the load characteristic and only the resistive-inductive load is applicable. To overcome this limitation, an adaptive droop control was proposed to adapt arbitrary resistive-inductive-capacitive load in [11]. Nevertheless, the aforementioned [10],[11] only focused on the islanded mode, which cannot be directly adopted to the grid-connected mode.

In the grid-connected mode, the decentralized control is rarely reported and is more concerning. In the latest research [12], a fully decentralized control for cascaded inverters was introduced. As all modules have fixed-voltage-amplitude and same flowing-current, their apparent powers are equal all the time. As a result, it is just suitable for modular inverters with same capacities and same power outputs [12]. However, the output powers of these inverters are required to be different for flexible power management in some special applications, such as in cascaded photovoltaic (PV) micro-inverters [4],[5] and cascaded energy storage inverters [6]. In these cascaded distributed generation (DG) systems [3]-[6], the decentralized control of [12] cannot provide independent power-regulation function.

To solve this limitation, this letter proposes an improved decentralized control for grid-connected cascaded inverters. Compared to [12], the proposed method has the following advantages:

- **Independent power-regulation for each inverter.** The solution proposed in this study adopts a varied-amplitude-fixed-phase voltage control to independently regulate the power output of each inverter, which is more flexible than the fixed-amplitude-varied-phase voltage control of [12].

- **Arbitrarily adjustable grid power factor.** In [12], there is a tradeoff between grid power factor (PF) and stability margin, and unity PF cannot be realized. But in this study, arbitrary PF can be realized without compromising system stability.

- **Adapt grid voltage fluctuation.** In [12], system stability is sensitive to grid voltage sags, while the control proposed in this letter can adapt to grid voltage fluctuations.

- **More generalized and practical.** In this work, not only fully modular inverters can be used, but also asymmetrical cascaded inverters are applicable. Each inverter is controlled independently without communicating with other inverters, resulting in high reliability and scalability.

II. IMPROVED DECENTRALIZED CONTROL

A. Grid-Connected Cascaded Inverters

Fig. 1 shows the system structure and overall control framework of grid-connected cascaded inverters. The system
consists of \( n \) cascaded inverters with DG resources. Some main features are:

- **Individual local controllers for inverters.** Each inverter is controlled by a local controller, which needs only local information.

- **Common grid flowing current.** All inverters have the common flowing grid current. Thus, the fundamental-frequency current component can be used as an inherent synchronizer, and the synchronization of voltage phase can be realized by power-factor-angle consistency.

- **Current-controlled for inverter-1.** To guarantee a required grid PF, inverter-1 is controlled as a current source, regulating the grid flowing current. Proper synchronization with the grid voltages at the point of common coupling (PCC) is required.

- **Voltage-controlled for remaining \( n-1 \) inverters.** The rest of inverters are controlled as voltage sources to ensure independent power-regulation and self-synchronization.

\[ \begin{align*}
I_g & = \left( K_{P_i} + \frac{K_{I_i}}{s} \right) \left( P_i^* - P_i \right) \\
\theta_g &= \theta_p - \phi^* 
\end{align*} \quad (i = 1)
\]

where \( P_i^* \) denotes the maximum power capacity from the primary DG-1 source. \( P_i \) is the output active power of inverter-1. \( K_{P_i} \) and \( K_{I_i} \) are the proportional-integral (PI) coefficients. \( \theta_p \) is the voltage phase at PCC. \( \phi^* \) is the predesigned PF angle, which can be flexibly set by considering the grid requirement and reactive-power compensation capability of each inverter. Particularly, for cascaded PV micro-inverters, \( P_i^* \) can be determined by the maximum power point tracking (MPPT) algorithm, and unity PF can be realized by setting \( \phi^* = 0 \).

\[ \begin{align*}
I_i^* & = \frac{V_i^*}{n} + \left( K_{P_i} + \frac{K_{I_i}}{s} \right) \left( P_i^* - P_i \right) \\
\phi_i &= \omega_i + \left( K_{P_i} + \frac{K_{I_i}}{s} \right) \left( \phi^* - \phi_i \right) 
\end{align*} \quad (i = 2, 3, ..., n)
\]

where \( P_i^* \) denotes the maximum power capacity from the primary DG-i source. \( P_i \) is output active power of inverter-i. \( K_{P_i} \) and \( K_{I_i} \) are the PI coefficients of amplitude control. \( V_i^* \) denotes the rated grid voltage amplitude. \( \omega_i \) denotes the rated grid angular frequency. \( K_{P_i} \) and \( K_{I_i} \) are the PI coefficients of frequency control. \( \phi^* \) is the predesigned PF angle. \( \phi_i \) is output PF angle, which is calculated by the difference of output voltage phase and current phase.
C. Steady-State Analysis

Fig. 4 shows the voltage phasor diagram in the steady state. Due to the zero steady-state error of PI control in (2), the PF angles of the inverters would be identical \( \phi_2=\phi_3=\cdots=\phi_n=\phi^* \). Then, by combining (1)-(3), the same voltage phases are obtained because of the common grid current

\[
\varphi_i = \theta_i - \theta_g \quad (i = 2,3,\ldots,n)
\]

Due to the same PF angles and grid current of all inverters, the active power flow \( P_i^* = V_i \theta_i \cos \phi^* \) is proportional to the voltage amplitude \( V_i \) in the steady-state.

\[
P_1^* : P_2^* : \cdots : P_n^* = V_1 : V_2 : \cdots : V_n
\]  

D. Synchronization-Mechanism Analysis

As the grid current is shared by all inverters, the fundamental current component is used as a common synchronization baseline. That is, the voltage phase synchronization of the inverters can be realized by power-factor-angle consistency.

To better understand the proposed PF control, a synchronization mechanism analysis is carried out. Fig. 5 presents the equivalent circuit and phasor diagram of grid-connected cascaded inverters. For simplicity, unity PF operation is assumed by setting \( \phi^*=0 \).

In Fig. 5(b), \( u_i \) (blue phasor) leads the steady-state grid current (green phasor); while \( u_j \) (red phasor) lags it. Initially, \( \varphi^*>0 \). Then, \( \varphi^*<0 \) is obtained from (2). As a result, \( \varphi^* \) decreases \((\Delta \omega=0<0\)) while \( \varphi^* \) increases \((\Delta \omega=0>0\)). The convergence process will continue until \( \varphi^*=\phi^*=0 \), and \( \theta^*=(\theta_g+\phi^*) \).

III. EXPERIMENTAL RESULTS

To verify the feasibility of the proposed control, a grid-connected system comprised of three cascaded inverters has been built and tested in the lab. The system parameters are listed in Table I. The front-end dc-link of the inverters is an ideal dc constant-voltage source.

### Table I  
**Experimental Parameters**

| Description                     | Symbol | Value   |
|---------------------------------|--------|---------|
| Rated grid voltage             | \( V_g \) | 311 V   |
| Rated grid angular frequency   | \( \omega \) | 100π rad/s  |
| Grid line impedance            | \( L_{\text{lin}} \) | 0.3mH   |
| Cascaded number                | \( N \) | 3       |
| Inverter switching frequency   | \( f_{\text{PWM}} \) | 10 kHz  |
| PI coefficients of amplitude-control | \( K_{\text{Pvi}} \) | 0.2 |
|                                  | \( K_{\text{i}} \) | 0.6    |
| PI coefficients of frequency-control | \( K_{\text{Pvi}} \) | 2      |
|                                  | \( K_{\text{i}} \) | 0.2    |
| PF angle reference             | \( \phi^* \) | 0 (Case 1) |
|                                 |        | 0.128π (Case 2) |

A. Case 1: Source Power Change under Unity PF

To evaluate the independent power-regulation capability of each inverter, a test condition with different DG-source capacities is considered in Case 1. Fig. 6 shows experimental results. The available powers of the three inverters are changed from same values to different values at \( t=1s \).

Before \( t=1s \), output voltages \( u_1, u_2, u_3 \) of the three inverters are identical in Fig. 6(b), and the output active-powers \( P_1, P_2, P_3 \) are equal to 1.5kW in Fig. 6(c). After \( t=1s \), \( P_1 \) changes from 1.5kW to 1.3kW, \( P_3 \) changes to 1.1kW, while \( P_1 \) is unchanged. From the steady-state voltage in Fig. 6(a), output voltages \( u_1, u_2, u_3 \) have the same phase than the grid current \( i_g \), which reveals that a predefined unity PF is realized. Meanwhile, the voltage amplitude \( V_i \) is proportional to the output active power.
\(P^*\) in steady-state, which verifies the feasibility of the proposed varied-amplitude-fixed-phase voltage control. From Case 1, the proposed method can work in the different source power conditions and achieve unity PF.

From the steady-state voltage/current, (b) three output voltages \(u_1\sim u_3\), grid current \(i_g\), and (c) three output active powers \(P_1\sim P_3\).

**B. Case 2: Grid Voltage Sag under No-Unity PF**

This case study aims to test the performances of the proposed control under no-unity PF and grid voltage sag. The experimental results of Case 2 are shown in Fig. 7.

Different from Case 1, this case adopts a no-unity PF (\(\cos \phi = 0.92\)) to show the PF controllability of the proposed strategy. In this condition, each inverter provides reactive-power compensation to the utility grid. From the steady-state active/reactive power values in Figs. 7(b) and (c), the same power factor angle (\(\tan \phi = Q_i/P_i = 0.425\)) is ensured for the three inverters. That is, an identical no-unity PF=0.92 is realized to ensure power-factor-angle consistency.

Moreover, to demonstrate the effectiveness of the proposed strategy under grid contingencies, a 15% grid voltage sag is imposed. Before \(t=1s\), output voltages \(u_1\), \(u_2\), \(u_3\) of the three inverters have the same phase, and the voltage amplitude is proportional to the active power outputs. At \(t=1s\), a grid voltage sag occurs. To compensate for the grid voltage sag, output voltages \(u_1\), \(u_2\), \(u_3\) react immediately in Fig. 7(a). After about two cycles, \(u_1\), \(u_2\), \(u_3\) reach the new steady states, and the grid current amplitude \(i_g\) increases to guarantee the unchanged active power output. As shown in Figs. 7(b) and (c), the active/reactive powers have satisfactory dynamic responses.

Clearly, the results above indicate that the proposed method can achieve flexible PF regulation and adapt to grid voltage fluctuations.

**IV. CONCLUSION**

This letter has proposed an improved decentralized control of grid-connected cascaded inverters. Independent power-regulation for each inverter can be obtained by the proposed varied-amplitude-fixed-phase voltage control. The voltage amplitude is varied according to the primary source power. The voltage-phase synchronization is achieved by power-factor-angle consistency. Compared with the existing fixed-amplitude-varied-phase method, the proposed strategy has three main advantages: 1) suitable for asymmetrical cascaded DG sources; 2) adjustable grid power factor; and 3) immune to the grid voltage faults. As only local information is necessary for each inverter, the proposed method has the advantages of high reliability and scalability, which has promising applications in large-scale cascaded PV and energy storage inverters.
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