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A Unified Control Strategy in Grid-Tied and Islanded Operations in Distributed Generation for 3-Phase Inverter

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Abstract— **In this paper, a unified control strategy for both grid-tied and islanded modes of operations are performed. Here we are using a three phase inverter in distributed generation..DG delivers power to the utility and the local critical loads in grid-tied operation and upon the occurrence of utility outage, the islanding is formed. The inverter is regulated as a current source in grid-tied operation and a voltage source in islanded operation. The waveforms of grid current in grid-tied mode and load voltage in islanding mode are distorted under non-linear local loads with conventional strategy. The transients will be reduced by proposing a unified control strategy. Unified control strategy makes the current unity in both grid-tied and islanded operations. A single-phase DG, which injects harmonic current into the utility for mitigating the harmonic component of the grid current. This paper also presents the analysis and parameter design of control strategy.**

Index Terms— **Distributed Generation(DG), unified control, mitigating, grid-tied, islanded.**

I. INTRODUCTION

Distributed generation (DG) is emerging as a viable alternative when renewable energy resources are available, such as wind turbines, photovoltaic arrays, fuel cells, micro turbines. DG is a suitable form to offer high reliable electrical power supply, as it is able to operate either in the grid-tied mode or in the islanded mode. In the grid-tied operation, DG deliveries power to the utility and the local critical load. Upon the occurrence of utility outage, the islanding is formed. However, in order to improve the power reliability of some local critical load, the DG should disconnect to the utility and continue to feed the local critical load. The load voltage is key issue of these two operation modes, because it is fixed by the utility in the grid-tied operation, and formed by the DG in the islanded mode, respectively.

Droop-based control is used widely for the power sharing of parallel inverters, which is called as voltage mode control in this paper, and it can also be applied to DG to realize the power sharing between DG and utility in the grid-tied mode. In this situation, the inverter is always regulated as a voltage source by the voltage loop, and the quality of the load voltage can be guaranteed during the transition of operation modes.

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Moreover, the grid current is not controlled directly, and the issue of the inrush grid current during the transition from the islanded mode to the grid-tied mode always exists, even though phase-locked loop (PLL) and the virtual inductance are adopted. DG is controlled as a current source just by the inner current loop. Upon the occurrence of the grid outage,. The detailed operation principle of DG with the proposed control strategy is illustrated in Section III. Section IV investigates the proposed control strategy by simulation results.

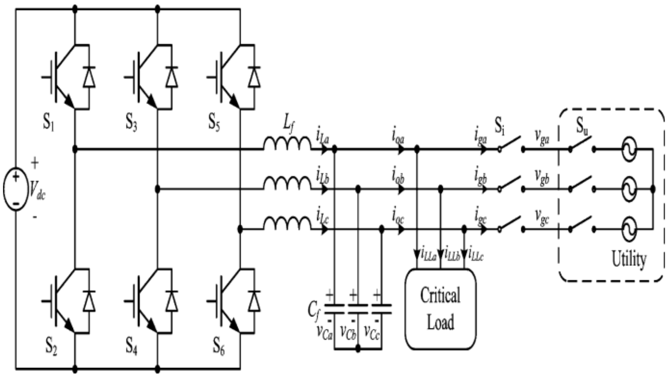


Fig1. Schematic diagram of the DG based on the proposed control strategy.

II. PROPOSED CONTROL STRATEGY

A. Power Stage:

This paper presents a unified control strategy for a three phase inverter in DG to operate in both islanded and grid-tied modes. The schematic diagram of the DG based on the proposed control strategy is shown by Fig1.The DG is equipped with a three-phase interface inverter terminated with a *LC* filter. The primary energy is converted to the electrical energy, which is then converted to dc by the front-end power converter, and the output dc voltage is regulated by it. Therefore, they can be represented by the dc voltage source *V*dc in Fig. 1. In the ac side of inverter, the local critical load is connected directly. It should be noted that there are two switches, denoted by Su and Si, respectively, in Fig.1, and their functions are different. The inverter transfer switch Si is controlled by the DG, and the utility protection switch Su is governed by the utility. When the utility is normal, both switches Si and Su are ON, and the DG in the grid-tied mode injects power to the utility. When the utility is in fault, the switch Su is tripped by the utility instantly, and then the islanding is formed. After the islanding has been confirmed by the DG with the islanding detection scheme, the switch Si is disconnected, and the DG is transferred from the grid-tied mode to the islanded mode. When the utility is restored, the DG should be resynchronized with the utility first, and then the switch Si is turned ON to connect the Distributed Generation with the grid.

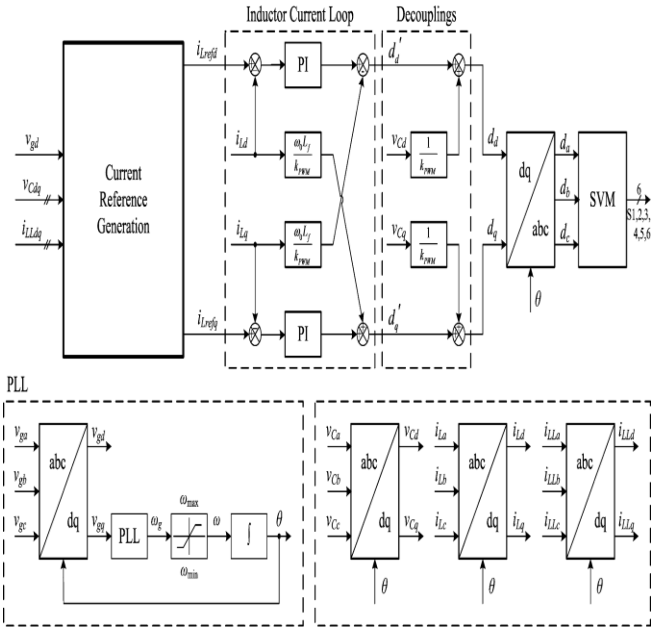


Fig 2. Overall block diagram of the proposed unified control strategy.

B. Basic Idea

With the hybrid voltage and current mode control, the inverter is controlled as a current source to generate the reference power $P_{DG} + jQ_{DG}$ in the grid-tied mode. And its output power $P_{DG} + jQ_{DG}$ should be the sum of the power injected to the grid Pg + jQg and the load demand Pl_{oad} $+jQ_{load}$, which can be expressed as follows by assuming that the load is represented as a parallel *RLC* circuit:

$$P_{load} = \frac{3}{2} \cdot \frac{V_m^2}{R} \tag{1}$$

$$Q_{load} = \frac{3}{2} \cdot V_m^2 \cdot \left(\frac{1}{\omega L} - \omega C\right). \tag{2}$$

In (1) and (2), V_m and ω represent the amplitude and frequency of the load voltage, respectively. When the nonlinear local load is fed, it can still be equivalent to the parallel RLC circuit by just taking account of the fundamental component. During the time interval from the of islanding happening to the moment of switching the control system to voltage mode control, the load voltage is neither fixed by the utility nor regulated by the inverter, so the load voltage may drift from the normal range. If both active power *Pg* and reactive power Q_g injected into the grid are positive in the grid-tied mode, then P_{load} and Q_{load} will increase after the islanding happens, and the amplitude and frequency of the load voltage will rise and drop, respectively, according to(1) and (2).With the previous analysis, if the output power of inverter $P_{DG} + jQ_{DG}$ could be regulated to match the load demand by changing the current reference before the islanding is confirmed, the load voltage excursion . In the proposed control strategy, the output power of the inverter is always controlled by regulating the three-phase inductor current *iLabc* while the magnitude and frequency of the load voltage v_{Cabc} are monitored. When the islanding happens, the magnitude and frequency of the load voltage may drift from the normal range, and then they are controlled to recover to the normal range automatically by regulating the output power of the inverter.

C. Control Scheme

Fig.2 describes the overall block diagram for the proposed unified control strategy, where the inductor current i_{Labc}, the utility voltage v_{gabc} , the load voltage v_{Cabc}, and the load current iLLabc are sensed. And the three-phase inverter is controlled in the SRF, in which, three phase variable will be represented by dc quantity. The control diagram is mainly composed by the inductor current loop, the PLL, and the current reference generation module.

In the inductor current loop, the PI compensator is employed in both *D*- and *Q*-axes, and a decoupling of the cross coupling denoted by ω_{0Lf} /k_{PWM} is implemented in order to mitigate the couplings due to the inductor. The output of the inner current loop d_{dq} together with the decoupling of the capacitor voltage denoted by $1/k_{PWM}$, sets the reference for the standard space vector modulation that controls the switches of the three-phase inverter. It should be noted that k_{PWM} denotes the voltage gain of the inverter, which equals to half of the dc voltage in this paper. The PLL in the proposed control strategy is based on the SRF PLL, which is widely used in the three-phase power converter to estimate the utility frequency and phase. If the current reference is constant, the inverter is just controlled to be a current source, which is the same with the traditional grid-tied inverter.

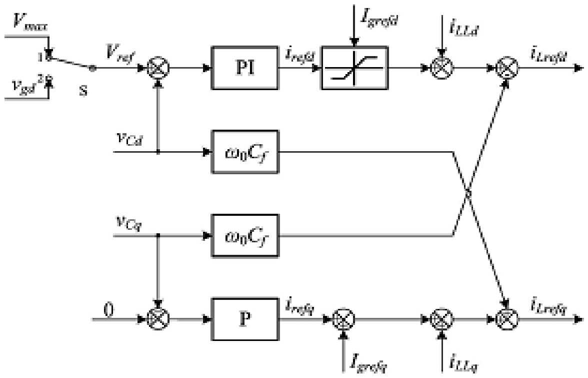


Fig.3. Block Diagram of the current reference generation module.

The block diagram of the proposed current reference generation module is shown in Fig. 3, which provides the current reference for the inner current loop in both grid-tied and islanded modes. In this module, it can be found that an unsymmetrical structure is used in *D*- and *Q*-axes. The PI compensator is adopted in *D*-axes, while the P compensator is employed in*Q*-axis. Besides, an extra limiter is added in the *D*-axis.

In the grid-tied mode, the load voltage v_{Cdq} is clamped by the utility. The current reference is irrelevant to the load voltage, due to the saturation of the PI compensator in *D*-axis, and the output of the P compensator being zero in *Q*-axis, and thus, the inverter operates as a current source. Upon occurrence of islanding, the voltage controller takes over automatically to control the load voltage by regulating the current reference, and the inverter acts as a voltage source to supply stable voltage to the local load; this relieves the need for switching between different control architectures. Another distinguished function of the current reference generation module is the load current feed forward. In the islanded mode, the load current feed forward operates still, and the disturbance from the load current, caused by the nonlinear load, can be suppressed by the fast inner inductor current loop, and thus, the quality of the load voltage is improved.

The inductor current control in Fig. 2 was proposed in previous publications the motivation of this paper is to propose a unified control strategy for DG in both grid-tied and islanded modes, which is represented by the current reference generation module in Fig. 3.The contribution of this module can be summarized in two aspects. First, by introducing PI compensator and P compensatory-axis and *Q*-axis respectively, the voltage controller is inactivated in the grid-tied mode and can be automatically activate upon occurrence of islanding. Therefore, there is no need for switching different controllers or critical islanding detection, and the quality of the load voltage during the transition from the grid-tied mode to the islanded mode can be improved.

III. OPERATION PRINCIPLE OF DG

The operation principle of DG with the proposed unified control strategy will be illustrated in detail in this section, and there are in total four states for the DG, including the grid-tied mode, transition from the grid-tied mode to the islanded mode, the islanded mode, and transition from the islanded mode to the grid-tied mode.

A. *Grid-Tied Mode*

When the utility is normal, the DG is controlled as a current source to supply given active and reactive power by the inductor current loop, and the active and reactive power can be given by the current reference of *D*- and *Q*-axis independently. First, the phase angle of the utility voltage is obtained by the PLL, which consists of a Park transformation expressed by (3), a PI compensator, a limiter, and an integrator

$$\begin{pmatrix} x_d \\ x_q \end{pmatrix} = \frac{2}{3}\begin{pmatrix} \cos\theta & \cos\left(\theta-\frac{2}{3}\pi\right) & \cos\left(\theta+\frac{2}{3}\pi\right) \\ -\sin\theta & -\sin\left(\theta-\frac{2}{3}\pi\right) & -\sin\left(\theta+\frac{2}{3}\pi\right)\end{pmatrix} \times \begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix}. \quad (3)$$

Second, the filter inductor current, which has been transformed into SRF by the Park transformation, is fed back and compared with the inductor current reference $i_{Lref\,dq}$, and the inductor current is regulated to track the reference $i_{Lref\,dq}$ by the PI compensator *GI*

The reference of the inductor current loop $i_{Lref\,dq}$ seems complex and it is explained as below. It is assumed that the utilityis stiff, and the three-phase utility voltage can be expressed as

$$\begin{cases} v_{ga} = V_g \cos\theta^* \\ v_{gb} = V_g \cos\left(\theta^* - \frac{2\pi}{3}\right) \\ v_{gc} = V_g \cos\left(\theta^* + \frac{2\pi}{3}\right) \end{cases} \quad (4)$$

$$\begin{cases} v_{gd} = V_g \cos(\theta^* - \theta) \\ v_{gq} = V_g \sin(\theta^* - \theta). \end{cases} \quad (5)$$

v_{gq} is regulated to zero by the PLL, so v_{gd} equals the magnitude of the utility voltage V_g . As the filter capacitor voltage equals the utility voltage in the gird-tied mode, v_{Cd} equals the magnitude of the utility voltage V_g , and v_{Cq} equals zero, too. In the *D*-axis, the inductor current reference $i_{Lref\,d}$ can be expressed by (6) according to Fig. 3

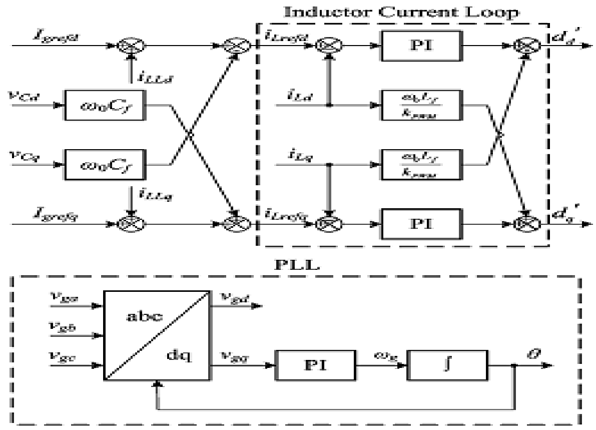


Fig.4. Simplified block diagram of the control strategy when DG operates in gried tied mode.

$$i_{Lrefd} = I_{grefd} + i_{LLd} - \omega_0 C_f \cdot v_{Cq}. \quad (6)$$

The first part is the output of the limiter. It is assumed that the given voltage reference V_{max} is larger than the magnitude of the utility voltage v_{Cd} in steady state, so the PI compensator, denoted by G_{VD} in the following part, will saturate, and the limiter outputs its upper value $I_{gref\,d}$. The second part is the load current of *D*-axis i_{LLd}, which is determined by the characteristic of the local load. The third part is the proportional part$-\omega_0 C_f \cdot v_{Cq}$, where ω_0 is the rated angle frequency, and C_f is the capacitance of the filter capacitor. It is fixed as v_{Cq} depends on the utility voltage. Consequently, the current reference $i_{Lref\,d}$ is imposed by the given reference $I_{gref\,d}$ and the load current i_{LLd}, and is independent of the load voltage. In the *Q*-axis, the inductor current reference $i_{Lref\,q}$ consists of four parts as

$$i_{Lrefq} = v_{Cq} \cdot k_{Gvq} + I_{grefq} + i_{LLq} + \omega_0 C_f \cdot v_{Cd} \quad (7)$$

where k_{Gvq} is the parameter of the P compensator, denoted byG_{VQ} in the following part. The first part is the output of G_{VQ}, which is zero as the v_{Cq} has been regulated to zero by the PLL. The second part is the given current reference $I_{gref\,q}$, and the third part represents the load current in *Q*-axis. The final part is the proportional part $-\omega_0 C_f \cdot v_{Cd}$, which is fixed since v_{Cd} depends on the utility voltage. Therefore, the current reference $i_{Lref\,q}$ cannot be influenced by the external voltage loop and is determined by the given reference $I_{gref\,q}$ and the load current i_{LLq} .

With the previous analysis, the control diagram of the inverter can be simplified as Fig. 4 in the grid-tied mode, and the inverter is controlled as a current source by the inductor current loop with the inductor current reference being determined by the current reference *Igref dq* and the load current *iLLdq* . In other words, the inductor current tracks the current reference and the load current.

B. Transition From the Grid-Tied Mode to the Islanded Mode

When the utility switch Su opens, the islanding happens, and the amplitude and frequency of the load voltage will drift due to the active and reactive power mismatch between the DG and the load demand. The transition, shown in Fig. 5, can be divided into two time interval. The first time intervals is from the instant of turning off Su to the instant of turning off Si when islanding is confirmed. The second time interval begins from the instant of turning off inverter switch Si .

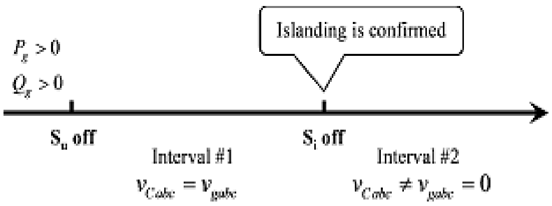


Fig 5. Operation sequence during the transition from the dried tied mode to the islanded mode.

During the first time interval, the utility voltage *vgabc* is still the same with the load voltage *vCabc* as the switch Si is in ON state. As the dynamic of the inductor current loop and the voltage loop is much faster than the PLL [52], while the load voltageand current are varying dramatically, the angle frequency of the load voltage can be considered to be not varied. The dynamic process in this time interval can be described by Fig. 6, and it is illustrated later.

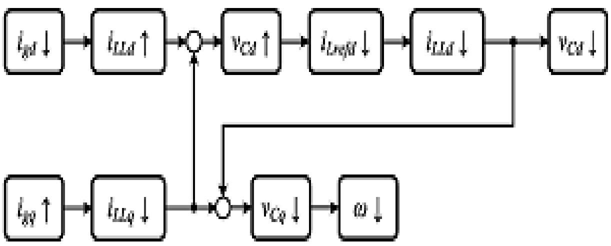


Fig.6. transient process of the voltage and current when the islandin happens.

In the grid-tied mode, it is assumed that the DG injects active and reactive power into the utility, which can be expressed by (8) and (9), and that the local critical load, shown in (10), represented by a series connected *RLC* circuit with the lagging power factor

$$P_g = \frac{3}{2}\cdot(v_{Cd}i_{gd} + v_{Cq}i_{gq}) = \frac{3}{2}v_{Cd}i_{gd} \qquad (8)$$

$$Q_g = \frac{3}{2}\cdot(v_{Cq}i_{gd} - v_{Cd}i_{gq}) = -\frac{3}{2}v_{Cd}i_{gq} \qquad (9)$$

$$\begin{aligned} Z_{sload} &= R_s + j\omega L_s + \frac{1}{j\omega C_s} \\ &= R_s + j\left(\omega L_s - \frac{1}{\omega C_s}\right) \\ &= R_s + jX_s. \end{aligned} \qquad (10)$$

When islanding happens, *igd* will decrease from positive to zero, and *igq* will increase from negative to zero. At the same time, the load current will vary in the opposite direction. The load voltage in *D*- and *Q*-axes is shown by (11) and (12), and each of them consists of two terms. It can be found that theload voltage in *D*-axis *vCd* will increase as both terms increase.However, the trend of the load voltage in*Q*-axis *vCq* is uncertainbecause the first term decreases and the second term increases,and it is not concerned for a while

$$v_{Cd} = i_{LLd}\cdot R_s - i_{LLq}\cdot X_s \qquad (11)$$

$$v_{Cq} = i_{LLq}\cdot R_s + i_{LLd}\cdot X_s. \qquad (12)$$

If it is higher than the lower value of the limiter *ω*min, the PLL can stilloperate normally, and the load voltage in *Q*-axis *vCq* will bezero.Otherwise, if it is fixed at *ω*min, the load voltage in *Q*-axis*vCq* will be negative. As the absolute values of *vCd* and *vCq*,at least the one of *vCd*, are raised, the magnitude of the loadvoltage will increase finally. And the inverter is transferred from the current source operation mode to thevoltage source operation mode autonomously. In the hybridvoltage and current mode control, the time delay ofislanding detection is critical to the drift of the frequency andmagnitude in the load voltage, because the drift is worse withthe increase of the delay time. However, this phenomenon isavoided in the proposed control strategy.

C. Islanded Mode

In the islanded mode, switching Si and Su are both in OFFstate. The PLL cannot track the utility voltage normally, and theangle frequency is fixed. In this situation, theDGis controlled asa voltage source, because voltage compensator *GV D* and *GV Q*can regulate the load voltage *vCdq* . The voltage references in*D*and *Q*-axis are *V*max and zero, respectively. And the magnitudeof the load voltage equals to *V*max approximately, which willbe analyzed in Section IV. Consequently, the control diagram ofthe three-phase inverter in the islanded mode can be simplified as shown in Fig. 7.

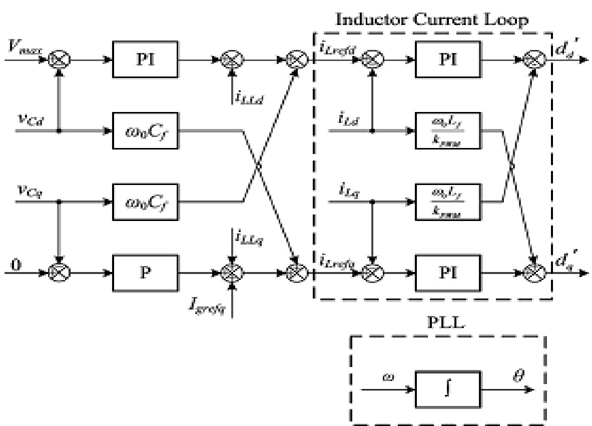


Fig.7.Simplified Block Diagram of the unified control strategy when DG operates in the islanded mode.

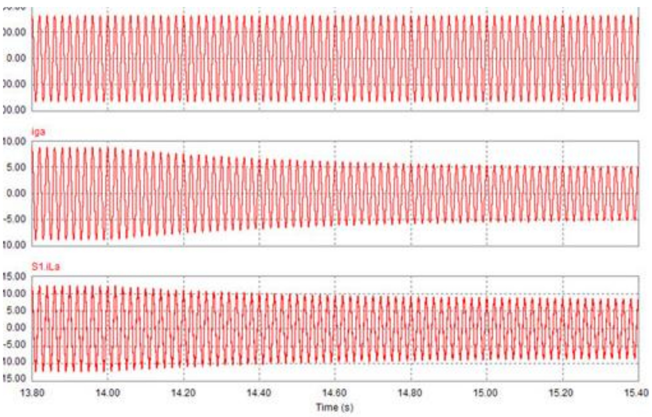
In Fig. 7, the load current *iLLdq* is partial reference of the inductor current loop. So, if there is disturbance in the load current, it will be suppressed quickly by the inductor current loop, and a stiff load voltage can be achieved.

D. Transition From the Islanded Mode to the Grid-Tied Mode

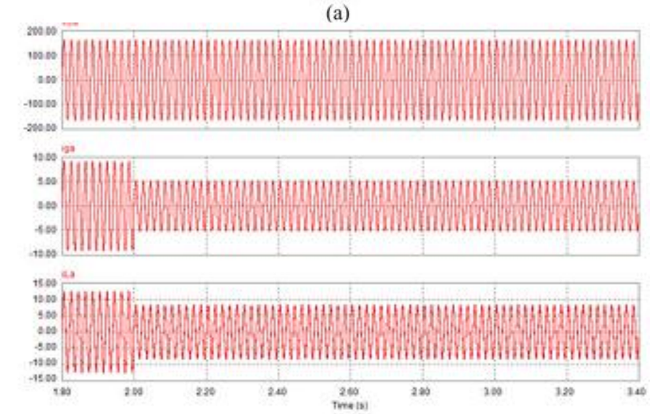
If the utility is restored and the utility switch Su is ON, theDG should be connected with utility by turning on switch Si . As a result, the phase angle of the load voltage *vCabc* will follow the grid voltage *vgabc*. As the voltage reference *Vref* equals *V*max, whichis larger than the magnitude of the utility voltage *Vg*, so the PI compensator *GV D* will saturate, and the limiter outputs its upper value *Igref d*. At the same time, *vCq* is regulated to zeroby the PLL according to (5), so the output of *GV Q* will be zero. Consequently, the voltage regulators *GV D* and *GV Q* areinactivated, and the DG is controlled as a current source just by the inductor current loop.

IV. SIMULATION RESULTS

Fig.14(a) Simulation waveforms of load voltage *vC a* , grid current *iga*, and inductor current *iLa* when DG is in the grid-tied mode under condition of the step down of the grid current reference from 9 A to 5 A with: (a) conventional voltage mode control.

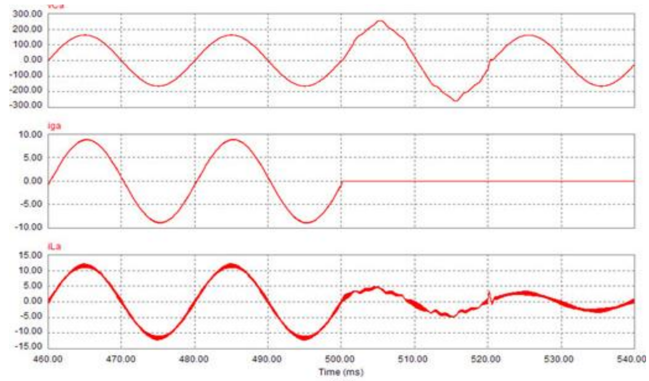


(a)



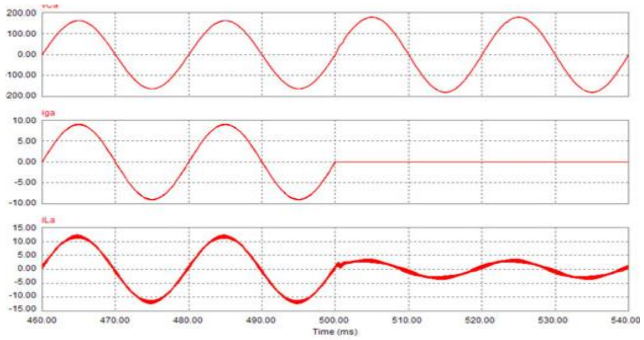
(b)

Fig.14(b) Simulation waveforms of load voltage *vC a* , grid current *iga*, and inductor current *iLa* when DG is in the grid-tied mode under condition of the step down of the grid current reference from 9 A to 5 A with: (b) proposed unified control strategy.



(a)

Fig.15(a). Simulation diagram and waveforms of load voltage *vC a* , grid current *iga*, and inductor current *iLa* when DG is transferred from the grid-tied mode to the islanded mode with: (a) conventional hybrid voltage and current mode control.



(b)

Fig.15(b). Simulation waveforms of load voltage *vC a* , grid current *iga*, and inductor current *iLa* when DG is transferred from the grid-tied mode to the islanded mode with: (b) proposed unified control strategy.

To investigate the feasible of the proposed control strategy, the simulation has been done in PSIM. The power rating of a three-phase inverter is 3kWin the simulation. The parameters in the simulation are shown in Tables I and II. The RMS of the rated phase voltage is 115 V, and the voltage reference *V*max is set as 10% higher than the rated value. The rated utility frequency is 50 Hz, and the upper and the lower values of the limiter in the PLL are given as 0.2 Hz higher and lower than the rated frequency, respectively.

TABLE II
PARAMETERS IN THE CONTROL SYSTEM

Parameters	Value
Voltage reference V_{max}	179 V
Rated current reference I_{grefd}	9 A
Rated current reference I_{grefq}	0 A
Upper value of the limiter ω_{max}	50.2×2π rad/s
Lower value of the limiter ω_{min}	49.8×2π rad/s

In the grid-tied mode, the dynamic performance of the conventional voltage mode control and the proposed unified control strategy is compared by stepping down the grid current reference from 9 A to 5 A. The simulation result of the voltage mode control is shown in Fig. 14(a), and the current reference is changed at the moment of 14 s. It is found that dynamic process lasts until around 15.2 s. In the proposed unified control strategy, the simulation result is represented in Fig. 14(b) and the time interval of the dynamic process is less than 5ms.

By comparing the simulation results above, it can be seen that the dynamic performance of the proposed unified control strategy is better than the conventional voltage mode control. During the transition from the grid-tied mode to the islanded mode, the proposed unified control strategy is compared with the hybrid voltage and current mode control, and the simulation scenario is shown as follows: 1) Initially, the utility is normal, and the DG is connected with the utility; 2) at 0.5 s, islanding happens; and 3) at 0.52 s, the islanding is confirmed.

Simulate results with the hybrid voltage and current mode control is shown in Fig. 15(a). It can be seen that the grid current drop to zero at 0.5 s, and that the load voltage is seriously distorted from 0.5 to 0.52 s. Then, the load voltage is recovered to the normal value after 0.52 s. Fig. 15(b) presents the simulate results with the proposed unified control strategy. Initially, the magnitude of grid current is 9 A and follows the current reference *Igref dq* . The magnitude and frequency of the load voltage are held by the utility. After the islanding happens, the amplitude of the load voltage increases a little to follow the voltage reference *V*max, and the output current of DG decreases autonomously to match the load power demand.

V. CONCLUSION

A unified control strategy was proposed for three-phase inverter in DG to operate in both islanded and grid-tied modes, with no need for switching between two different control architectures or critical islanding detection. A novel voltage controller was presented in this paper. It is inactivated in the grid-tied mode, and the DG operates as a current source with fast dynamic performance. Upon the utility outage, the voltage controller can automatically be activated to regulate the load voltage

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