A Unified Control Strategy for Three-Phase Inverter in Distributed Generation

K. Narsaiah, T. Srinivas

Abstract—This project presents a unified control strategy that enables both islanded and grid-tied operations of three-phase inverter in distributed generation, with no need for switching between two corresponding controllers or critical islanding detection. The proposed control strategy composes of an inner inductor current loop, and a novel voltage loop in the synchronous reference frame. The inverter is regulated as a current source just by the inner inductor current loop in grid-tied operation, and the voltage controller is automatically activated to regulate the load voltage upon the occurrence of islanding. Furthermore, the waveforms of the grid current in the grid-tied mode and the load voltage in the islanding mode are distorted under nonlinear local load with the conventional strategy. Finally, the effectiveness of the proposed control strategy is validated by the simulation and experimental results.

Index Terms—Distributed generation (DG), islanding mode, load current, seamless transfer, three-phase inverter, unified control strategy.

I. INTRODUCTION

Distributed generation (DG) is emerging as a viable alternative when renewable or nonconventional energy resources are available, such as wind turbines, photovoltaic arrays, fuel cells, micro turbines. Most of these resources are connected to the utility through power electronic interfacing converters, i.e., three-phase inverter. Moreover, 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. Under this circumstance, the DG must be tripped and cease to energize the portion of utility as soon as possible. However, in order to improve the power reliability of some local critical 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. Therefore, upon the happening of islanding, DG must take over the load voltage as soon as possible, in order to reduce the transient in the load voltage. And this issue brings a challenge for the operation of DG. 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. However, the limitation of this approach is that the dynamic performance is poor, because the bandwidth of the external power loop, realizing droop control, is much lower than the voltage loop. 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. The inverter is controlled as a current source by one sets of a controller in the grid-tied mode, while as a voltage source by the other sets of controller in the islanded mode. As the voltage loop or current loop is just utilized in this approach, a nice dynamic performance can be achieved. Besides, the output current is directly controlled in the grid-tied mode, and the inrush grid current is almost eliminated. In the hybrid voltage and current mode control, there is a need to switch the controller when the operation mode of DG is changed. During the interval from the occurrence of utility outage and switching the controller to voltage mode, the load voltage is neither fixed by the utility, nor regulated by the DG, and the length of the time interval is determined by the islanding detection process. Therefore, the main issue in this approach is that it makes the quality of the load voltage heavily reliant on the speed and accuracy of the islanding detection method. When the nonlinear local load is fed, the harmonic component of the load current will fully flow into the utility. A single-phase DG, which injects harmonic current into the utility for mitigating the harmonic component of the grid current, the voltage mode control is enhanced by controlling the DG to emulate a resistance at the harmonic frequency, and then the harmonic current flowing into utility can be mitigated. In the islanded mode, the nonlinear load may distort the load voltage, many control schemes have been proposed to improve the quality of the load voltage, including a multiloop control method, resonant controllers, sliding mode control. However, existing control strategies, dealing with the nonlinear local load in DG, mainly focus on either the quality of the grid current in the grid-tied mode or the one of the load voltage in the islanded mode, and improving both of them by a unified control strategy is seldom. Third, the proposed control strategy is enhanced by introducing a unified load current feedforward, in order to deal with the issue caused by the nonlinear local load; this scheme is implemented by adding the load current into the reference of the inner current loop. In the grid-tied mode, the DG injects harmonic current into the grid for compensating the harmonic component of the grid current, and thus, the harmonic component of the grid current will be mitigated. Moreover, the benefit of the proposed load current feedforward can be extended into the islanded operation mode, due to the improved quality of the load voltage.

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II. PROPOSED CONTROL STRATEGY

A. Power Stage

This paper presents a unified control strategy for a threephase 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 Fig. 1. 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. In the ac side of inverter, the local critical load is connected directly.

The inverter transfer switch S_i is controlled by the DG, the utility protection switch S_u is governed by the utility. When the utility is normal, both switches S_i and S_u are ON, and the DG in the grid-tied mode injects power to the utility. When the utility is in fault, the switch S_u 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 S_i is disconnected, and the DG is transferred from the grid-tiedmode to the islanded mode. When the utility is restored, the DG should be resynchronized with the utility first, and then the switch S_i is turned ON to connect the DG with the grid.

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 P_g + jQ_g and the load demand P_{load} +jQ_{load}, which can be expressed as follows by assuming that the load is represented as a parallel *RLC* circuit:

$$P_{load} = (3/2)\cdot(V_m^2/R) \quad (1)$$

$$Q_{load} = (3/2)\cdot V_m^2(1/\omega L - \omega C) \quad (2)$$

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 instant 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. And this phenomenon can be explained as below by the power relationship. During this time interval, the inverter is still controlled as a current source, and its output power is kept almost unchanged. However, the power injected to utility decreases to zero rapidly, and then the power consumed by the load will be imposed to the output power of DG. If both active power P_g and reactive power Q_g injected into the grid are positive in the grid-tiedmode, 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).

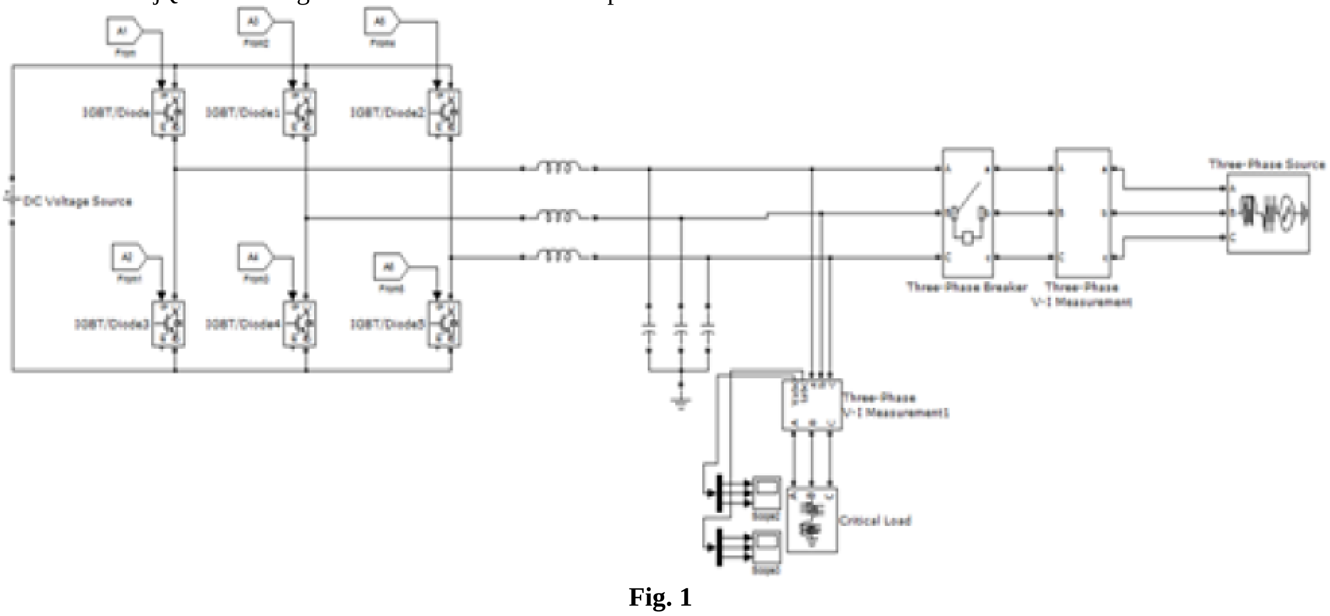

Fig. 1

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, 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, a PI compensator, a limiter, and an integrator. 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 G_I .

The reference of the inductor current loop $i_{Lref\,dq}$ seems complex and it is explained as below.

It is assumed that the utility is stiff, and the three-phase utility voltage. By the Park transformation, the utility voltage is transformed into the SRF, which is shown as

$$v_{gd} = V_g \cos(\theta_* - \theta)$$

$$v_{gq}=V_g\sin(\theta_* - \theta) \tag{5}$$

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.

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

When the utility switch S_u 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 can be divided into two time interval. The first time interval is from the instant of turning off S_u to the instant of turning off S_i when islanding is confirmed. The second time interval begins from the instant of turning off inverter switch S_i. When the islanding happens, the local load must absorb the extra power injected to the grid, as the output power of inverter is not changed instantaneously. According to (1), the magnitude of the load voltage V_m will rise with the increase of P_{load}. At the same time, the angle frequency ω should drop, in order to consume more reactive power with (2). Therefore, the result through the power relationship coincides with the previous analysis.

The second time interval of the transition begins from the instant when the switch S_i is open after the islanding has been confirmed by the islanding detection method. If the switch S_i opens, the load voltage v_{Cabc} is independent with the grid voltage v_{gabc} . At the same time, v_{gabc} will reduce to zero theoretically as the switch S_u has opened. Then, the input of the compensator G_{PLL} becomes zero and the angle frequency is invariable and fixed to the value at the end of the first interval. Under this circumstance, v_{Cdq} is regulated by the voltage loop, and the inverter is controlled to be a voltage source. With the previous analysis, it can be concluded that the drift of the amplitude and frequency in the load voltage is restricted in the given range when islanding happens. And the inverter is transferred from the current source operation mode to the voltage source operation mode autonomously. In the hybrid voltage and current mode control, the time delay of islanding detection is critical to the drift of the frequency and magnitude in the load voltage, because the drift is worse with the increase of the delay time. However, this phenomenon is avoided in the proposed control strategy.

C. Islanded Mode

In the islanded mode, switching S_i and S_u are both in OFF state. The PLL cannot track the utility voltage normally, and the angle frequency is fixed. In this situation, the DG is controlled as a voltage source, because voltage compensator G_{VD} and G_{VQ} can regulate the load voltage v_{Cdq} . The voltage references in$D$and Q-axis are V_{max} and zero, respectively. And the magnitude of the load voltage equals to V_{max} approximately, which will be analyzed in Section IV. Consequently, the control diagram of the three-phase inverter in the islanded mode can be simplified. the load current i_{LLdq} 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 S_u is ON, the DG should be connected with utility by turning on switch S_i . However, several preparation steps should be performed before turning on switch S_i. First, as soon as utility voltage is restored, the PLL will track the phase of the utility voltage. As a result, the phase angle of the load voltage v_{Cabc} will follow the grid voltage v_{gabc}. If the load voltage v_{Cabc} is in phase with the utility voltage, v_{gd} will equal the magnitude of the utility voltage the magnitude of the load voltage V_{max} is larger than the utility voltage magnitude V_g , the voltage reference V_{ref} will be changed to V_g by toggling the selector S from terminals 1 to 2. As a result, the load voltage will equal to the utility voltage in both phase and magnitude.

IV. ANALYSIS AND DESIGN

In this section, the three-phase inverter with the proposed control strategy is analyzed and designed in both steady state and transient state. In the steady state, the operation points of DG in both grid-tied and islanded modes are analyzed, and the limiters and references are selected. In the transient state, compensators in both inductor current loop and the external voltage loop are designed based on the small-signal model, and the impact of the load current feed forward is analyzed as well.

2) Selection of References and Limiters: In the grid-tied mode, the active power injected into the grid P_g is given by the current reference $I_{gref\,d}$, and it is the upper value of the limiter in D-axis. Therefore, the selection of $I_{gref\,d}$ depends on the power rating of the inverter. As a result, the reactive power Q_g cannot be very large, in order to make the magnitude of the load voltage within the normal range in the islanded mode.

In the grid-tied mode, V_{max} should be larger than the magnitude of the utility voltage V_g . At the same time, the load In order to guarantee that the PLL operates normally in the grid-tied mode, the utility angle frequency ω should not touch the upper value ω_{max} or lower value ω_{min} of the limier in the PLL. Besides, the angle frequency ω is restricted between ω_{max} and ω_{min} in the islanded mode, and it should not drift from the normal value too far. So, ω_{max} and ω_{min} are selected as the maximum and minimum angle frequencies allowed by the utility standard.

B. Transient State

1) Small-Signal Model of the Power Stage: Before the compensators in the voltage and current loops are designed and the transient performance is analyzed, the three-phase inverter in the DG needs to be modeled. According to the power stage 1, the dc-link voltage V_{dc} is regulated by the front-end converter in DG. Then, it is assumed that the dc voltage V_{dc} is very stiff, and its dynamic is not concerned in this paper. Then, it can be found that there are couplings introduced by the inductor L_f and capacitors C_f between D and Q-axes.

2) Design and Analysis of the Current Loop: The inductor current loop should operate normally to regulate the inductor current loop in both islanded and grid-tied modes. In the islanded
mode, the small-signal model of the control-to-current can be obtained according to (28), which is shown as

$$G_{id1}(s) = \frac{\hat{I}_L(s)}{\hat{d}(s)} = \frac{V_{dc}}{2} \cdot \frac{sC}{s^2 L_f C_f + sR_l C_f + 1}. \quad (29)$$

in the grid-tied mode, the dynamic of the capacitor C_f is ignored due to the stiff utility, and the small-signal model of the control-to-current.

3) Design and Analysis of the Voltage Loop: The voltage loop just operates in the islanded mode to regulate the load voltage, and the simplified block diagram, where G_{ic} (s) and G_{vi}(s) denote the closed-loop transfer function of an inductor loop and the impedance of the filter capacitor C_f, respectively.

4) Impact of Load Current Feed forward: In, the load current $\hat{i}_{LL}$ is a part of the inductor current reference, and the disturbance from the load current can be suppressed by the inductor current loop directly. To evaluate the effect of the load current feedforward in the islanded mode, the transfer function of the output impedance is derived. it can be found that an extra factor $[1 - G_{ic}(s)]$ appears in the output impedance with load current feed forward, and the magnitude of the output impedance will be reduced in the low frequency range because the gain of the closed-loop transfer function G_{ic} (s) closes to unity in the bandwidth of the current loop. The Bode plot of the output impedance of these two conditions, and it can be seen that the magnitude of the output impedance is reduced from dc to 600 Hz with the load current feedforward. Consequently, the quality of the load voltage v_{Cabc} will be improved with the load current feedforward. In the grid-tied mode, the inductor current is regulated by the inductor current loop directly, and the inductor current reference is mainly composed by the current reference $I_{gref\,dq}$, and the load current i_{LLdq}. If the load current is not fed forward, the output current i_{odq} of the inverter will be fixed by $I_{gref\,dq}$. As a result, the disturbance of the load current will be fully injected into the utility, with the load current feedforward, the disturbance of the load current can be compensated by the inverter, and the transfer function from the load current to the grid current.

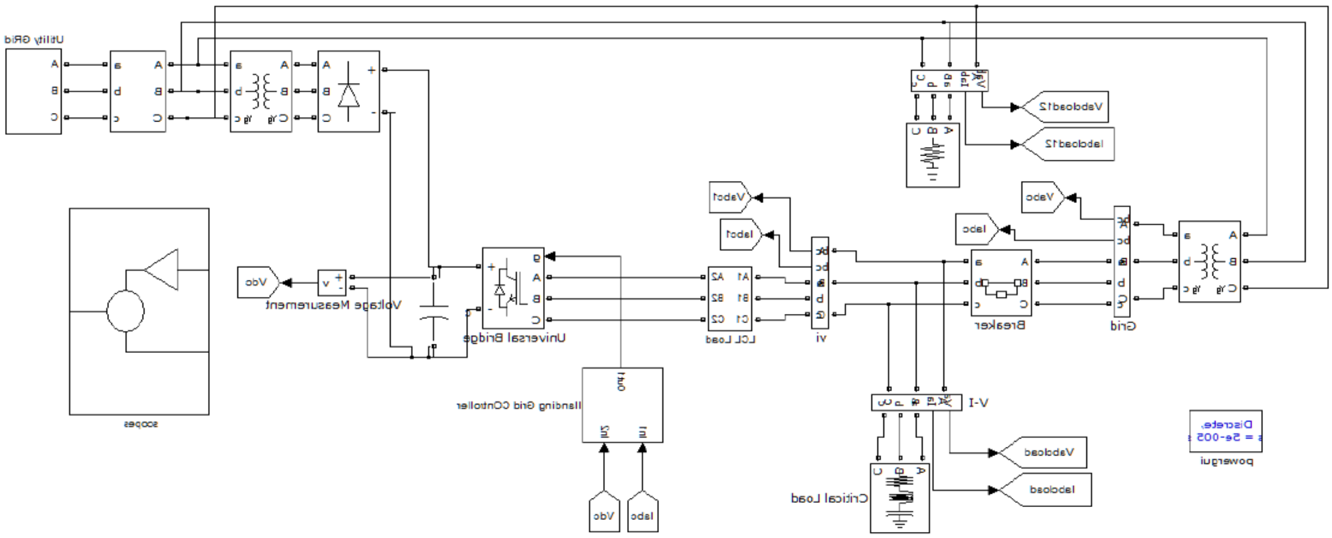

Fig. 2

V. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulation Results

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. TheRMS of the rated phase voltage are 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. 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.2, and the current reference is changed at the moment of 14 s. It is found that dynamic process lasts until around and the time interval of the dynamic process is less than 5 ms. 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.

Fig. 3, presents the simulate results with the proposed unified control strategy. Initially, the magnitude of grid current is 9 A and follows the current reference $I_{gref\,dq}$. 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. Comparing the simulation results above,

it can be found that the voltage quality is improved deeply by the proposed control strategy in the transition from the grid-tied mode to the islanded mode, and the speed of the islanding detection is no more critical.
Then, the magnitude of the load voltage is regulated to equal the utility voltage. At the moment of 350 ms, the switch S_i is turned on, and the current injected into the grid i_{ga} increases smoothly without huge inrush current, and the load voltage is stable during the transition.

When DG feeds nonlinear load in the grid-tied mode, It can be seen that with the load current feed forward, there is harmonic component in the inductor current i_{La}, and the harmonics component in the grid current is reduced. The THD of the grid current under different power of the nonlinear load and different amplitude of the grid fundamental current is investigated. It can be found that with the increase of the load power, the THD of the grid current rises, and the THD of the grid current is reduced with the load current feed forward. In the power of the nonlinear load is set at around 600 W and the amplitude of the grid fundamental current is changed. It can
be seen that the THD of the grid current can be mitigated at different magnitude of the grid fundamental current.

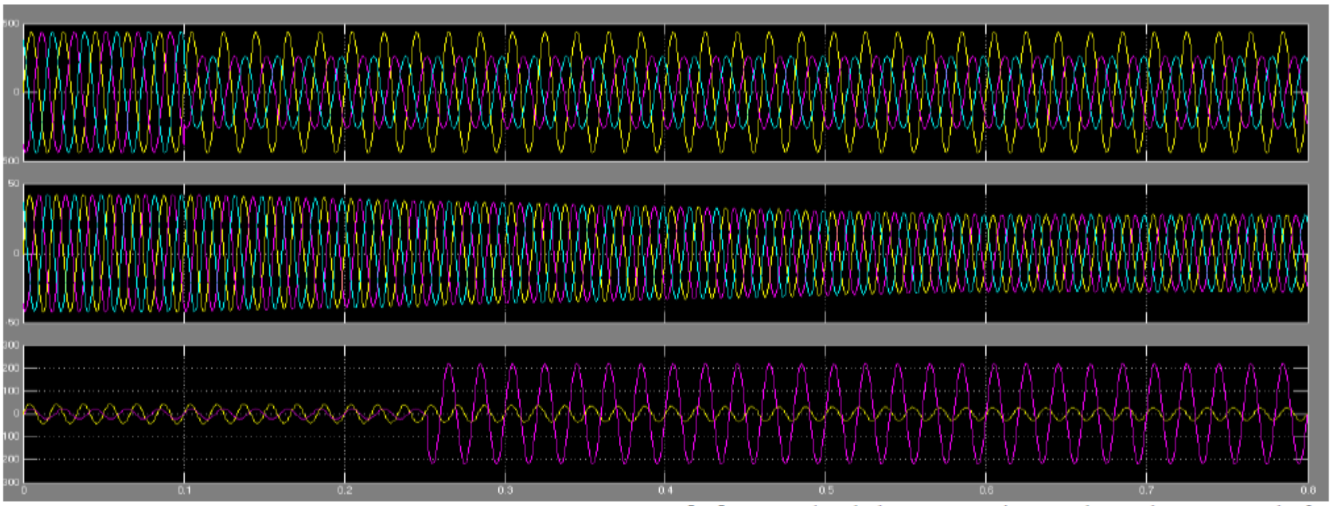

Fig. 3

VI. 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. 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. Moreover, a novel load current feedforward was proposed, and it can improve the waveform quality of both the grid current in the grid-tied mode and the load voltage in the islanded mode. The proposed unified control strategy was verified by the simulation and experimental results.

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