Investigation on Integrated Control Strategies for Grid-tied Inverters under Unbalanced Grid Voltage

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***Abstract*—This paper investigates integrated control strategies for a three-phase grid connected inverter especially under unbalanced grid conditions. The PWM controlled three-phase voltage sourced inverters (VSI) are widely used in renewable energy based power generation systems for performing various advanced energy management and power flow control functions, e.g., power smoothing control of wind and solar power generation systems as well as fast charging and discharging control of battery energy storage systems (BESS). Voltage unbalance in a three-phase power system causes severe performance degradation of a grid connected VSI with conventional control methods in which unbalanced output currents and the 120-Hz ripples in the controlled real and reactive powers appear. To achieve a better efficiency, power quality and enhanced functional performance, some potential control algorithms have been presented in the open literature. In this paper, the reported control methods are firstly reviewed and an integrated approach for handling the current commands is then proposed. The detailed mathematical investigations on the proposed control methods are carried out along with a set of comprehensive computer simulation studies. Typical simulation results are presented to demonstrate the effectiveness and possible limits of the proposed control algorithm under various VSI operating modes.**

***Index Terms*—voltage sourced inverter, renewable energy, battery energy storage systems, distributed power generation**

I. INTRODUCTION

IN recent years, the application of renewable energy based power generations (REBPG), e.g., photovoltaic (PV) power and wind turbine generators (WTG) is extremely extensive and more and more MW-level REBPG based power stations, acting as conventional power plants, are connected directly to the distribution and transmission networks. As the power level and grid penetration of the REBPG increase steadily, the control algorithms and operating schemes of the REBPG start to have significant impacts on the stability and power quality of the power network. Therefore, high-performance power converter systems, compensators and advanced control schemes have to be developed to improve the overall characteristics of the technologies regarding power quality issues, the effective and smooth control of power flow of three-phase inverters in REBPG under unbalanced grid voltages is very important for the secure grid-connected operations of the state-of-the-art distribution systems embedding multiple REBPG units and BESS, or so called active power distribution systems (APDS). In theory, the real-time calculation of the current references is a key technology deciding the overall power flow control results of VSI under unbalanced grid voltage. In the literature, a number of approaches of finding current references for the inverter according to different objectives have been presented. In [1], the elimination of harmonics in the DC output voltage is the main control objective. Positive and negative sequence controllers and power-balanced principle are used in the proposed control strategy. Moreover, feed-forward and decoupled PI controllers, phase lock loop (PLL), and notch filters are utilized to achieve good performance. In [2], a smooth output-power-control method is proposed, aiming at achieving a stable instantaneous power regulation. Near unity power factor and easy implementation are achieved. Experimental results obtained from an 1kW laboratory prototype show the feasibility of the proposed method. In [3], an effective three-phase PLL system is designed and verified. Three other controllers are also proposed to improve the system performance under unbalanced grid conditions, including a PI, a PID, and a novel factional PI. In [4], PI-controlled positive and negative sequence currents in their respective synchronous reference frames (SRFs) are used to eliminate voltage unbalance. Additional hardware for the second SRF isn't required because the controller is completely implemented with software. In [5], a PWM rectifier is modeled and analyzed, aiming at stabilizing the controlled power network. Positive and negative sequence signals are separated with Clarke transformation techniques, and a line current compensation loop helps achieving good stabilizing performance. In [6], a two-vector-oriented control strategy is proposed to eliminate undesired power fluctuations. Current references under positive and negative d-q axis are obtained with real-time measured voltage, current and power signals. In [7], a wind energy conversion system (WECS) is modeled and analyzed under grid disturbances with MATLAB/SPS. Maximum power extraction and better ride through capability are demonstrated. In [8], a control system for wind power generation is proposed with a grid-connected permanent magnet synchronous generator (PMSG). A number of PI controllers, an active power controller, a DC link voltage

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controller, and two PLL based observers are utilized. A good ride through capability under single- two-, and three-phase voltage sags is achieved. In [9], a strategic reference current vector expression and a control method are proposed. The method controls positive and negative sequences parameters for achieving a stable power flow. Effective voltage adjusting results are shown in the simulation cases. In [10], an ADALINE neural network and an RBF neural network are utilized to control grid-connected inverter. Simulation and experimental results show effectiveness and feasibility of the proposed strategy. More design examples related to the control issues investigated in this paper can be referred in [11-16].

In this paper, an integrated control scheme based on the derivation of control parameters in stationary reference frame is proposed for obtaining current commands of the grid-tied three-phase VSI. The proposed control scheme is able to simultaneously perform all control tasks or the selective ones, such as perfect control of the real and reactive powers in normal grid conditions, cancellation of real and reactive power oscillations, regulation of sinusoidal and balanced inverter currents under a variety of unbalanced grid voltages. The arrangement of sections in this paper is as follows. In section II, the main topology of the grid-tied inverter is briefly addressed and the mathematical model is derived. The two-axis controllers for the real and reactive power regulations are also derived in this section. The proposed integrated control scheme and the calculation of control signals are presented in section III. In section IV, a set of control cases is stated and typical results obtained from simulation studies are presented with brief discussions. Section V gives a short summary on the concerned technical issues and the overall performance of the proposed control scheme.

II. THE MATHEMATICAL MODELING OF A GRID-TIED INVERTER

The mathematical model of a grid-tied three-phase inverter can be derived simply based on the Kirchhoff's voltage and current laws. Based on the three-phase voltage and current equations derived from the inverter system shown in Fig. 1, one can have the following set of equations.

$$\begin{aligned} V_{nN} - V_{NA} - L_s \frac{dI_{s,a}}{dt} - V_{an} &= 0 \\ V_{nN} - V_{NB} - L_s \frac{dI_{s,b}}{dt} - V_{bn} &= 0 \\ V_{nN} - V_{NC} - L_s \frac{dI_{s,c}}{dt} - V_{cn} &= 0 \end{aligned} \tag{1}$$

In the case of a balanced three-phase system, the following equations describing the inverter's parameters are valid.

$$I_{s,a} + I_{s,b} + I_{s,c} = 0 \tag{2}$$

$$V_{nN} = \frac{(V_{NA} + V_{NB} + V_{NC}) + (V_{an} + V_{bn} + V_{cn})}{3} \tag{3}$$

$$-\frac{V_{dc}}{2V_{tri}} V_{con,ABC} = -K_{pwm} V_{con,ABC} \tag{4}$$

$$\begin{bmatrix} V_{NA} \\ V_{NB} \\ V_{NC} \end{bmatrix} = \frac{-V_{dc}}{2} \begin{bmatrix} 1 + \dfrac{V_{conA}}{V_{tri}} \\ 1 + \dfrac{V_{conB}}{V_{tri}} \\ 1 + \dfrac{V_{conC}}{V_{tri}} \end{bmatrix} \tag{5}$$

$$K_{pwm} A V_{con,ABC} - L_s \frac{d}{dt} I_{s,abc} - A V_{abc,n} = 0 \tag{6}$$

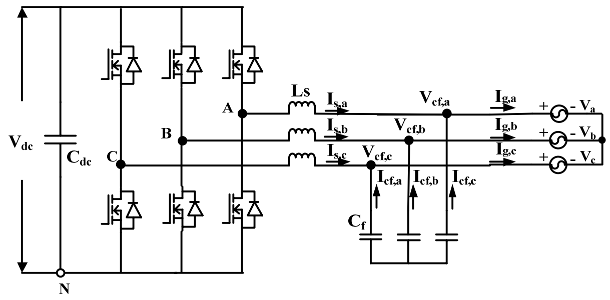


Fig. 1 The schematic of a grid connected three-phase inverter system.

In Fig. 1, L_s it is the filter inductor of the inverter, C_f is the filter capacitor of the inverter, C_{dc} it is the DC capacitor; V_a 、V_b 、V_c are respectively the three-phase voltages, $I_{g,a}$ 、$I_{g,b}$ 、$I_{g,c}$ are the grid side currents, and $V_{cf,a}$ 、$V_{cf,b}$ 、$V_{cf,c}$ are the terminal voltages of the filter capacitors. With some mathematical manipulations, the equations, (1) to (6) can be rewritten as follows.

$$K_{pwm} V_{con,\alpha} - L_s \frac{d}{dt} I_{s,\alpha} - V_\alpha = 0 \tag{7}$$

$$K_{pwm} V_{con,\beta} - L_s \frac{d}{dt} I_{s,\beta} - V_\beta = 0 \tag{8}$$

Using the above equations, the inner-loop current feedback controller can be designed with a feed forward control path. The feedback control loop is used to adjust the direction and magnitude of the output currents of the inverter. The feed forward control signal using the sensed AC voltage multiplied by the gain of PWM is utilized to cancel the disturbance of voltage on the current loop. After some arrangement in parameters, the complete set of two-axis control block diagrams can be constructed as shown in Fig. 2.

III. THE PROPOSED CONTROL SCHEMES

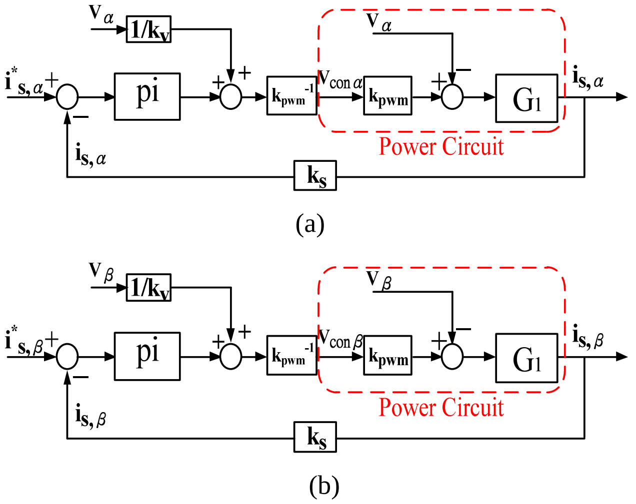
In the case of a unbalanced three-phase voltage, the positive and negative sequences decomposition techniques can be used and the unbalanced voltages are decomposed into two sets of corresponding positive and negative balance voltages. The previous derived equations can then be rearranged in SRF using positive and negative sequence components of the system voltages and currents along with a set of given real and reactive power commands as follows.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = [T_{dq}^{+}]^{-1}\begin{bmatrix} v_d^{+} \\ v_q^{+} \end{bmatrix} + [T_{dq}^{-}]^{-1}\begin{bmatrix} v_d^{-} \\ v_q^{-} \end{bmatrix}$$
$$= \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix}\begin{bmatrix} v_d^{+} \\ v_q^{+} \end{bmatrix} + \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix}\begin{bmatrix} v_d^{-} \\ v_q^{-} \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = [T_{dq}^{+}]^{-1}\begin{bmatrix} i_d^{+} \\ i_q^{+} \end{bmatrix} + [T_{dq}^{-}]^{-1}\begin{bmatrix} i_d^{-} \\ i_q^{-} \end{bmatrix}$$
$$= \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix}\begin{bmatrix} i_d^{+} \\ i_q^{+} \end{bmatrix} + \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix}\begin{bmatrix} i_d^{-} \\ i_q^{-} \end{bmatrix} \quad (10)$$

$$P(t) = \frac{3}{2}(v_\alpha i_\alpha + v_\beta i_\beta)$$
$$Q(t) = \frac{3}{2}(v_\alpha i_\beta - v_\beta i_\alpha) \quad (11)$$

$$\begin{bmatrix} i_\beta^{+*} \\ i_\alpha^{+*} \\ i_\beta^{-*} \\ i_\alpha^{-*} \end{bmatrix} = \frac{2P_o}{3\{(V_\beta^{+})^2 + (V_\alpha^{+})^2 - k[(V_\beta^{-})^2 + (V_\alpha^{-})^2]\}} \times \begin{bmatrix} V_\beta^{+} \\ V_\alpha^{+} \\ -kV_\beta^{-} \\ -kV_\alpha^{-} \end{bmatrix}$$
$$+ \frac{2Q_o}{3\{(V_\beta^{+})^2 + (V_\alpha^{+})^2 + k[(V_\beta^{-})^2 + (V_\alpha^{-})^2]\}} \times \begin{bmatrix} V_\alpha^{+} \\ -V_\beta^{+} \\ kV_\alpha^{-} \\ -kV_\beta^{-} \end{bmatrix} \quad (12)$$



(a)

(b)

Fig. 2 The complete set of two-axis control block diagrams; (a) alfa-axis current controller, (b) beta-axis current controller.

As can be seen in (12), by giving k = 1, the set of four current control signals for the ripple cancellation of real power is calculated. When k = -1, another set of current control signals for the ripple cancellation of reactive power is obtained. When k = 0, the set of current control signals is for obtaining the balanced inverter's output currents. In this paper, the conventional PI controllers are used for demonstrating purposes. Fig. 3 and 4 show two types of implementations of the proposed integrated P-Q control schemes under unbalanced three-phase grid voltages. As can be seen in the figures, less current controllers are required in the first control scheme which is used in the simulation studies and analyses carried out in this study.

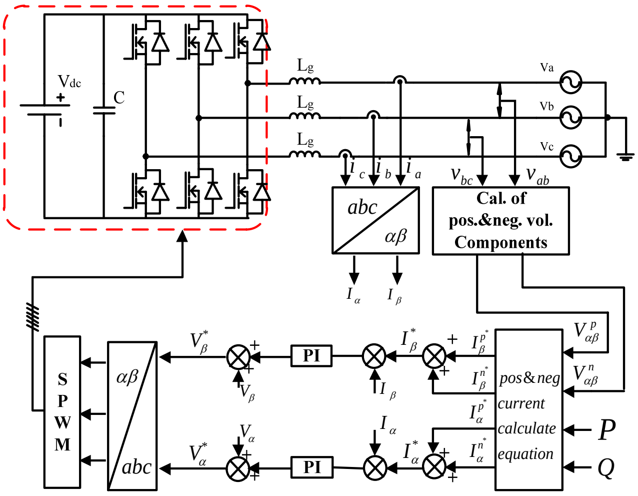


Fig. 3 the proposed P-Q control scheme under unbalanced three-phase grid voltages (PI*2).

IV. The Simulation Studies and Results

In this section, the proposed integrated control scheme based on the derivation of control parameters in stationary reference frame is verified with simulations on the PowerSIM (PSIM) software The test system parameters are arranged as follows: The three-phase AC grid has a line to line voltage of 110V, the rated voltage of DC Bus is 200V. The power rating of the inverter is 1kVA. The final PSIM model for simulation studies is shown in Fig. 5.

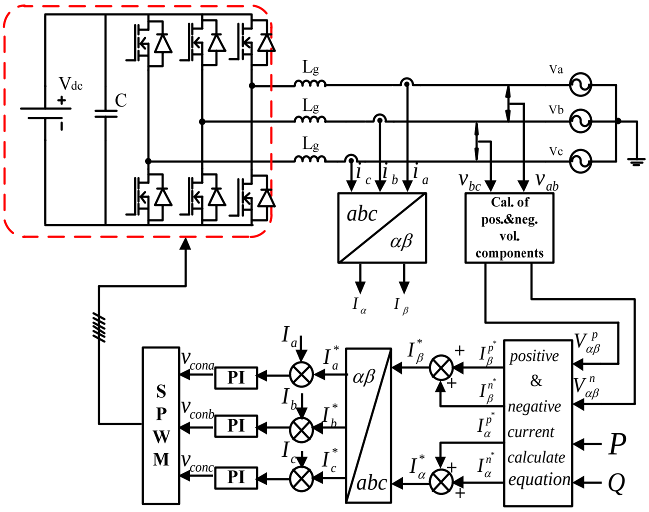


Fig. 4 the proposed P-Q control scheme under unbalanced three-phase grid voltages (PI*3).

A. Simulation Scenarios and Results

In this simulation case, the grid-tied inverter shown in Fig. 3 is acting as a power interface of a certain BESS system and the battery bank is modeled with a DC source with the nominal voltage of 200V. In practice, there are a number of control functions designed for the power interface of this kind of BESS, e.g. charging and discharging functions, voltage supporting for the grid and the reactive power compensation for the load or the power network. For simplicity only the control function of load reactive power compensation is investigated in this section. To verify the effectiveness of the proposed control scheme four control modes are tested, i.e., the cancellation of real and reactive power oscillations including simultaneously and individually, the regulation of sinusoidal and balanced inverter's output currents under a variety of unbalanced grid voltages. In this simulation study, the voltage conditions of the grid voltage are set as: two-phase voltage dip for 0.5p.u. The total simulation time is arranged for 5 seconds. Fig. 6 (a) to (f) show the simulation results of the arranged voltage sag scenario. Fig. 7 (a) to (f) show the detailed system parameters under different control modes in this simulation scenario.

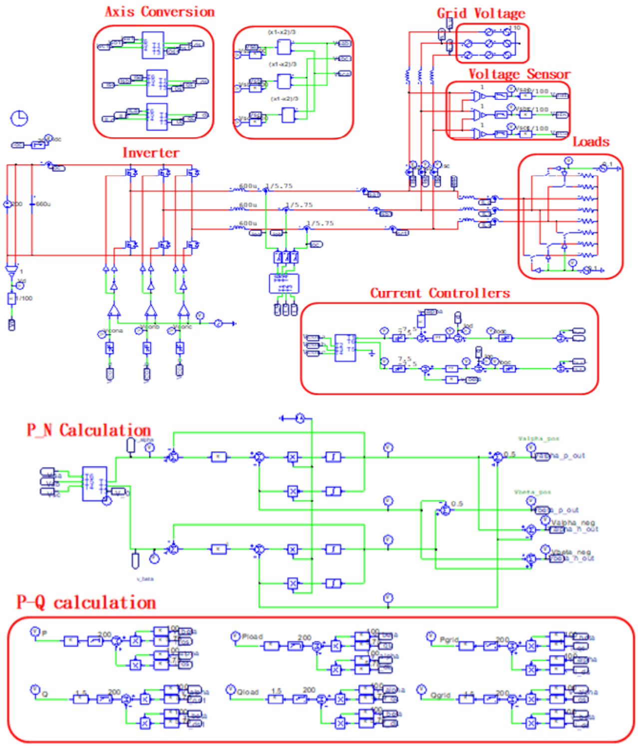


Fig. 5 The PSIM model of the grid-tied inverter for simulation studies.

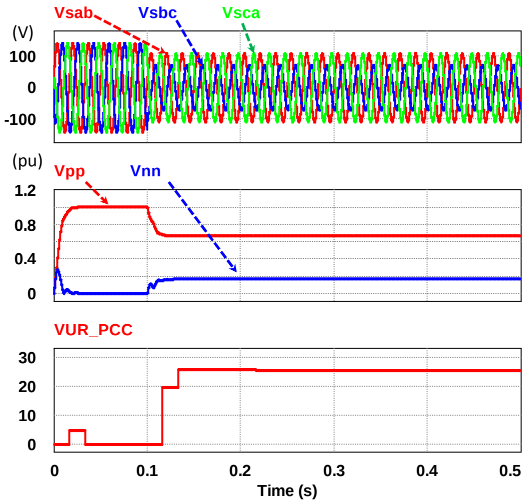


Fig. 6 (a) The simulation results of grid voltages, the positive and negative sequence voltages and the voltage unbalance ratio of the system.

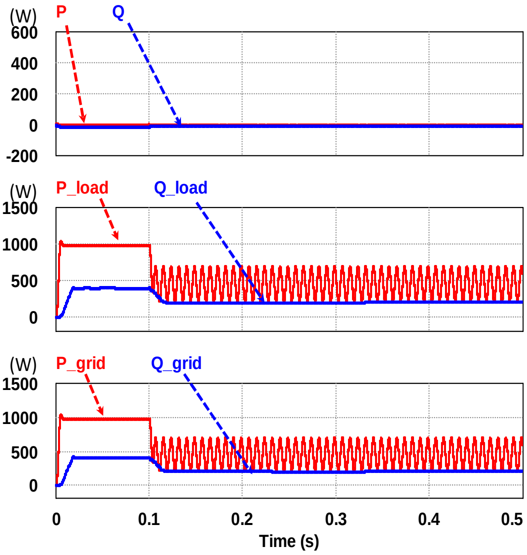


Fig. 6 (b) The simulation results of the inverter's output, P-Q(0W, 0Var), the load power, P-Q, the P-Q power flow from the grid.

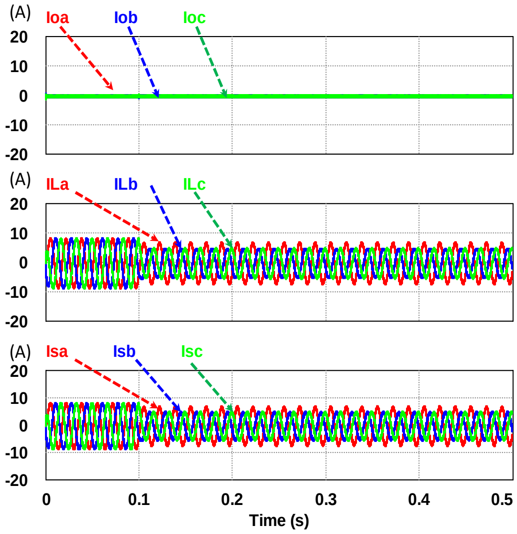


Fig. 6 (c) The simulation results of the corresponding three-phase currents of the inverter, load and the grid.

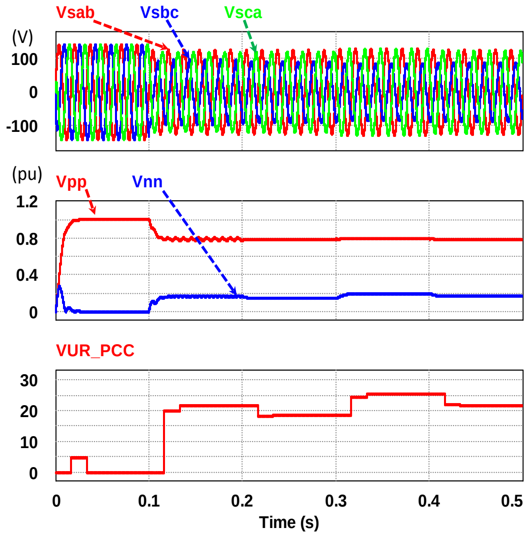


Fig. 6 (d) The simulation results of grid voltages, the positive and negative sequence voltages and the voltage unbalance ratio of the system after a reactive power of 1000Vars output from the inverter.

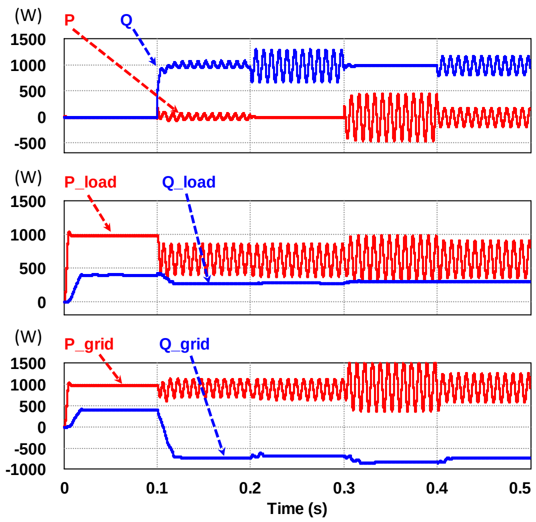


Fig. 6 (e) The simulation results of the inverter's output power, P-Q (0W, 1000Vars), the load power, P-Q and the P-Q power flow from the grid.

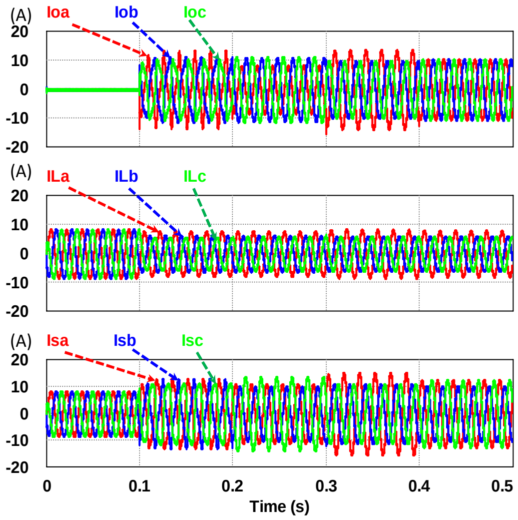


Fig. 6 (f) The simulation results of the corresponding three-phase currents of the inverter, load and the grid.

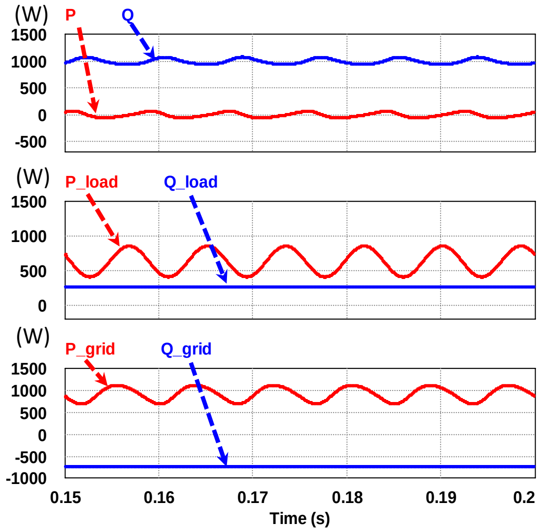


Fig. 7 (a) The detailed simulation results of the inverter's output, P-Q (0W, 1000Vars), the load power, P-Q and the P-Q power flow from the grid, during the simulation time of 0.15s~0.2s.

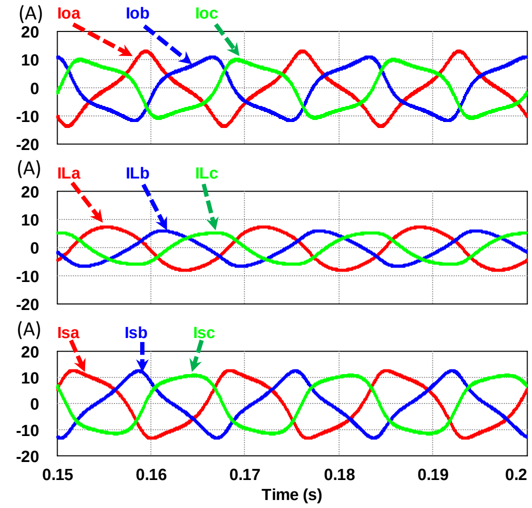


Fig. 7 (b) The detailed simulation results of the corresponding three-phase currents of the inverter, load and the grid during the simulation time of 0.15s~0.2s.

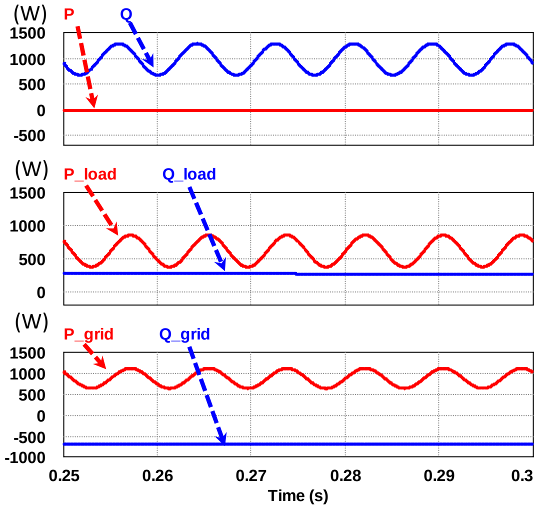


Fig. 7 (c) The detailed simulation results of the inverter's output, P-Q (0W, 1000Vars), the load power, P-Q and the P-Q power flow from the grid, during the simulation time of 0.25s~0.3s.

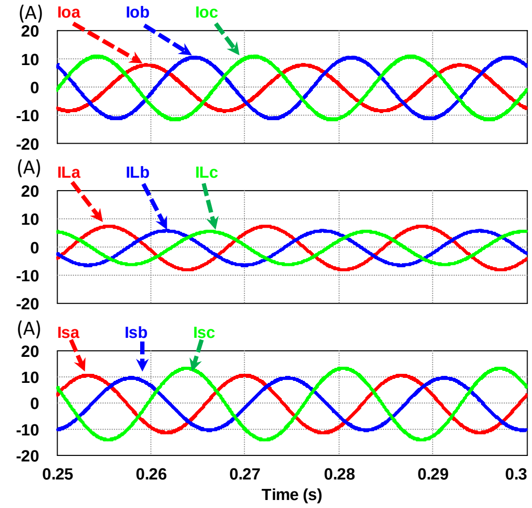


Fig. 7(d) The detailed simulation results of the corresponding three-phase currents of the inverter, load and the grid during the simulation time of 0.25s~0.3s.

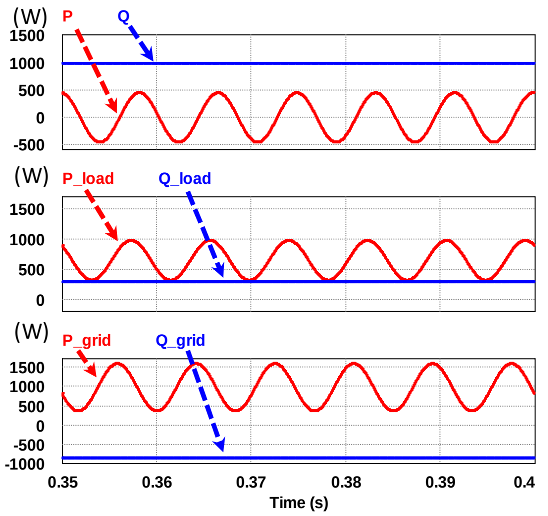


Fig. 7 (e) The detailed simulation results of the inverter's output, P-Q (0W, 1000Vars), the load power, P-Q and the P-Q power flow from the grid, during the simulation time of 0.35s~0.4s.

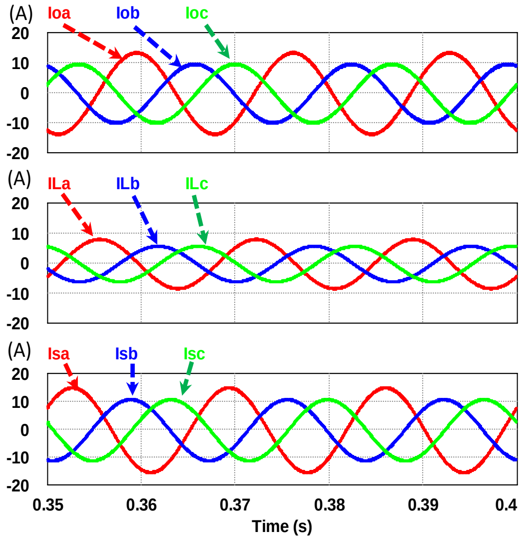


Fig. 7 (f) The detailed simulation results of the corresponding three-phase currents of the inverter, load and the grid during the simulation time of 0.35s~0.4s.

V. CONCLUSION

It has been well accepted that the concept of micro-grids and the use of renewable energy based power generations has many advantages, however, a number of new technical problems regarding operation, protection, power quality, system optimization and real-time power flow control are still call for researches for finding better solutions. In this paper, based on the analysis of the mathematical model of grid-tied three-phase VSI under unbalanced grid conditions, an integrated control scheme is established to handle the real-time current commands corresponding to the desired inverter's operating modes. In an unbalanced three-phase system, the positive and negative sequence current controllers can be designed with proper PI controllers and with special consideration to work separately for achieving fast and good P-Q decoupled control effects. It has been found that with the proposed control methods the grid-tied inverter can effectively eliminate active and reactive power oscillations individually or simultaneously, however, the three-phase output currents of the inverter are distorted when both active and reactive power oscillations are to be eliminated at the same time. The effectiveness and overall performance of the proposed control scheme with the developed current controllers have been demonstrated with a set of comprehensive simulation studies and the related power flow control results.

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