



Independent Active and Reactive Power Control of Single Phase Grid Tied Voltage Source Inverter for PV Applications

B. H. Khan¹, Farah Naz² and Hafizur Rahman³

^{1,3}Professor, ²M.Tech. Student

Department of Electrical Engineering

A.M.U. Aligarh 202002 (U.P.)

INDIA

Abstract: In this paper a grid tied, single phase, Voltage Source Inverter (VSI), having independent active and reactive power control, suitable for residential photovoltaic (PV) power applications is described. A local load is also considered at the output of the inverter. The design of controller and the grid synchronization methods are described in detail. Simulation results validate the effectiveness of the controller.

Keywords: Grid tied inverter, micro-grid, reactive power control, solar inverter

I. Introduction

With increasing use of distributed generation (DG), the need that the DG units actively supplying reactive power to the grid is being felt. These DGs will supply the reactive power to their local loads as well as help in supporting local grid voltage, partially reducing the burden of delivering reactive power from central generation to the local distribution level [1]-[4].

A typical two-stage PV inverter configuration is shown in Fig. 1. A DC/DC converter is used for voltage amplification and maximum power point tracking. A full bridge voltage source inverter (VSI) with a LCL filter is provided to control the active and reactive power flow.

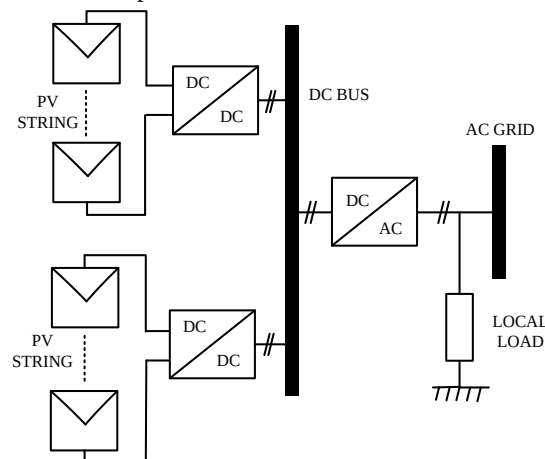


Figure 1: Two stage single phase PV inverter system.

In this paper, a computationally efficient method for independent control of active and reactive power is developed for single phase VSIs connected to a grid as well as local load. Two independent reference values for active and reactive currents are created to maintain synchronization. The proposed synchronization method is helpful in numerous ways: (i) It provides two decoupled components, one parallel and the other orthogonal to grid voltage. This is in contrast to techniques that only duplicate the grid voltage to produce a current that has the same phase as the grid voltage and zero reactive current [5]. (ii) The proposed method is also immune to grid voltage distortion and hence the generated current reference remains undistorted. The synchronous frame Phase Locked Loops (PLLs) discussed in [6]-[8], although not explicitly specified, also has the potential to provide sufficient phase information to the controller for the reactive current reference generation. However its

implementation process can be complicated due to: (i) the need for an orthogonal component emulator and (ii) real time sine and cosine operations while performing $\alpha\beta$ -dq transforms.

A simple grid synchronization method that utilizes a two by two matrix to reproduce parallel and orthogonal components of the grid voltage is given in [9]. The final reference current is then created through a simple summing and normalization process of these components. However, no local load is considered at the output of the inverter.

In this paper the idea given in [9] is further extended for the case where a variable local load is also present at the output of the inverter in addition to grid.

In section II, the proposed control scheme of the single phase grid tied VSI is discussed, which includes design of a sinusoidal pulse width modulation (SPWM) based current controller using a proportional resonant (PR) compensator. The design of a voltage controller that uses a notch filter in the voltage feedback path. The inclusion of notch filter helps to reduce the size of the DC-link capacitor. The design of the proposed grid synchronization method is discussed in section III. Simulation results that validate the control scheme and the grid synchronization method are shown in section IV. The simulation results are obtained for local load at varying magnitude and power factor.

II. Control Scheme for Single Phase Grid Tied VSI

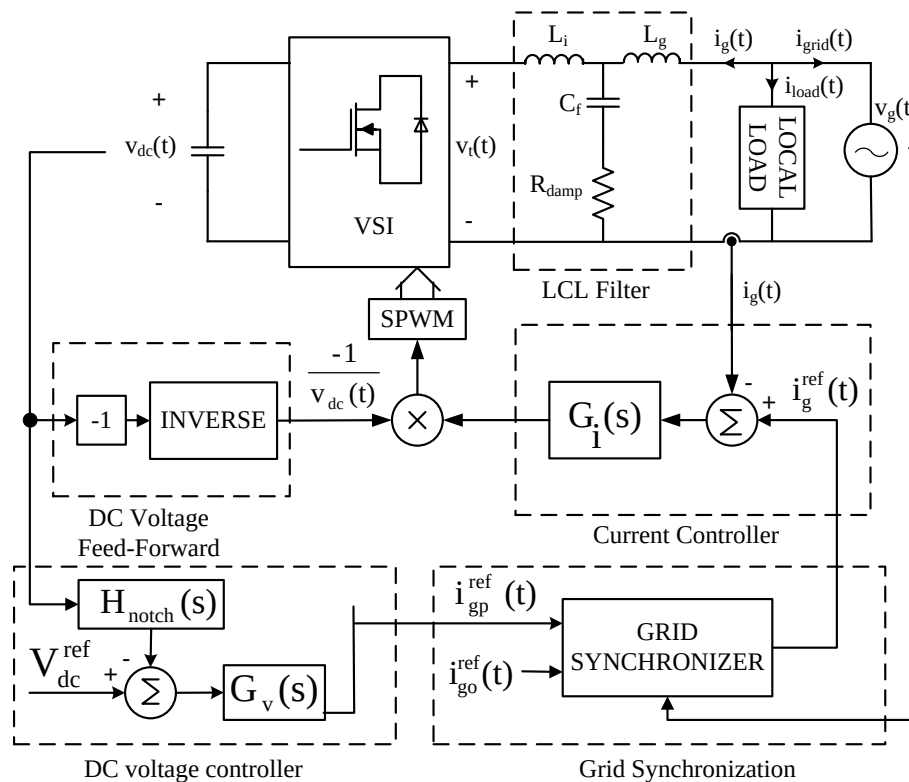


Figure 2: Controller block diagram

A block diagram of the proposed controller is shown in Fig. 2. The design of the controller for the inverter can be divided into three parts: (i) current controller, (ii) DC voltage controller and (iii) grid synchronization. The current controller regulates the AC output current of the inverter and the voltage controller regulates the DC voltage input to the inverter. A DC voltage feed-forward signal is multiplied with the output of the current controller so that the modulation signal sent to the SPWM modulator cancels out the effect of the double-line frequency ripple that appears on the DC-link. Unlike controlling a three phase VSI [10], the active and reactive power of the single phase VSI cannot be controlled by varying i_d and i_q in the d-q frame. Instead, a low complexity grid synchronization method is proposed to create a grid current reference signal, which incorporates the control of the active and the reactive power flow. This grid synchronization method is described in detail in section III.

A. Current Control Using Proportional Resonant Compensator

A feedback current loop, as shown in Fig. 3, is used to regulate the output current of the inverter. The plant $G_f(s)$ is simply the transfer function of the LCL filter, which is of the form:

$$G_f(s) = \frac{s C_f R_d + 1}{s^3 L_i L_g C_f + s^2 C_f R_d (L_i + L_g) + s (L_i + L_g)} \quad (1)$$

In case of SPWM controlled single phase VSI, space vector theory cannot be applied and the controller design cannot be done in d-q frame. For this reason, the controller needs to track a single sinusoidal current reference directly. A traditional PI controller is not a good choice for tracking of a sinusoidal reference signal as it would

lead to steady state magnitude and phase errors [11]. Alternately, a PR compensator, based on the “internal model principle” first proposed by Francis and Wonham [12] can be used. It has an “infinite gain” at the reference signal’s oscillating frequency [13], [14]. This would eliminate the steady state error when tracking a sinusoidal signal. Therefore, in this work a PR compensator, $G_i(s)$ is used for tracking of the reference current. The PR compensator $G_i(s)$ used, has a transfer function of the form:

$$G_i(s) = K_p^c + \frac{K_i^c s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \quad (2)$$

Where, K_p^c and K_i^c are proportional and integral gains respectively, ζ is the damping coefficient and ω_0 is the fundamental frequency of the grid voltage, at which the gain is infinite and this closed loop controller perfectly tracks the reference signal. The damping term ζ reduces the “infinite gain” marginally to widen the bandwidth and to ensure that the controller internal dynamics remain stable.

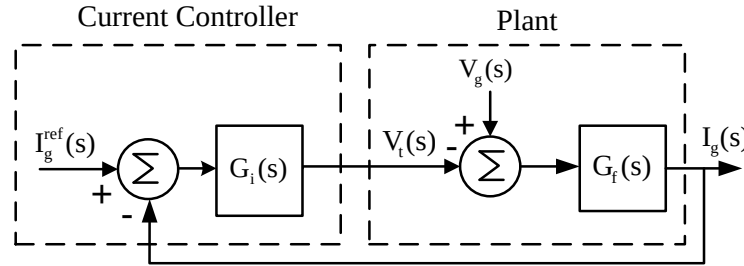


Figure 3: Current Controller Block diagram

B. Voltage Controller

In rooftop PV application, the use of electrolytic capacitors at dc link are less desirable for their short operational lifetime, as they are exposed to outdoor temperatures [15], [16]. Long life-time film type capacitors can be used as substitutes. However, their high prices limit the size that can be used with PV inverters. This would practically limit the size of the DC-link capacitor, causing significant double line frequency ripple to appear on the DC-link voltage. This double line frequency ripple may further couple through the control loop and causes undesirable low order harmonics distortion on the output current. Therefore, a notch filter is inserted on the DC voltage feedback path to attenuate the ripple component as shown in Fig. 2. The notch filter is given by:

$$H_{notch}(s) = \frac{s^2 + 2\zeta_1\omega_n s + \omega_n^2}{s^2 + 2\zeta_2\omega_n s + \omega_n^2} \quad (3)$$

Where, ω_n is twice the fundamental frequency. A simple PI compensator is then used as $G_v(s)$ in the voltage control loop to regulate the DC link voltage.

III. Grid Synchronization Method for Generating Active and Reactive Current Reference

The grid synchronizer consists of two parts: (i) a grid voltage estimator, and (ii) an amplitude identifier as shown in Fig. 4.

A. Grid Voltage Estimator

The grid voltage estimator takes the grid voltage as its input and outputs two signals: (i) one that is aligned with the grid voltage (parallel component, v_{gp}), and (ii) a second that leads the grid voltage by 90° (orthogonal component, v_{go}). This estimator can be expressed in the state space form.

$$\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} &= \begin{bmatrix} 0 & \omega_0 \\ -\omega_0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} k_{sync} \\ 0 \end{bmatrix} (v_g - x_1) \\ \begin{bmatrix} v_{gp} \\ v_{go} \end{bmatrix} &= \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{aligned} \quad (4)$$

The estimator in eqn. (4) takes $(v_g - x_1)$ as its input and outputs x_1 as the parallel component of v_g . Thus, this essentially resembles a feedback loop as illustrated in Fig. 5, where the output x_1 tracks v_g .

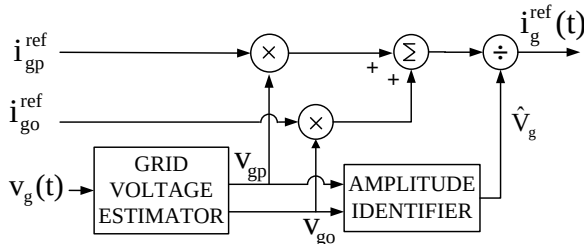


Figure 4: Grid synchronizer block diagram

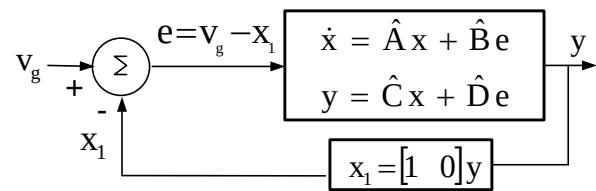


Figure 5: Feedback loop of the grid voltage estimator

The reference signal of this feedback loop is v_g a sinusoidal signal oscillating at the grid frequency. The state matrix $\hat{A}$, which is an internal oscillator, that oscillates at ω_o . This provides the estimator with infinite gain at ω_o in the frequency domain.

The term k_{sync} in the above equation introduces damping to the oscillator. It widens the estimator's bandwidth and reduces the gain at ω_o . Therefore, setting ω_o to the fundamental frequency of the grid results in x_1 tracking the input v_g at its fundamental frequency, while also rejecting other harmonics that appear on the grid voltage. On the other hand, x_2 , has the same amplitude as x_1 but leads x_1 by 90° . Consequently, the output y_1 is denoted as v_{gp} to indicate its alignment with the grid voltage and the output y_2 is denoted as v_{go} to indicate that it is orthogonal to the grid voltage.

The state space form of the compensator as given by eqn. (4) can be further rewritten to the standard state space form shown in eqn. (5), so that v_g is expressed as the input to the estimator and the outputs are the parallel component and the orthogonal component of v_g .

$$\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} &= \underbrace{\begin{bmatrix} -k_{sync} & \omega_o \\ \omega_o & 0 \end{bmatrix}}_{\hat{A}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \underbrace{\begin{bmatrix} k_{sync} \\ 0 \end{bmatrix}}_{\hat{B}} (v_g) \\ \begin{bmatrix} v_{gp} \\ v_{go} \end{bmatrix} &= \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}}_{\hat{C}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{aligned} \quad (5)$$

The bode plot of each output of the compensator's responses are as shown in Fig. 6.

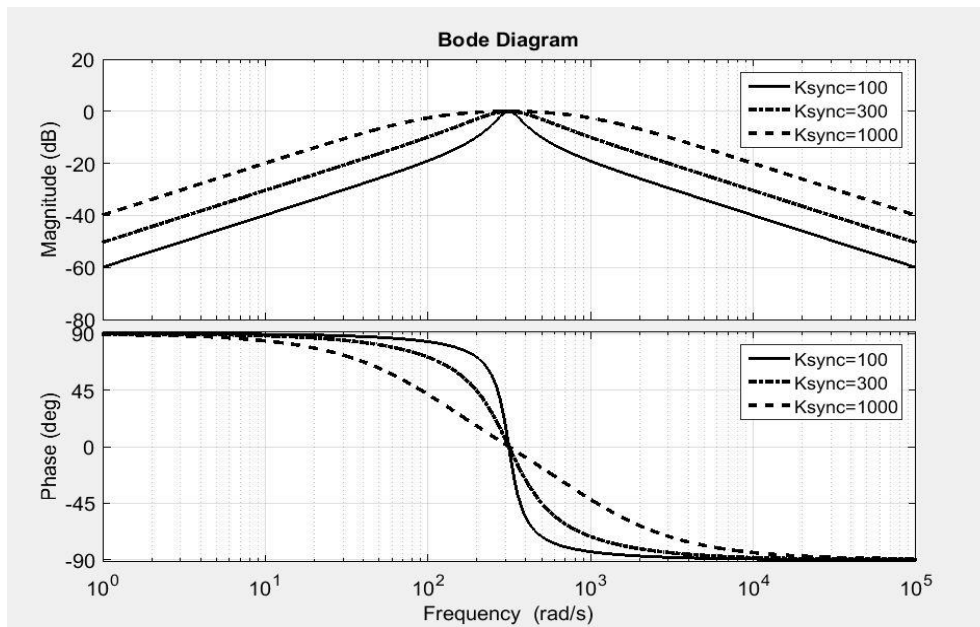


Figure 6 (a): Bode plot of $\frac{v_{gp}(j\omega)}{v_g(j\omega)}$

In Fig. 6(a), the $\frac{v_{gp}(j\omega)}{v_g(j\omega)}$ response has a magnitude of 0 dB and a phase of 0° at the grid fundamental frequency and filters out distortions at any other frequencies. In Fig. 6(b), the $\frac{v_{go}(j\omega)}{v_g(j\omega)}$ response also keeps the magnitude at 0 dB at the grid fundamental frequency but filters out distortions only at higher frequencies. Meanwhile, the

phase of the $\frac{v_{go}(j\omega)}{v_g(j\omega)}$ response is at 90° at the grid fundamental frequency so that v_{go} leads v_g by 90° . It can also be observed from Fig. 6, the more the k_{sync} increases, the less the synchronizer become sensitive to variations of the grid fundamental frequency but more vulnerable to noise at other frequencies. Furthermore, the larger the k_{sync} gets, the wider the controller's bandwidth extends, which means the faster the v_{gp} locks on v_g .

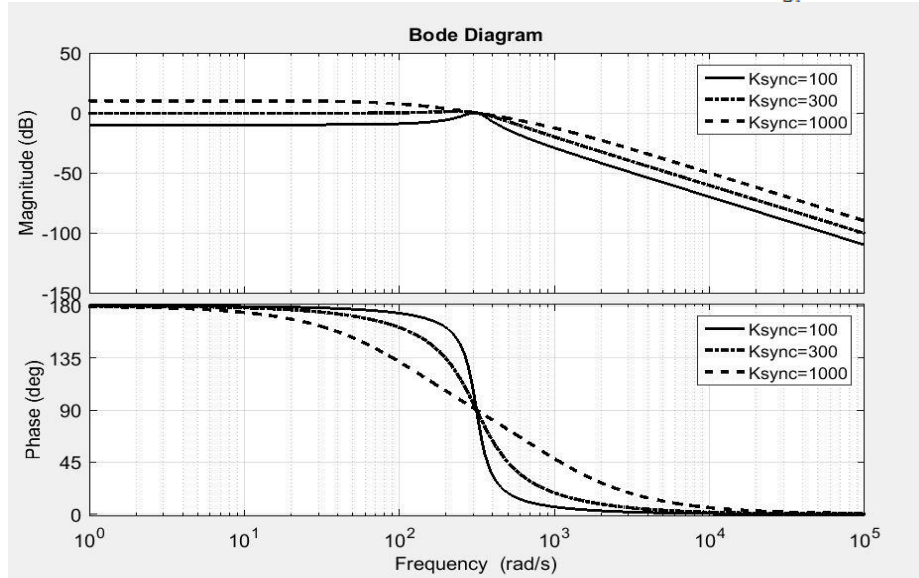
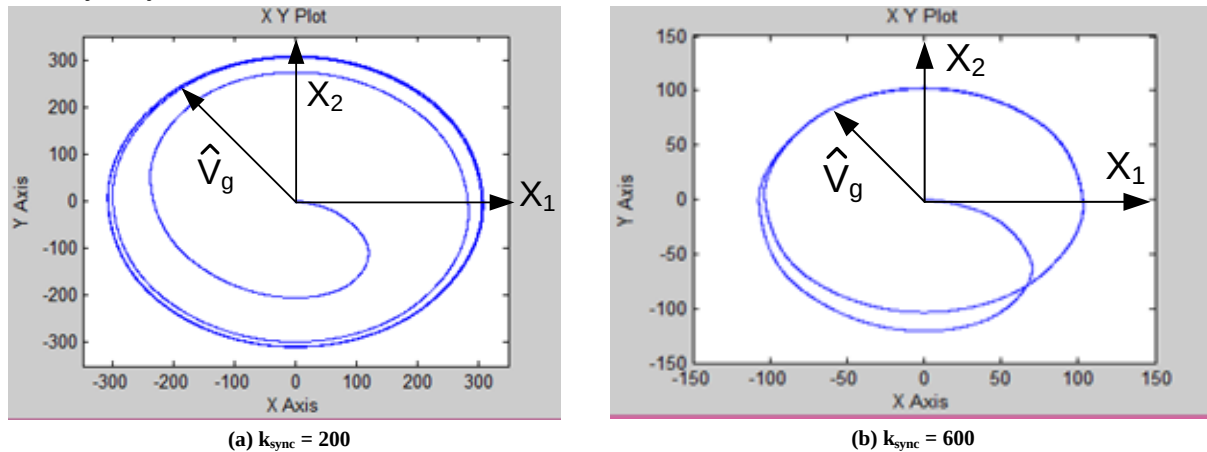


Figure 6(b): Bode plot of $\frac{v_{go}(j\omega)}{v_g(j\omega)}$

Fig. 7 shows the start-up trajectories of the state variables x_1 and x_2 for different values of k_{sync} and Zero initial conditions. From the two plots, several facts may be inferred: (i) The final state trajectories are identical circles proving that x_1 and x_2 are sinusoidal functions with 90° phase difference. (ii) The radius of the circle is equal to the magnitude of the grid voltage, indicating that both sinusoidal functions have an amplitude equal to the magnitude of grid voltage. This effectively demonstrates that the grid estimator resembles the fundamental component of the grid voltage and emulates an orthogonal component with the same magnitude. (iii) With the initial conditions of states x_1 and x_2 equal to zero, the plot with the larger k_{sync} has a faster speed to reach the final trajectory.



(a) $k_{sync} = 200$ (b) $k_{sync} = 600$
Figure 7: Start up trajectory of the estimator's state variable for different k_{sync} values

B. Amplitude Identifier

A grid voltage amplitude identifier is needed to determine the amplitude of the grid voltage. The amplitude identifier has the form:

$$\hat{V}_g = \sqrt{v_{gp}^2 + v_{go}^2} \quad (6)$$

Which may also be written as: $\hat{V}_g = \sqrt{x_1^2 + x_2^2}$

Other options of implementing the amplitude identifier may include peak detection of the grid voltage or peak detection of either output of the grid voltage estimator (v_{gp} or v_{go}). Both methods avoid using the square root operation. However, peak detection of either V_{gp} and V_{go} is preferred because the grid voltage estimator

attenuates the harmonic distortion that appears on the grid voltage. Therefore the peak detection of the output of the estimator is more accurate than that of the grid voltage itself.

C. Synchronized Current reference Generation

Once the V_{gp} and V_{go} are obtained from the grid voltage estimator, and $\hat{V}_g$ is obtained from the amplitude identifier, the control of the phase of the synchronized current reference becomes possible. Given the grid reference current's parallel and orthogonal components, i_{gp}^{ref} and i_{go}^{ref} , a synchronized current reference signal can be obtained by the following equation:

$$i_g^{ref} = \frac{i_{gp}^{ref} v_{gp} + i_{go}^{ref} v_{go}}{\hat{V}_g}$$

Since, the parallel component of the current reference i_{gp}^{ref} is alignment with the grid voltage, this component controls the active power flow to the grid. On the other hand, since the orthogonal component of the current reference i_{go}^{ref} leads the grid voltage by 90° , this component controls the reactive power flow to the grid. The overall control system is given in Fig 2. The output of the voltage controller serves as parallel current input command i_{gp}^{ref} and controls the active power supplied by the inverter. The i_{gp}^{ref} depends on the amount of power transferred by the front end DC-DC converter. The i_{go}^{ref} is the user defined independent orthogonal input command to synchronizer, allowing control of reactive power. The value of i_{go}^{ref} is limited by the current rating of the inverter. Thus a decoupled control of active and reactive power is obtained.

IV. Simulation Results

To verify the effectiveness of the control scheme, both the current controller and the voltage controller were simulated in MATLAB separately. The front end DC/DC converter is emulated using a constant current source. The system parameters and component values used for the MATLAB model are listed in Table I. The capability of the inverter to supply pure active power, pure reactive power, as well as the combination of active and reactive powers is demonstrated by measuring the power supplied to the load, power supplied to the grid and total power supplied by the inverter under different magnitudes and power factors of local loads. The results are shown in Table II.

Table I Inverter parameters and component values

Grid Voltage V_g	230 V (RMS)
Rated Output Current of the inverter I_g^{rated}	10 A (RMS)
DC-Link Nominal Voltage V_{dc}^n	400 V
DC-Link Capacitor C_{dc}	230 μ F
Grid Side Inductor L_g	100 μ H
Bridge Side Inductor L_i	300 μ H
Filter Capacitor C_f	30 μ F
Filter Damping Resistor R_{damp}	1.5 Ω
Switching Frequency f_{sw}	30 kHz

Table II Active and reactive power control with different local loads

(a) Inverter supplies active power only								(b) Inverter supplies reactive power only							
Nature of Local Load		Power supplied to the local Load		Power supplied to the Grid		Total Power supplied by the inverter		Nature of Local Load		Power supplied to the local Load		Power supplied to the Grid		Total Power supplied by the inverter	
Magnitude (Ω)	Power Factor	P_L (kW)	Q_L (kVAr)	P_g (kW)	Q_g (kVAr)	P_i (kW)	Q_i (kVAr)	Magnitude (Ω)	Power Factor	P_L (kW)	Q_L (kVAr)	P_g (kW)	Q_g (kVAr)	P_i (kW)	Q_i (kVAr)
52.91	1.0	1.0	0.0	1.3	0.0	2.3	0.0	52.91	1.0	1.0	0.0	-1.0	2.3	0.0	2.3
17.63	1.0	3.0	0.0	-0.7	0.0	2.3	0.0	17.63	1.0	3.0	0.0	-3.0	2.3	0.0	2.3
52.64	0.995	1.0	0.1	1.3	-0.1	2.3	0.0	52.64	0.995	1.0	0.1	-1.0	2.2	0.0	2.3
17.63	0.999	3.0	0.1	-0.7	-0.1	2.3	0.0	17.63	0.999	3.0	0.1	-3.0	2.2	0.0	2.3

(c) Inverter supplies both active and reactive powers							
Nature of Local Load		Power supplied to the local Load		Power supplied to the Grid		Total Power supplied by the inverter	
Magnitude (Ω)	Power Factor	P_L (kW)	Q_L (kVAr)	P_g (kW)	Q_g (kVAr)	P_i (kW)	Q_i (kVAr)

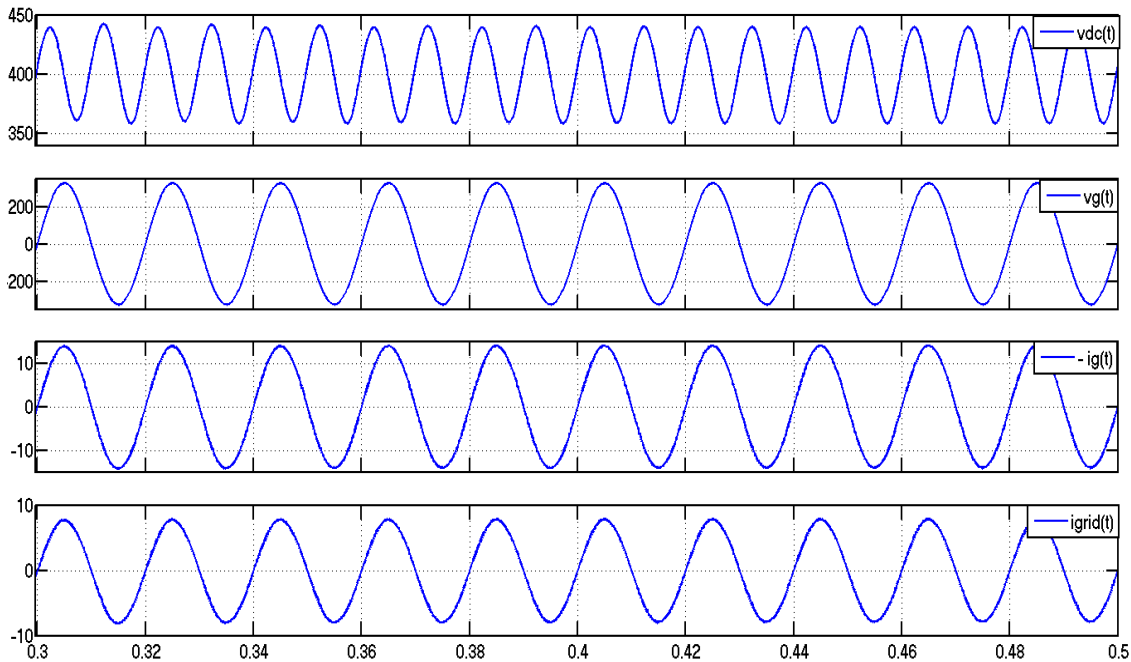
52.91	1.0	1.0	0.0	0.626	1.626	1.626	1.626
17.63	1.0	3.0	0.0	-1.374	1.626	1.626	1.626
52.64	0.995	1.0	0.1	0.626	1.526	1.626	1.626
17.63	0.999	3.0	0.1	-1.374	1.526	1.626	1.626

TABLE III Inverter steady state operation results

Figures	Power supplied by the inverter		THD of inverter output current (%)	Dc –Link Voltage Ripple (%)
	P_i (kW)	Q_i (kVar)		
Fig. 8(a)	2.3	0.0	0.6	10
Fig. 8(b)	0.0	2.3	0.6	07
Fig. 8(c)	1.626	1.626	0.6	8.5

A. Steady State Response

Fig. 8 shows the steady state operating DC-link voltage $v_{dc}(t)$, grid voltage $v_g(t)$, output current of the inverter - $i_g(t)$ and the current flowing into the grid $i_{grid}(t)$. The inverter is running at its rated current $i_g(t) = 10$ A (RMS) and a grid frequency of 50Hz. Figs. 8(a) through 8(c) depict various waveforms under conditions where the inverter is generating pure active power, pure reactive power, and a combination of both active and reactive power, respectively. The corresponding calculated values are listed in Table III. These simulation results demonstrate the reactive power control capability of the inverter. In addition, it can be seen that with a fairly large magnitude of double line frequency voltage ripple present on the DC-link, the total harmonic distortion (THD) of the output inverter current in all the three cases are well below 5%. This proves the effectiveness of the non-linear DC voltage feed-forward signal and the notch filter in the DC voltage control loop.



(a) Inverter current is in phase with the voltage (Local Load: 52.91 Ω , pf : 1.0).

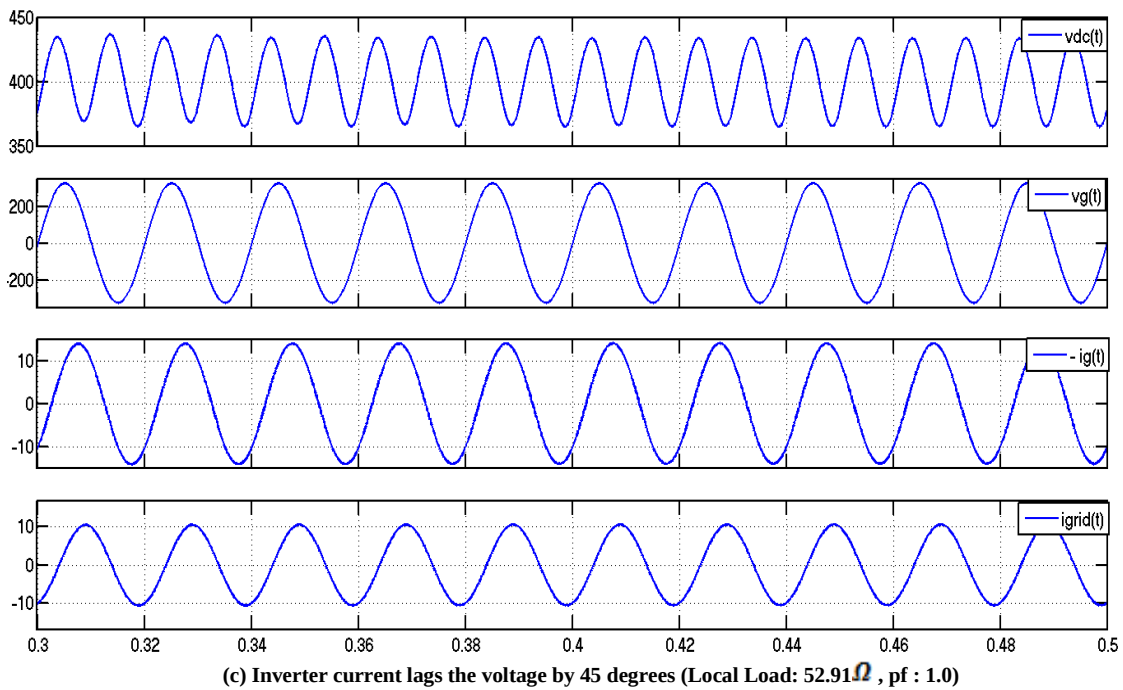
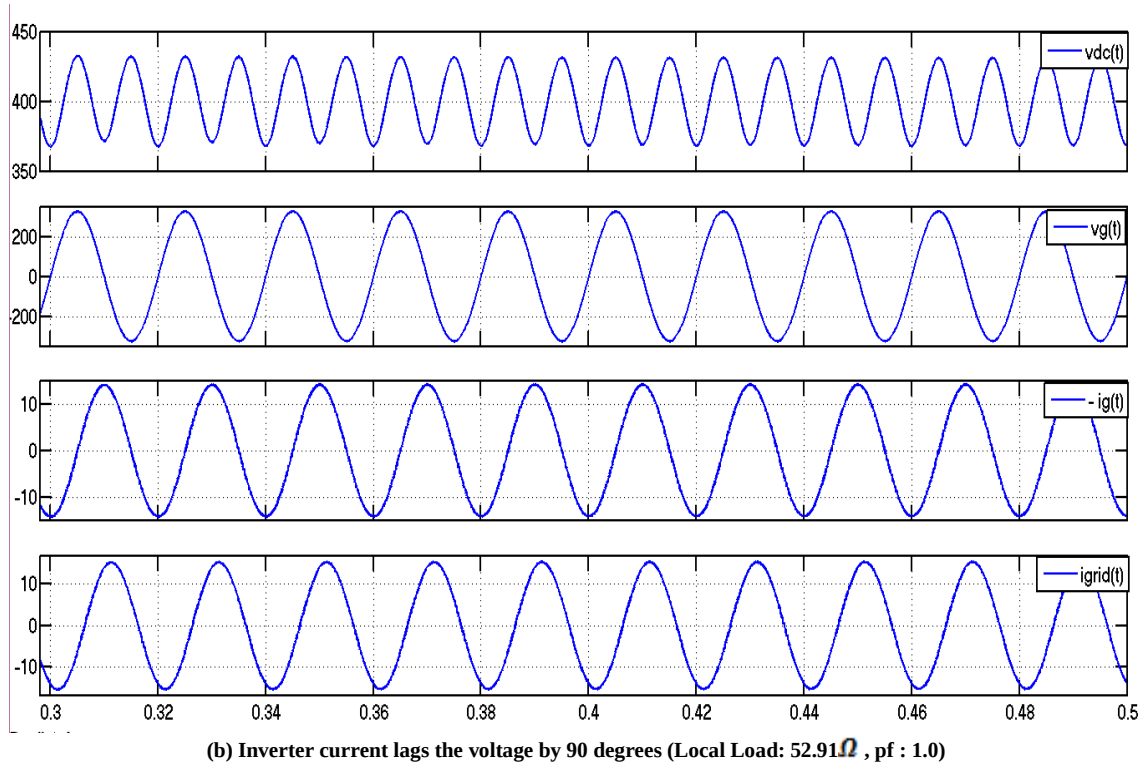


Figure 8: Steady state operation of the inverter

B. Transient response

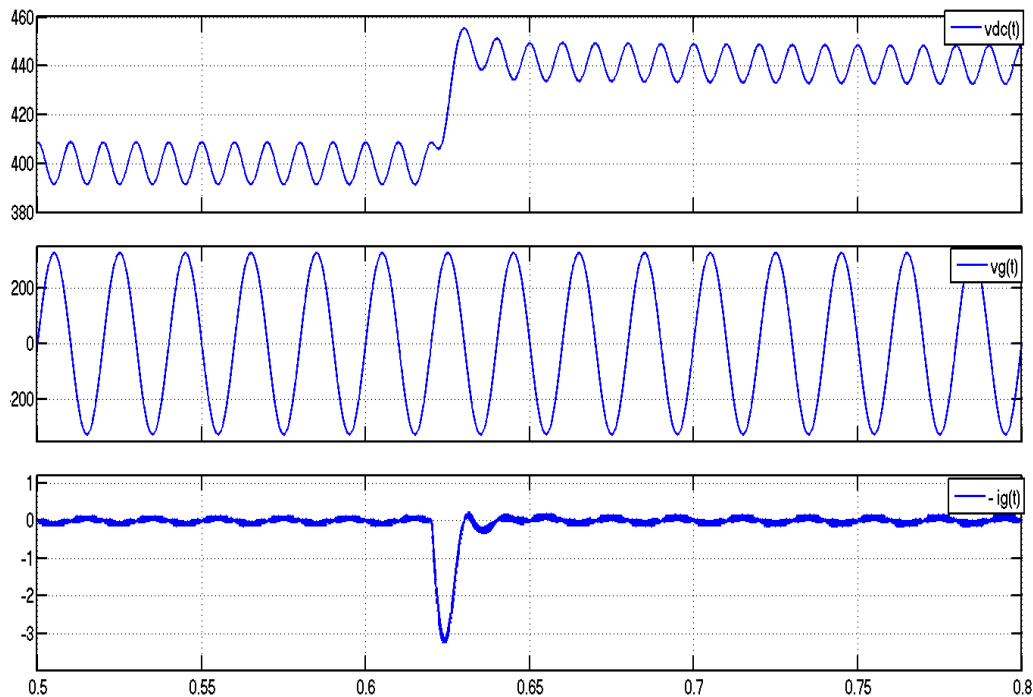
Fig. 9(a) shows the transient response of the inverter for the DC-link voltage step change from 400 V to 440 V while the output grid current is kept at 0 A. The DC voltage transient response demonstrates good system dynamics where the DC-link voltage settling time is around 20 ms and the percentage overshoot is less than 30%. Fig. 9(b) shows the step response of the inverter for step change in reactive power control command i_{qo}^{ref} steps up from 0 A to 10 A (RMS) while the DC-link voltage is kept constant at 400 V. The result demonstrates a good decoupling of the parallel and orthogonal components of the controller as the step change in i_{qo}^{ref} causes little impact on the average value of DC-link voltage.

V. Conclusion

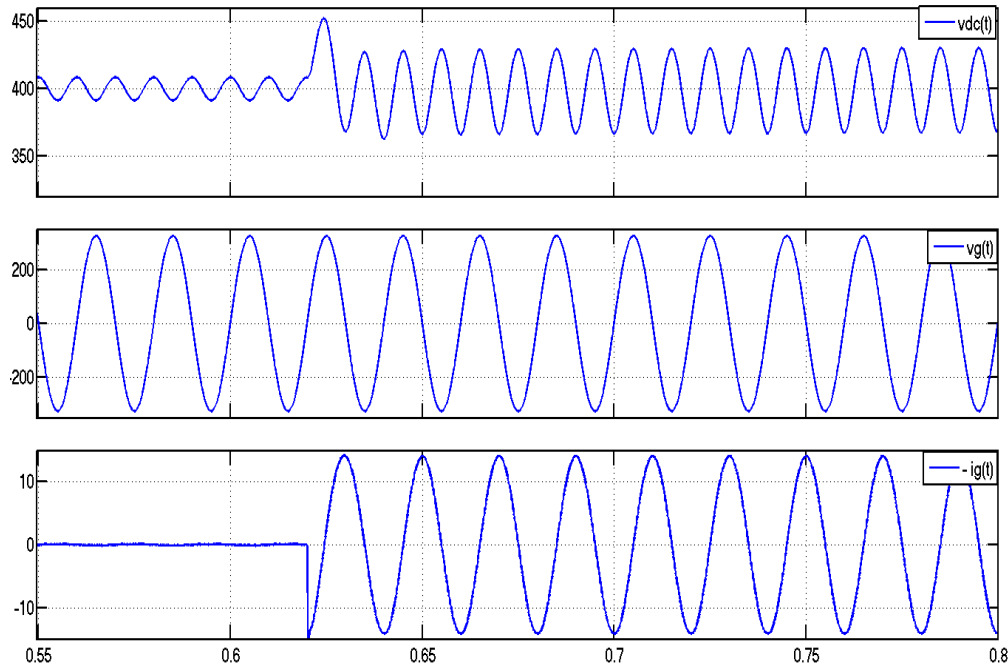
In this paper, a reactive power control method is developed for single phase grid tied VSIs feeding the grid as well as local load. The proposed method is immune to grid voltage distortion and the generated current reference remains unaffected in presence of these disturbances. A PR compensator is used in the current control loop for tracking a sinusoidal reference current. Also, a PI compensator is used in the voltage control loop. A notch filter is added to the DC-link voltage feedback signal to filter out the double line frequency ripple component appearing on the DC-link voltage so that the output grid current is not distorted by this ripple component.

A simple grid synchronization method involving less computational effort, is developed to create a current reference that consists of active and reactive components. The reactive component i_{qo}^{ref} is used as the reactive power control command which tells the inverter about the amount of reactive current needed to be injected/absorbed. This feature provides the inverter the ability of independently controlling the reactive power flow. Furthermore, the proposed grid synchronizer uses only a two by two state matrix to generate the parallel and orthogonal components. This lowers the implementation complexity and the computational burden on the digital processor compared to the methods using synchronous frame PLLs, which require sine and cosine calculations for d-q frame transformation. The drawback of the grid synchronization method is the need for a square root calculation in the amplitude identifier, which could increase the processing time of the digital processor. A viable solution to this problem is the use of peak detection of the output of the grid voltage estimator to avoid the square root calculation.

The simulation results prove the effectiveness of the controller by demonstrating the inverter's capability of generating active power, reactive powers and a combination of active and reactive power. The transient response demonstrates good dynamic response of the control system.



(a) Dc link voltage step response.



(b) Reactive power controlling command i_{go}^{ref} step response.

Figure 9: Transient response of the inverter.

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