

# Analysis and Control of Single-Phase Converters for Integration of Small-Scaled Renewable Energy Sources into the Power Grid

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**Abstract**—A comprehensive dynamic model based on Direct-Quadrature (DQ) rotating frame is proposed in this paper that is used along with a capability curve (CC) based on the active and reactive power to control a grid-connected single-phase voltage-source inverter (SPVSI). With the proposed dynamic model, a droop-passivity based controller can be designed for the grid-connected inverter in the presence of nonlinear loads. Stability analysis of the proposed control technique is also discussed in the paper as well as design principles. Moreover, an accurate performance area of SPVSI active and reactive power in dynamic transitions is achieved using the CC. Furthermore, an effective harmonic compensation scheme along with a proper active and reactive power sharing algorithm are performed by a well-designed reference waveform generation process. Performance of the grid-connected SPVSI, under the proposed controller, is thoroughly evaluated in the Matlab/Simulink environment.

**Keywords**—grid-connected; single-phase voltage-source inverter; passivity based controller; Droop Control; active and reactive power sharing.

## I. INTRODUCTION

Integration of renewable energy resources into power grid via power electronic interfaced-converters has been widely investigated by numerous literatures from a diverse viewpoints including accurate performance of active and reactive power sharing, harmonic compensation, unity power factor achievement and so on [1-2]. Single-phase voltage-source inverter (SPVSI) has been employed in distributed generation and grid-connected applications as an applicable solution. In these applications, a properly obtained dynamic model and a well-designed control technique are substantial parts of SPVSI use process. In [3], a simple control method is proposed for the purpose of stabilization of a grid-connected inverter in both grid-connected and stand-alone modes, whereas in another study, harmonic impacts of nonlinear loads on grid currents are eliminated by adding the load current into the filter inductor current loop [4]. In [5], a synchronous reference frame PI controller (SRFPI) and a multi-resonant harmonic compensator are utilized to regulate the output current with zero steady state error and to provide an efficient attenuation of the grid voltage harmonic distortion respectively. Also, an average power controller is used to control the active and reactive power sharing [5].

For compensating current harmonics and electromagnetic interferences, a current-mode asynchronous sigma-delta modulation (CASDM) is employed for single phase grid-tied photovoltaic (PV) inverters [5]. Also, for an effective control of reactive power, a cost-effective micro-controller is proposed [5]. An adaptive control technique is proposed in [6] for single-phase grid-connected PV inverters to compensate lower order harmonics introduced by the core saturation induced distorted magnetizing current of the transformer and the dead-time of the inverter and so on. Also, a Proportional-Resonant-Integral (PRI) controller is used to eliminate the dc component in the control system.

In this paper, a comprehensive Direct-Quadrature (DQ) rotating frame based dynamic model is proposed for a SPVSI. Then, a droop-passivity [7-8] based controller is used considering the harmonic effects of nonlinear loads. The complete design process and the system stability analysis are discussed in detailed. A CC is proposed to assess SPVSI active and reactive power areas in dynamic operation conditions. Also a well-designed reference generation process is utilized for the power sharing purposes. Finally Matlab/Simulink environment is employed to verify the validity of the proposed controller.

## II. DYNAMIC MODEL OF GRID-CONNECTED SPVSI

The proposed grid-connected SPVSI is illustrated in Fig.1. The inverter consists of a dc link, and the output resistance and inductance of  $R_c$  and  $L_c$  respectively. Utility is connected to the point of common coupling (PCC) as depicted in Fig.1. In addition, a nonlinear load draws harmonic current from grid that should be compensated by SPVSI [9-11]. Renewable energy sources of PV and wind turbine system (WTS) utilize dc-dc and ac-dc converters respectively to generate a dc voltage. As shown in Fig.1,  $i_{dc}$  and  $C_{dc}$  are the dc-link current and the output capacitor, respectively. According to Fig.1, the mathematical model of a grid-connected SPVSI is obtained as,

$$\begin{aligned} L_c \frac{di_c}{dt} + R_c i_c + v_c + v_{dc} u_c &= 0 \\ C_{dc} \frac{dv_{dc}}{dt} &= i_c u_c + i_{dc} \end{aligned} \quad (1)$$

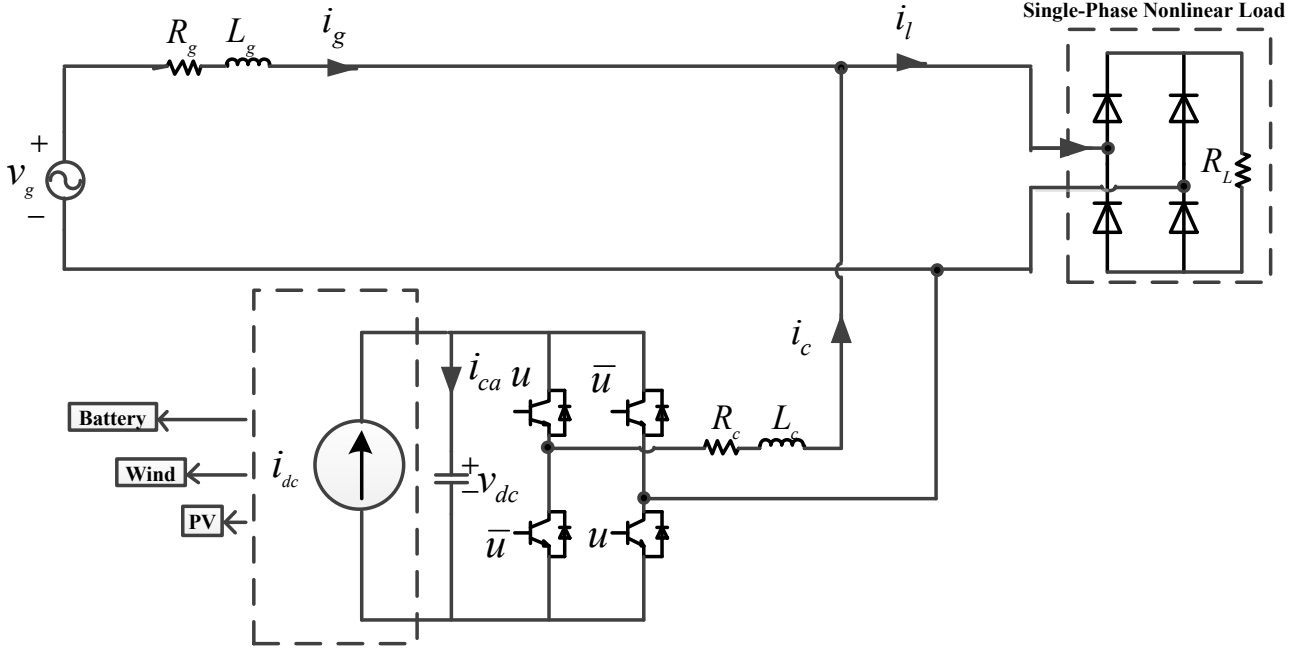


Fig. 1. The proposed grid-connected SPVSI

where  $i_c$  and  $v_c$  are the output inverter current and PCC voltage, respectively, and  $u_c$  is SPVSI switching function. If the real state variable of SPVSI is equal to:

$$x_r = x_m \sin(\omega t + \varphi) \quad (2)$$

where  $x_m$ , is the state variable,  $\varphi$  is the initial phase and  $\omega$  is the angular frequency. Also, the imaginary state variable of the proposed inverter is:

$$x_i = x_m \cos(\omega t + \varphi) \quad (3)$$

where  $x_{(ir)} \in \{i_c, v_{dc}\}$ . Considering equations (2) and (3), the d-q frame transformation matrix can be written as:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) \\ \cos(\omega t) & -\sin(\omega t) \end{bmatrix} \begin{bmatrix} x_r \\ x_i \end{bmatrix} \quad (4)$$

Using (1), (2) and (3), the real-imaginary coordinate-based dynamic model of SPVSI is derived as,

$$\begin{bmatrix} L_c & 0 & 0 & 0 \\ 0 & L_c & 0 & 0 \\ 0 & 0 & C_{dc} & 0 \\ 0 & 0 & 0 & C_{dc} \end{bmatrix} \begin{bmatrix} \dot{i}_{cr} \\ \dot{i}_{ci} \\ \dot{v}_{dcr} \\ \dot{v}_{dci} \end{bmatrix} + \begin{bmatrix} R_c & 0 & 0 & 0 \\ 0 & R_c & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{cr} \\ i_{ci} \\ v_{dcr} \\ v_{dci} \end{bmatrix} + \begin{bmatrix} 0 & 0 & u_{cr} & 0 \\ 0 & 0 & 0 & u_{ci} \\ -u_{cr} & 0 & 0 & 0 \\ 0 & -u_{ci} & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{cr} \\ i_{ci} \\ v_{dcr} \\ v_{dci} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ i_{dcr} \\ i_{dci} \end{bmatrix} = 0 \quad (5)$$

$v_{dc(ri)}$  and  $i_{dc(ir)}$  are the real and imaginary components of SPVSI dc-link voltage and current, respectively.

To maintain the dc link voltage and current at a constant value in both states, therefore  $v_{dc(ri)} = v_{dc}$  and  $i_{dc(ir)} = i_{dc}$ . Therefore, by applying the matrix of (4) to (5), the d-q dynamic model of SPVSI is obtained as,

$$\begin{bmatrix} L_c & 0 & 0 \\ 0 & L_c & 0 \\ 0 & 0 & C_{dc} \end{bmatrix} \begin{bmatrix} \dot{i}_{cd} \\ \dot{i}_{cq} \\ \dot{v}_{dc} \end{bmatrix} + \begin{bmatrix} R_c & 0 & 0 \\ 0 & R_c & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \\ v_{dc} \end{bmatrix} + \begin{bmatrix} 0 & \omega L_c & 0 \\ -\omega L_c & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \\ v_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 & u_{cd} \\ 0 & 0 & u_{cq} \\ -u_{cd}/2 & -u_{cq}/2 & 0 \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \\ v_{dc} \end{bmatrix} + \begin{bmatrix} v_d \\ v_q \\ -i_{dc} \end{bmatrix} = 0 \quad (6)$$

### III. PROPOSED CONTROL METHOD

An effective harmonic compensation with unity power factor as well as a good dynamic execution of active and reactive power sharing in the grid-connected SPVSI requires design of an appropriate closed-loop controller with fast dynamic responses. The proposed controller is discussed in details in this section.

#### A. Current-based closed-loop controller

In this section, a passivity-based controller including injection of damping resistances and shaping energy is used to design proposed control technique. To use the proposed controller for the system model shown in Fig.1, a closed-loop dynamic model based on the error state variables to be achieved, so initially (6) is rewritten as following matrix demonstration:

$$\begin{aligned}
I\dot{X} + RX + WX + UX + S &= 0 \\
I &= \begin{bmatrix} L_c & 0 & 0 \\ 0 & L_c & 0 \\ 0 & 0 & C_{dc} \end{bmatrix}, X = \begin{bmatrix} i_{cd} \\ i_{cq} \\ v_{dc} \end{bmatrix}, W = \begin{bmatrix} \omega L_c & 0 & 0 \\ 0 & -\omega L_c & 0 \\ 0 & 0 & 0 \end{bmatrix}, \\
R &= \begin{bmatrix} R_c & 0 & 0 \\ 0 & R_c & 0 \\ 0 & 0 & 0 \end{bmatrix}, U = \begin{bmatrix} 0 & 0 & u_{cd} \\ 0 & 0 & u_{cq} \\ -u_{cd}/2 & -u_{cq}/2 & 0 \end{bmatrix} \\
S &= \begin{bmatrix} v_d \\ v_q \\ -i_{dc} \end{bmatrix} \quad (7)
\end{aligned}$$

By defining the error state variables vector as (8),

$$\begin{aligned}
E = X - X^* &= [e_1 \quad e_2 \quad e_3]^T = \\
&= \begin{bmatrix} i_{cd} - i_{cd}^* & i_{cq} - i_{cq}^* & v_{dc} - v_{dc}^* \end{bmatrix}^T \quad (8)
\end{aligned}$$

$X^*$  is the reference values vector of the proposed system state variables. Thus, the error closed-loop dynamic model of the proposed SPVSI can be obtained by substituting (8) into (7) as,

$$\begin{aligned}
I\dot{E} + RE + WE + UE &= \\
-S - (I\dot{X}^* + RX^* + WX^* + UX^*) & \quad (9)
\end{aligned}$$

In order to have a faster transient response and zero steady state error in different operational conditions, a damping resistance matrix of  $R_d$  is added to (9) as,

$$\begin{aligned}
I\dot{E} + (R + R_d)E + WE + UE &= \\
-S - (I\dot{X}^* + RX^* + WX^* + UX^* - R_d E) & \quad (10)
\end{aligned}$$

where  $R_d$  is considered as,

$$R_d = \begin{bmatrix} R_{d1} & 0 & 0 \\ 0 & R_{d2} & 0 \\ 0 & 0 & R_{d3}^{-1} \end{bmatrix} \quad (11)$$

As the first step for the design of the proposed controller, the SPVSI output currents and dc-link voltage should track their reference values that lead to  $E = 0$ . Thus, based on (10), (12) is obtained as,

$$I\dot{E} + (R + R_d)E + WE + UE = 0 \quad (12)$$

The asymptotical stable operation of the grid-connected SPVSI along with the proposed controller can be proved by the use of system total saved energy function developed based on the error state variables. The function is defined as,

$$H(\bar{e}) = \frac{1}{2}L_c e_1^2 + \frac{1}{2}L_c e_2^2 + \frac{1}{2}C_{dc} e_3^2 \quad (13)$$

According to Lyapunov stability theory, the total saved energy of a stable system has to be minimized.

Therefore, by making a derivative of (13) and using (12), the following equation is yield.

$$\begin{aligned}
\dot{H}(\bar{e}) &= L_c \dot{e}_1 e_1 + L_c \dot{e}_2 e_2 + C_{dc} \dot{e}_3 e_3 = E^T I \dot{E} = \\
&= -E^T ((R + R_d)E + WE + UE) \quad (14)
\end{aligned}$$

It is noticed that the terms related to the damping resistances in (14) are much larger than other terms. Thus, (14) can be rewritten as,

$$\begin{aligned}
\dot{H}(\bar{e}) &= -E^T (R + R_d)E = -(R_c + R_{d1})e_1^2 \\
&= -(R_c + R_{d2})e_2^2 - R_{d3}^{-1}e_3^2 \quad (15)
\end{aligned}$$

Equation (15) verifies that the designed controller based on the closed-loop error dynamic model presented in (10) is able to make the proposed system stable and to reach zero errors. Substitution of (12) into (10) results in:

$$U = (-S - I\dot{X}^* - RX^* - WX^* + R_d E) X^{*-1} \quad (16)$$

Switching functions obtained from (16) are utilized to control the grid-connected SPVSI during various operating conditions.

#### B. Calculation of SPVSI reference currents

SPVSI is responsible for injecting the required harmonic components of both active and reactive power of nonlinear loads. Also, in order to achieve high quality grid currents and power, the whole reactive power of the load has to be supplied by the SPVSI. Thus, an accurate calculation of SPVSI currents in d-q frame is necessary to meet the addressed targets.

According to Fig.1, the relation between the grid, SPVSI and load currents can be written as,

$$\begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) \\ \cos(\omega t) & -\sin(\omega t) \end{bmatrix} \begin{bmatrix} i_{gr} + i_{lr} \\ i_{gi} + i_{li} \end{bmatrix} = \begin{bmatrix} i_{gd} + i_{ld} \\ i_{gq} + i_{lq} \end{bmatrix} \quad (17)$$

$i_g$  and  $i_l$  are the grid and load currents, respectively. Since the load generates harmonic components in the proposed system, the d-q component of load currents can be stated as,

$$i_{ldq} = I_{ldq1} + \sum_{n=2}^{\infty} i_{ldqhn} \quad (18)$$

$I_{ldq1}$  and  $\sum_{n=2}^{\infty} i_{ldqhn}$  are the fundamental-frequency and

harmonic components of the load current. The grid-connected SPVSI has to supply the whole harmonic parts of the nonlinear load current. Also, the q-component of grid current to be zero in order to achieve the unity power factor, so  $i_{gq} = 0$ .

Consequently, the SPVSI currents should be equal to,

$$i_{cd} = \alpha I_{ld1} + \sum_{n=2}^{\infty} i_{ldhn} \quad (19)$$

$$i_{cq} = i_{lq}$$

$\alpha$  shows a respective portion of d-component of load current at main frequency to be injected by SPVSI. Thus, grid should generate  $(1-\alpha)I_{ld1}$  during controller operation. Considering (19), reference currents of SPVSI can be achieved as,

$$i_{cd}^* = \left( i_{cd} - \alpha I_{ld1} - \sum_{n=2}^{\infty} i_{ldhn} \right) (k_{pd} + k_{id} / s) \quad (20)$$

$$i_{cq}^* = (i_{cq} - i_{iq}) (k_{pq} + k_{iq} / s)$$

Where  $k_{pdq}$  and  $k_{idq}$  are the proportional and integral coefficients of the PI controllers used in the reference current calculation process of SPVSI that are effective in the convergence rate of zero state variables errors.

### C. Droop controller

A new droop control method is presented in this section for the grid-connected SPVSI which is based on d and q components of its current. This feature is added to the controller in order to complete the passivity-based controller of (16) with an accurate estimation of  $S$  vector. Considering conventional droop controller equations as follows,

$$\omega = \omega^* - m_p P \quad (21)$$

$$E = E^* - m_q Q$$

where  $\omega^*$  and  $E^*$  are the desired value of angular frequency and voltage magnitude of the inverter, respectively.  $m_p$  and  $m_q$  are also the conventional droop coefficients of frequency and voltage magnitude, respectively. The instantaneous SPVSI active and reactive power with respect to the d-q components of the inverter current and voltage can be written as,

$$p = v_d i_{cd} + v_q i_{cq} \quad (22)$$

$$q = v_q i_{cd} - v_d i_{cq}$$

By an acceptable assumption, the active and reactive power of SPVSI at fundamental frequency can be obtained as,

$$P = v_m i_{cd1}, Q = -v_m i_{cq1} \quad (23)$$

where  $v_m$  and  $i_{cdq1}$  are the reference values of the inverter voltage magnitude and the fundamental frequency components of SPVSI current, respectively. By substituting (23) into (21), the new droop equation can be obtained as,

$$\omega = \omega^* - m'_p i_{cd1} \quad (24)$$

$$E = E^* + m'_q i_{cq1}$$

where  $m'_p = m_p v_m$  and  $m'_q = m_q v_m$ .

## IV. CAPABILITY CURVE OF SPVSI

A significant criterion for evaluating a good performance of SPVSI in the grid-connected mode is a proper execution of active and reactive power sharing in presence of dynamic load changes.

In this case, knowing the maximum and minimum active and reactive power of SPVSI can assist the proposed controller to perform in a more effective manner.

The grid-connected SPVSI switching functions can be achieved through the two first terms of (6) as,

$$u_{cd} = -\left( LI_{avcd} + Ri_{cd} + \omega Li_{cq} + v_d \right) / v_{dc} \quad (25)$$

$$u_{cq} = -\left( LI_{avcq} + Ri_{cq} - \omega Li_{cd} + v_q \right) / v_{dc}$$

By substitution of (25) into the last term of (6) and also after simplifying the equation, (26) can be achieved as,

$$\left( i_{cd} + \frac{LI_{avcd} + v_d}{2R} \right)^2 + \left( i_{cq} + \frac{LI_{avcq} + v_q}{2R} \right)^2 = \quad (26)$$

$$\frac{(LI_{avcd} + v_d)^2 + (LI_{avcq} + v_q)^2 + 8Ri_{dc}v_{dc} - 8RC_{dc}\bar{v}_{dc}v_{dc}}{4R^2}$$

$I_{avdq}$  and  $\bar{v}_{dc}$  are the average values of the inverter currents and dc-link voltages, respectively. By substituting (22) in (25), and with an acceptable approximation and also considering  $v_q = 0$ , the active and reactive power based curve is obtained as,

$$\left( p + \frac{LI_{avcd}v_d + v_d^2}{2R} \right)^2 + \left( q - \frac{LI_{avcq}v_d}{2R} \right)^2 = \quad (27)$$

$$\frac{(LI_{avcd}v_d + v_d^2)^2 + (LI_{avcq}v_d)^2 + 8Ri_{dc}v_{dc}v_d^2 - 8RC_{dc}\bar{v}_{dc}v_{dc}v_d^2}{4R^2}$$

Equation (27) is plotted in Fig. 2. As evident, the maximum and minimum active and reactive power of SPVSI can be achieved by the means of center coordinates and radius value. It can be understood that the active and reactive power of the inverter are dependent of the dc and ac link parameters of SPVSI.

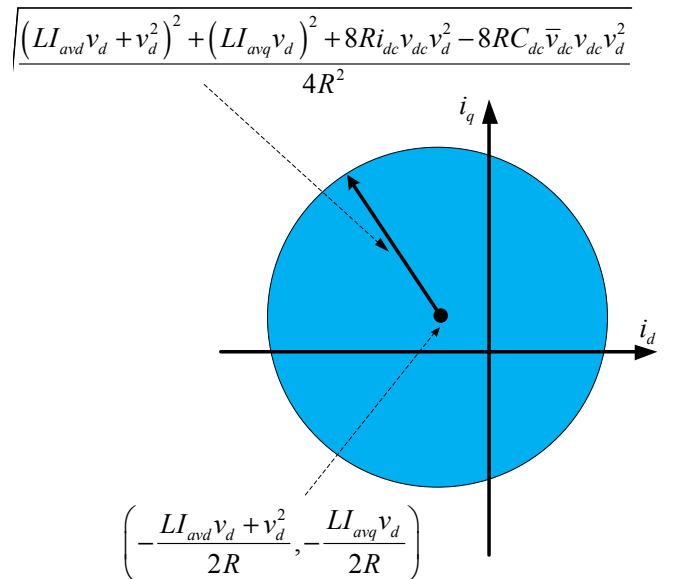


Fig. 2. Capability curve of SPVSI active and reactive power

## V. SIMULATION RESULTS

The assessment of the proposed control technique is carried out based on the overall structure presented in Fig.3. The Matlab/Simulink environment is used to verify the excellent performance of the grid-connected SPVSI during various operating conditions. The system parameters are given in Table I.

TABLE I  
SIMULATION MODEL PARAMETERS

Parameter	Value
Load of diode rectifier	20+j0.3
dc-link voltage set-point ( $v_{dc}$ )	200 V
ac voltage	120V
Fundamental frequency	50 Hz
Switching/Sampling frequency	10 kHz
SPVSI resistance	0.1 m $\Omega$
SPVSI inductance	1 mH

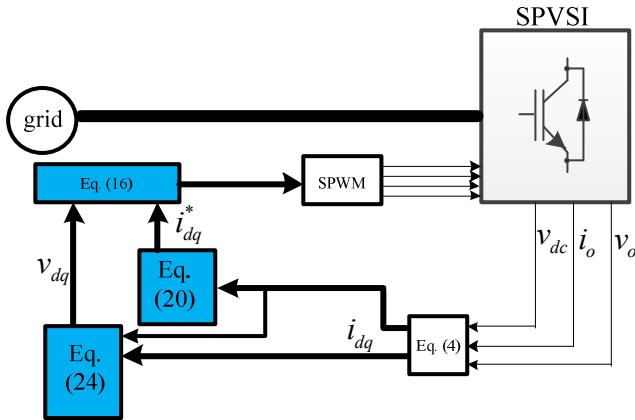


Fig. 3. Overall structure of the proposed controller

### A. The SPVSI active and reactive power evaluation

Firstly, the grid supplies a single-phase full-bridge diode rectifier as a nonlinear load in the time interval of [0, 0.05].

Then, SPVSI is connected to the point of common coupling at  $t=0.05$ s. Active and reactive power of SPVSI, grid, and load are illustrated in Fig. 4.

As can be seen from the figure, when the SPVSI is not connected, both active and reactive power of the load are withdrawn from the grid and its respective powers for the inverter are zero. Then, after SPVSI connection, the whole reactive power of the load is supplied by the inverter and also the total harmonic components of active power and a fraction of active power at fundamental frequency are produced by SPVSI as depicted in Fig. 4.

This test verifies that the proposed controller can accomplish an effective active and reactive power contribution during any sudden changes.

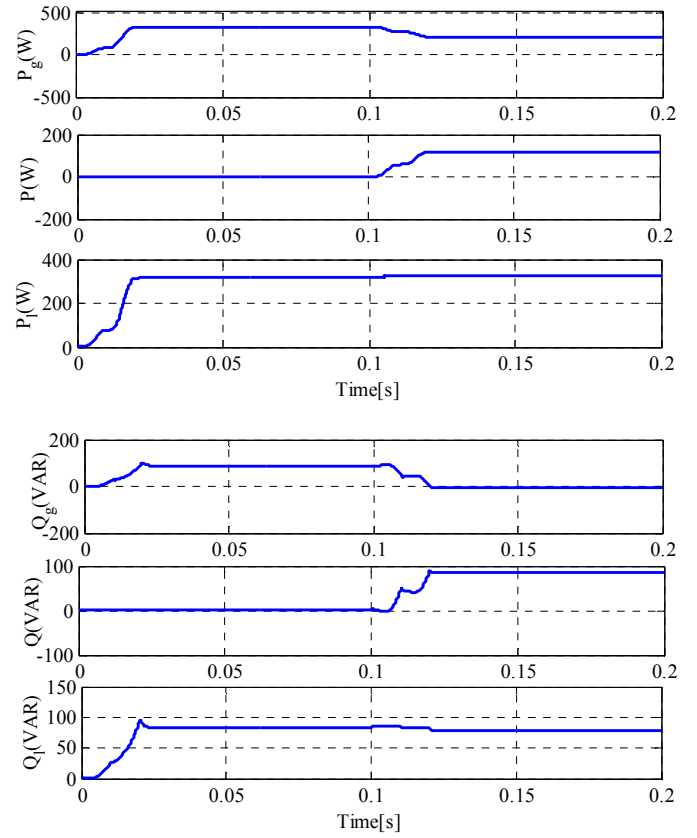


Fig. 4. Active and reactive power of grid, load and SPVSI

### B. Analysis of the grid current

In order to assess the merit of the proposed controller in enhancement of power quality and compensation of harmonic components, the upstream grid current is analyzed in this section.

Fig. 5 shows the grid current and voltage, load current, and SPVSI current. As can be seen in Fig.5, once SPVSI is connected to the grid, the grid current will become sinusoidal and also in phase with the grid voltage that demonstrates a complete generation of load reactive power through SPVSI.

Fig. 6 illustrates the harmonic spectrum of grid current during SPVSI connection. This figure shows that the SPVSI is able to properly inject the required harmonic components of the load and make the grid current pure sinusoidal with a low THD.

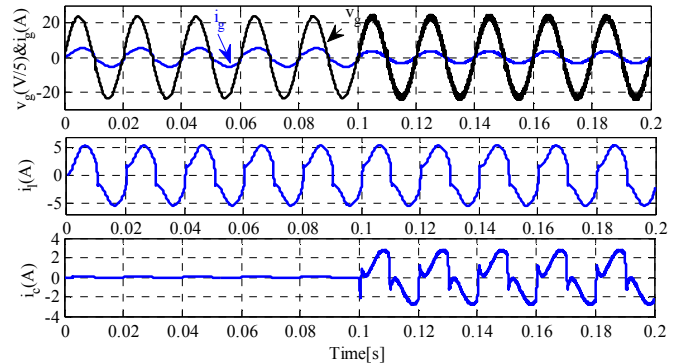


Fig. 5. Grid current and voltage, load current, and SPVSI current

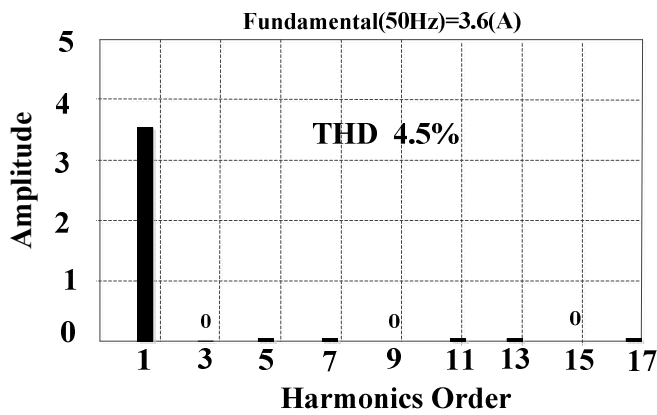


Fig. 6. Harmonic spectrum of grid current

## VI. CONCLUSION

A comprehensive Direct-Quadrature (DQ) rotating frame based dynamic model for a grid-connected SPVSI was developed in this paper to design a droop-passivity based controller for a better performance in presence of nonlinear loads. Also, details of the controller design principles and its stability issues were thoroughly discussed. Moreover, an accurate operation area for SPVSI active and reactive power was obtained that was used as a capability curve for achieving a more precise power sharing performance. By using a well-designed reference generation scheme, an effective harmonic compensation was attained in the proposed controller. Finally, the proposed controller impacts on the grid-connected SPVSI operation was evaluated in Matlab/Simulink environment.

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