



Multifunctional Single-Phase Single-Stage Grid-Connected PV System

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Abstract. This paper presents the analysis of a multifunctional single-phase single-stage grid connected photovoltaic (PV) system. The primary function of the grid connected inverter in a single stage (PV) system is to supply active power to both load and grid in a way that complies with the applied grid connection standards. The added functions to the grid connected inverter are compensation for reactive power requirements and mitigation of the harmonics produced by the nonlinear loads connected to the point of grid connection.

The single stage topology utilized in the grid connected PV system has the advantages of high efficiency and low cost compared with the two stage topology. Maximum power point tracking (MPPT) is achieved using perturb and observe algorithm. A test system composed of the PV array, single phase inverter, single phase supply, and three different types of single phase loads is modeled to evaluate the performance of the multifunctional operation of the PV grid connected system. The results of the test system simulation, using MATLAB/Simulink environment, validate the effectiveness of the system to perform the multifunctional operation of the grid connected inverter.

Key words

Active Filter, Grid Connection, Photovoltaic, and Single Phase.

1. Introduction

PV systems generate electricity without producing CO₂. They are clean, pollution free, and inexhaustible. These properties have led to worldwide government policies aimed at increasing the deployment of grid connected PV systems that are connected to local loads and the utility power networks. The price of the PV modules was in the past the major contribution to the cost of these systems. A downward tendency is now seen in the price for the PV modules due to a massive increase in their production capacity [1].

Conventionally, a two-stage PV system is employed to connect a PV array to the electrical power system. The converter of the first stage (DC/DC converter) is controlled

so as to track the maximum power point of the PV array, and to transfer energy to the second stage converter. The second stage converter (DC/AC inverter) is controlled to produce an output current in phase with the grid voltage and to obtain a unity power factor. The main advantage of this topology is easier controller design as the two converters have independent control goals and architectures. Yet, the system has poor efficiency, due to a large number of devices, excessive size, heavy weight, and high cost [2].

In this paper, a single stage PV system is used to convert energy to both local loads and utility grid. Regardless of its control complexity, the single stage PV system is more efficient and cheaper than the two stage system.

Due to the proliferation of nonlinear loads which depend on power electronics converters, there is an increasing concern to control and reduce the harmonics current in distribution power systems. These types of loads draw non-sinusoidal currents from the grid, causing harmonics power quality problems [3].

This paper presents the analysis of a multifunctional single-phase single-stage grid connected PV system. It can be used to supply reactive type loads as well as nonlinear loads without degrading the quality of the grid current, as a result of the added reactive power compensation capability and the active filtering function to the grid connected inverter control scheme.

2. System Description and Modeling

The system presented in this paper uses a current controlled voltage source inverter as an interfacing circuit that connects the PV module to both the utility grid and the local loads. The maximum power point tracking (MPPT) algorithm is implemented in the inverter control along with reactive power compensation and harmonics elimination control.

A. Power Circuit

The power circuit of the proposed PV system, is shown in Fig. 1. consists of a PV array connected to a dc link capacitor (C_d). The purpose of this capacitor is to stabilize the dc link voltage and to dampen the oscillation in the output power of the inverter which is running at twice the supply frequency. The dc link terminals are directly connected to a single-phase H bridge voltage source inverter to convert the dc voltage output from the PV array to a controlled ac voltage. The ac side of the inverter is connected to the grid and the local loads through a LC filter that attenuates the high frequency harmonics in the inverter output voltage/current which result from the inverter switching.

The grid is assumed to be a perfectly sinusoidal single phase supply. The local loads connected to the system are of three types: linear loads with only active power requirements, linear loads with both active and reactive power requirements, and nonlinear loads.

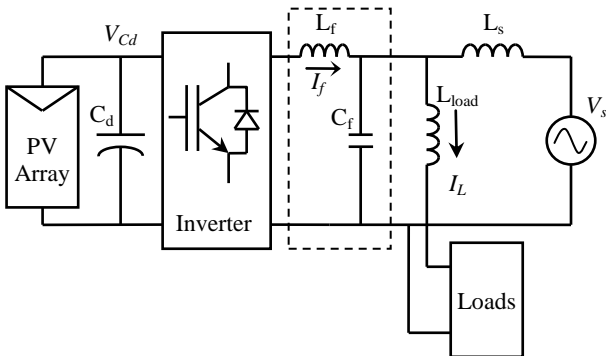


Fig. 1 Power circuit of the PV system

B. PV Array Modeling

A PV cell is the basic element of the PV array. The traditional equivalent circuit of a PV cell is shown in Fig. 2. It consists of an ideal dc current source (I_{ph}) in parallel with an anti-parallel diode (D). A series resistance (R_S) is added to represent the sum of several structural resistances of the device, while a shunt resistance (R_{SH}) is added to the circuit to account for the leakage current of the $p-n$ junction of the PV cell.

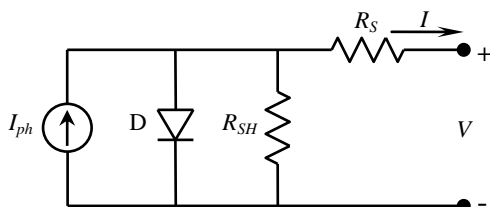


Fig. 2. PV cell equivalent circuit

The following equation mathematically describes the I-V characteristic of the ideal PV cell [4]:

$$I = I_{ph} - I_o \left[e^{\left(\frac{q(V+IR_S)}{k \times A \times T_c} \right)} - 1 \right] - \frac{V+IR_S}{R_{SH}} \quad (1)$$

I_{ph} light-generated current

I_o	PV cell saturation current
q	Charge of an electron
k	Boltzmann's constant
A	Ideality factor of the p-n junction
T_c	PV junction temperature
R_S	Intrinsic series resistance of the PV cell
R_{SH}	Shunt resistance of the PV cell

Normally, several PV cells are connected in series, results in PV module, in order to obtain the required dc output voltage. A series parallel combination of PV modules forms a PV array.

Modeling of the PV array is implemented in MATLAB/Simulink as a programmed block with three inputs (PV array voltage, irradiance and cell temperature) and two outputs (PV array output current and output power) as shown in Fig. 3.

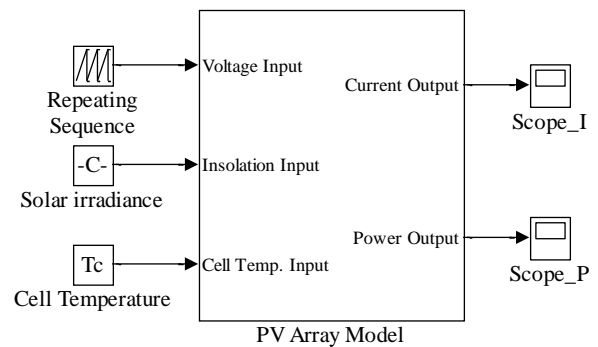


Fig. 3. PV array model using MATLAB/Simulink

The simulation results of the PV module I-V characteristics with different temperature conditions is shown in figures 4.

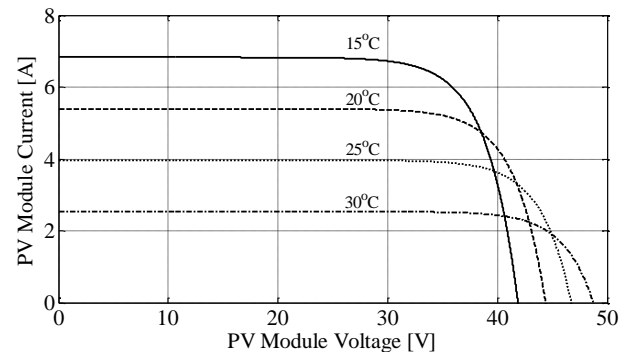


Fig. 4. PV module I-V characteristics

C. Maximum Power Point Track Algorithm

The algorithm used to achieve MPPT is the Perturbed and Observe algorithm. It is based on perturbing the PV array voltage and observing the rate of the array output power change with respect to the voltage (dP/dV). The direction of the derivative shows if the voltage is higher or lower than its optimum value, and it has to be decreased or increased until the MPP is reached when the derivative is zero. As this algorithm is based on perturbation, there will always be some oscillations around the MPP even when this MPP is reached [5]. Fig. 5 shows the flow chart that describes the procedures used

to implement the perturb and observe method. When the dP/dV is positive, the maximum power occurs at a voltage higher than the optimum voltage, whereas when dP/dV is negative the maximum power occurs at a voltage lower than the optimum voltage. When dP/dV approaches zero, the desired voltage is obtained.

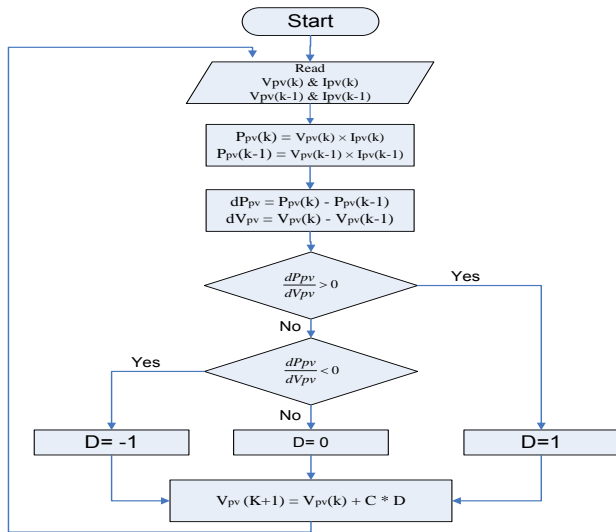


Fig. 5. Flowchart of the perturb and observe method

3. System Control

The presented PV system has two control loops. An outer loop for dc link voltage control and maximum power point tracking, and an inner loop for output current control. The dc link voltage control time constant is considered greater than that of the current control loop so that both loops can be studied separately. The block diagram of the overall control system is shown in Fig. 6.

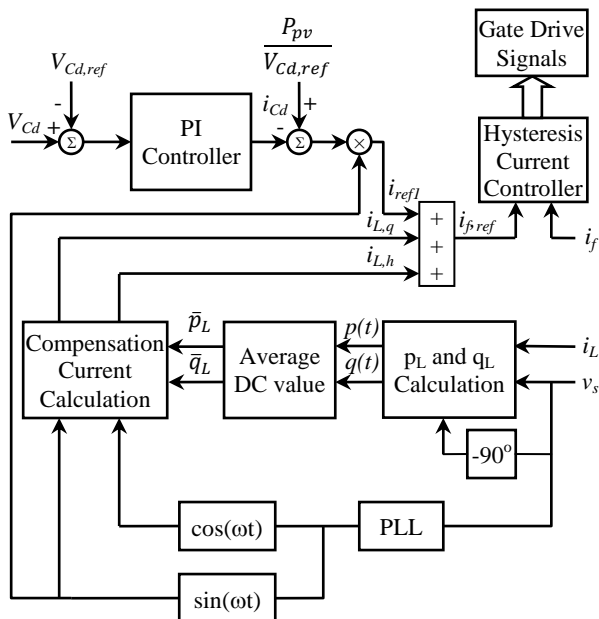


Fig. 6. Block diagram of the overall control system

A. Voltage Control Loop

The dc voltage across the dc link capacitor is detected and compared with its reference voltage ($V_{Cd,ref}$). The compared result is processed by a PI controller to obtain the desired amplitude of the dc link capacitor charging current (I_{Cd}). The proportionality constant (K_p) of the PI controller determines the dynamic response of the voltage control loop and its value is determined using the energy balance principle. The integration constant (K_i) affects the settling time and is determined empirically [6].

B. Current Control Loop

The instantaneous active/reactive power calculator receives the load current and source voltage signals in real time. The instantaneous active load power (p_L) and instantaneous reactive load power (q_L) are calculated based on the extension p-q theorem [7]. Their dc components are filtered with digital second-order Butterworth LPFs. These dc components are then fed to the compensation current reference generator to obtain the reactive load current ($i_{L,q}$) and harmonic load current ($i_{L,h}$). The summation of these two current signals along with the active power requirement current component, forms the compensation current reference signal ($i_{f,ref}$).

In order to generate the compensation current that follows the estimated current reference signal, the hysteresis current control method is adopted. The estimated compensation current reference signal ($i_{f,ref}$) and the actual compensation current signal (i_f) are both fed to a fixed band hysteresis current controller to generate appropriate gating signals for the inverter switching transistors.

1) Compensation Current Generation

Based on the extension p-q theorem, the load current for a single-phase two-wire system with nonlinear load, can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} \sqrt{2} I_L \sin(n\omega t + \theta_n) \quad (2)$$

Under normal circumstances, the voltage at the point of common coupling (PCC) can be assumed to be a sinusoidal, i.e

$$v_s(t) = \sqrt{2} V_s \sin(\omega t + \phi) \quad (3)$$

Therefore, the instantaneous active power of the nonlinear load can be calculated as

$$P_L(t) = v_s(t) \cdot i_L(t) = \bar{p}_L + \tilde{p}_L \quad (4)$$

The instantaneous reactive power of the nonlinear load can be written as follows

$$q_L(t) = v_s'(t) \cdot i_L(t) = \bar{q}_L + \tilde{q}_L \quad (5)$$

where \bar{p}_L and \bar{q}_L represent the dc components, \tilde{p}_L and \tilde{q}_L denote the varying components, and $v_s'(t)$ denotes the PCC voltage shifted by 90° .

According to the pervious results, the active power current component ($i_{L,p}$), reactive power current component ($i_{L,q}$) and the harmonics current components ($i_{L,h}$) of a nonlinear load current can be calculated as follows :

$$i_{L,p}(t) = \sqrt{2} \frac{\bar{P}_L}{V_s} \cdot u(t) \quad (6)$$

$$i_{L,q}(t) = \sqrt{2} \frac{\bar{Q}_L}{V_s} \cdot u(t - 90^\circ) \quad (7)$$

$$i_{L,h}(t) = i_L(t) - i_{L,p}(t) - i_{L,q}(t) \quad (8)$$

where $u(t)$ is a unit sine function in phase with the PCC voltage. Finally, the compensation current reference can be expressed as

$$i_{f,ref} = i_{L,q} + i_{L,h} + \frac{P_{pv}}{V_{Cd,ref}} \cdot u(t) \quad (9)$$

Where P_{pv} is the active power of the PV array and $V_{Cd,ref}$ is the dc link capacitor voltage reference. The compensation current reference is used as input for the hysteresis current controller.

2) Hysteresis Current Controller

In applications such as a grid connected PV system, it is the output current that needs to be controlled, even though a voltage source inverter is often used. Hysteresis current control technique imposes a bang-bang type instantaneous control that forces the compensation current to follow its estimated reference. The actual compensation current is subtracted from its estimated reference. The resulting error is sent through a hysteresis controller to determine the appropriate gating signals. The hysteresis current control scheme has the advantage of limiting the output current. Hysteresis current control is illustrated in Fig. 7.

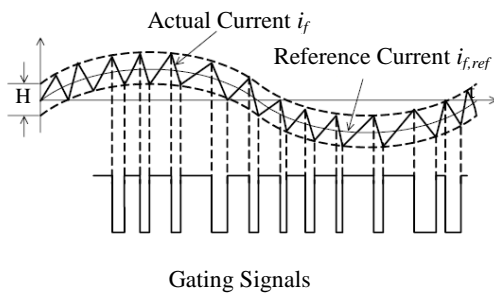


Fig. 7. Hysteresis Current Control

In hysteresis current control the switching frequency is variable depending on how fast the current changes from the upper limit to the lower limit and vice versa. The resulting current response depends mainly on the equivalent system inductance.

4. Simulation Results

The multifunctional single phase single stage grid connected PV was simulated using MATLAB/Simulink environment. The main system parameters are listed in Table 1.

Table 1 system parameters

Symbol	Quantity	Values
P_{MPPT}	PV Module rated power	175 W
V_{MPPT}	PV Module rated voltage	35.4 V
I_{MPPT}	PV Module rated current	4.95 A
V_{OC}	PV Module open-circuit voltage	44.4 V
I_{SC}	PV Module short-circuit current	5.4 A
N_s	Number of series PV cells per module	72
N_p	Number of parallel PV cells per module	1
N_{Sm}	Number of series PV modules per array	11
N_{Pm}	Number of parallel PV modules per array	3
P_{rated}	PV Array rated power	5.7 kW
T_c	PV Cell Temperature	25°C
V_s	Grid voltage in RMS	220 V
f	Frequency	50 Hz
L_f	Output filter inductor	0.01mH
C_d	dc-link capacitor	215.8 mF

The PV system is simulated under three different load types: Linear resistive load to proof the system capability for active power generation, linear resistive plus inductive load to examine the reactive power compensation requirement and a nonlinear load (single phase diode rectifier with shunt resistor and capacitor on its dc side) to validate the harmonics mitigation function.

A. Active Power Generation Condition

The system under test is modeled and simulated first with 3 kW resistive loads. The simulation results for the grid voltage and current are shown in Fig. 8a while, the simulation results for the grid voltage and PV inverter current are shown in Fig. 8b.

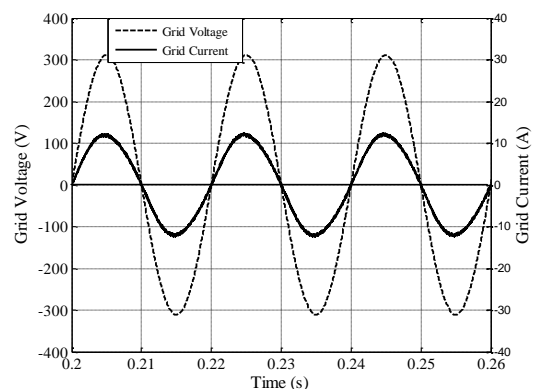


Fig. 8a. Simulation results for grid voltage and current with 3 kW resistive linear loads

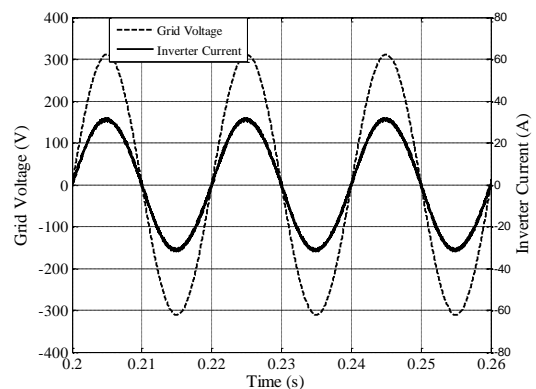


Fig. 8b. Simulation results for grid voltage and inverter current with 3 kW resistive linear loads

The results show that both the grid current and the inverter current are in phase with the grid voltage. This means that the PV supplies active power to the load as well as to the grid, i.e. the load active power requirement is below the rated PV output power, so that the rest of the PV power is injected into the grid.

The system resistive load is now increased from 3kW to 7kW (above the PV rated output power).The simulation results are shown in Fig. 9a and Fig.9b. It is clear that the grid current is now out of phase with respect to the grid voltage, while the inverter current is still in phase with it. This means that both the PV and the grid are supplying the load requirement as it is above the rated PV output power.

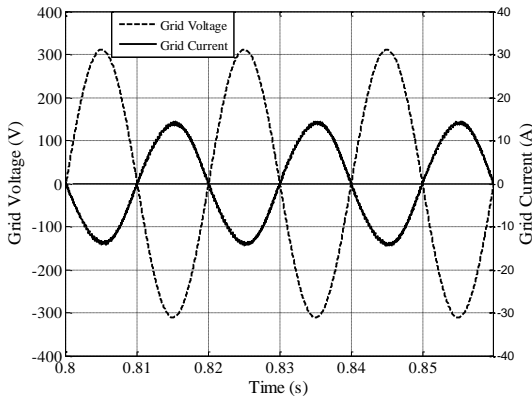


Fig. 9.a Simulation results for grid voltage and grid current with 7 kW resistive linear loads

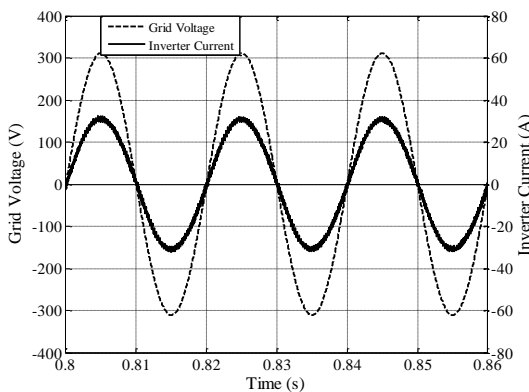


Fig. 9.b Simulation results for grid voltage and inverter current with 7 kW resistive linear loads

B. Reactive Power Compensation Condition

To emphasize the inverter capability to compensate for local reactive loads, the inverter has been operated with an inductive load type. The simulation results for the load and grid currents with 3 kW & 2 kVAr load are shown in Fig. 10a and Fig.10b. The load current lags the grid voltage by about 33.7 electrical degrees (inductive load), while it can be noted that the grid current remains purely active (in phase with grid voltage) since the inverter completely compensates for the load reactive power requirements. For a load of 7 kW & 2 kVAr, the simulation results are shown in Fig. 11a and Fig.11b. The load current lags the load voltage by about 16 electrical degrees and the grid current is out of phase with respect to the grid voltage, which means pure active power generation from the grid (without supplying any reactive power). In this case the PV supplies

the entire load reactive power requirement but it cannot satisfy alone its active power requirements.

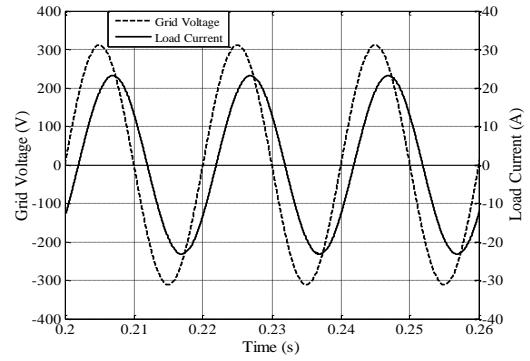


Fig. 10.a. Simulation results for grid voltage and load current with 3 kW & 2 kVAr inductive linear loads

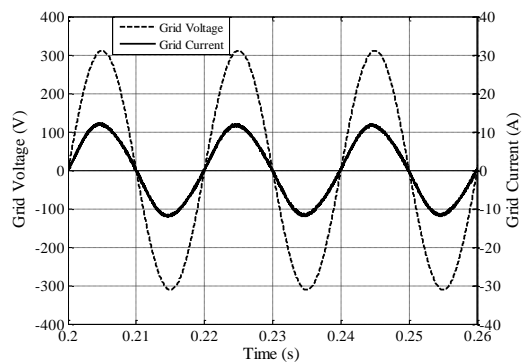


Fig. 10.b. Simulation results for grid voltage and current with 3 kW & 2 kVAr inductive linear loads

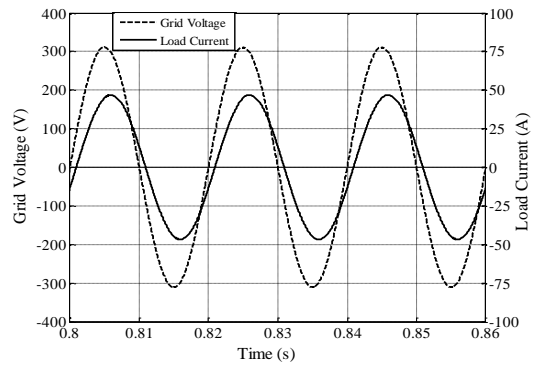


Fig. 11.a Simulation results for Grid voltage and load currents with 7 kW & 2 kVAr inductive linear loads

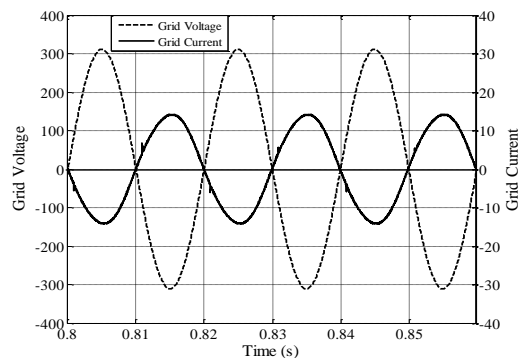


Fig. 11.b Simulation results for Grid voltage and currents with 7 kW & 2 kVAr inductive linear loads

C. Current Harmonic Compensation Condition

The load in this case is a nonlinear load with 3 kW and 2 kVAr. The simulation results for the load current and the grid current are shown Fig. 12a and Fig.12.b. It can be noted that the grid current is still pure sinusoidal and in phase with the grid voltage, i.e. the PV inverter produces the required load harmonics current (active filtering function) without degrading the quality of the grid current. Fig. 12.c shows the harmonics spectrum for both load current and grid current. The total harmonic distortion (THD) of the load current is 34.5%, and of the grid current is 4.9%.

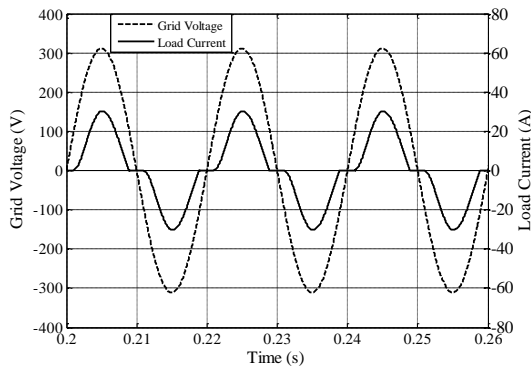


Fig 12.a Simulation results for grid voltage and load current with 3 kW & 2 kVAr nonlinear load

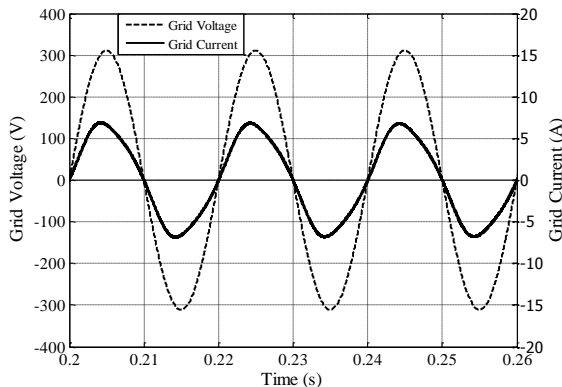


Fig 12.b Simulation results for grid voltage and grid current with 3 kW & 2 kVAr nonlinear load

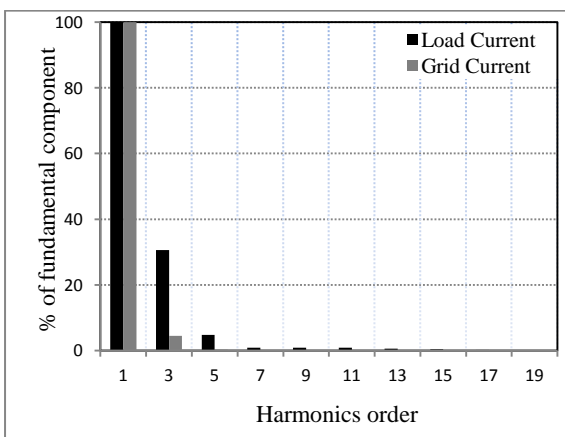


Fig 12.c Simulation results for harmonics spectrum of load current and grid current with 3 kW & 2 kVAr nonlinear load

5. Conclusion

In this paper, a multifunctional single-phase single-stage PV system has been presented. The modeling of the PV array was discussed and its simulation performed with MATLAB/Simulink environment. A test system was chosen to verify the concept of a multifunctional grid connected PV system. The system utilizes hysteresis current controlled voltage source inverter to perform the required functions. Perturb and Observe Algorithm was used for MPPT achievement and an extension of the p-q theorem was implemented for reference current extraction. The simulation of the test system model was performed under three different load types; resistive linear load, reactive type load and nonlinear loads. Each load type was subjected to incremental change to ensure the grid supplying capability for the PV system whenever the load requirements are below the PV output power. The simulation results prove the ability of the system to compensate for reactive load power requirements and mitigate the harmonics produced by the nonlinear loads connected to the PCC.

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