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SRF based control of single stage dual purpose three-phase grid integrated solar PV system

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Solar Photovoltaic (SPV) offers alternative sources of energy which is in general pollution free, environment friendly, sustainable and unlimited in nature. The concerns of environment due to green house gases and global warming force research communities to develop a smart power system that has capability to integrate Solar Photovoltaic with the power grid. There are many challenges in integrating SPV generation with the grid like efficiency, power quality, stability, cost of the energy conversion, load management, reliability etc. Moreover, power quality problems at distribution level like harmonics, unbalanced supply, unbalanced loads, reactive power, load management etc. affect the operation of grid connected SPV systems. Single stage grid connected PV systems has the advantage of use of a single VSC for MPPT (Maximum Power Point Tracking) and inverter operation. The proposed grid interfaced SPV generating system consists of a SPV array, VSC (Voltage Source Converter), three-phase grid and linear/nonlinear loads. The SPV energy is injected in to the DC bus of VSC during sunshine hours. The DC bus voltage of a three- phase VSC is regulated for MPPT from the PV array. Secondly, this system serves to provide harmonics elimination, load balancing, power factor correction (PFC) and regulating the terminal voltage at the PCC (Point of Common Coupling). In this paper, a SRF (Synchronous Reference Frame) based control of a single stage dual purpose grid connected SPV system is proposed and simulation based on MATLAB and Simpower System Blockset demonstrates the dual purpose of the system.

Keywords: *Solar photovoltaic, MPPT, voltage source converter, UPF operation, harmonic elimination.*

1.0 INTRODUCTION

With an increase in the demand of renewable energy sources, grid connected solar photovoltaic (PV) system is emerging as a major research area these days. Solar photovoltaic (SPV) offers alternative sources of energy which is in general pollution free, environment friendly, sustainable and unlimited in nature. However, there are a number of potential challenges in integrating solar photovoltaic (SPV) to the grid due to its unpredictable nature [1]. There is a need for robust, sustainable and climate friendly power generating systems that are intelligent, reliable, and green. Many grid interfaced converter topologies are available for integrating renewable energy to the grid. There are number of dominant problems being faced while the grid is interfaced to SPV [2]. These are related mainly with power quality like power factor correction, reactive power compensation and voltage regulation.

There are many challenges in integrating SPV generation with the grid like efficiency, power quality, stability, cost of

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the energy conversion, load management, fault ride through, reliability etc. Moreover, power quality problems at distribution level like harmonics, unbalanced supply, unbalanced loads, reactive power, load management etc. affect the operation of grid connected SPV systems [3]. However, while integrating renewable energy of any sources to the electric grid, it has to fulfil standard power quality requirements so that the grid is not polluted due to such interface.

There are many three phase grid integrated SPV system systems reported in the literature [4-8]. Maximum power point tracking (MPPT) from SPV array is also a challenging task and there are various MPPT techniques: Hill climbing or P&O, fuzzy logic control, incremental conductance, neural network, Fractional Open Circuit Voltage (FOCV), Fractional Short Circuit Current (FSCI) etc. have been discussed and compared in the literature [8]. The SPV system which serve the power quality improvement along with active power injection is also reported in the literature [9-14]. The SPV energy system compensates for linear and nonlinear loads with objectives of load balancing, harmonics elimination and correction of power factor to unity. This increases the utilization of the SPV system and helps in early recovery of cost of the PV system.

Recently, a single stage topology of SPV system is reported which can eliminate the dc-dc converter from the conventional system [15-16]. However, it has been shown by Barnes et.al [16], that a single stage topology is more effective than a double stage topology for the system with DC link voltage greater than 340 V. The Least Mean Fourth (LMF) based control [17] and unit vector theory [18] control of single stage topologies are reported.

In this paper, a SRF (Synchronous Reference Frame) based control of a single stage dual purpose grid connected SPV system is proposed. The SRF control algorithm gives the system a better dynamics because of the inherent capability of control in the stationary reference frame. The design of the system, control of the system, modeling and simulation and the conclusions are presented in the subsequent sections of this paper.

2.0 DESIGN OF PROPOSED CONFIGURATION

A SPV system integrated to a three phase grid having loads as shown in Fig. 1. The system components to be designed are SPV array, DC bus voltage, DC link capacitance, IGBT (Insulated Gate Bipolar Transistor) based VSC rating, interfacing inductances and the ripple filter.

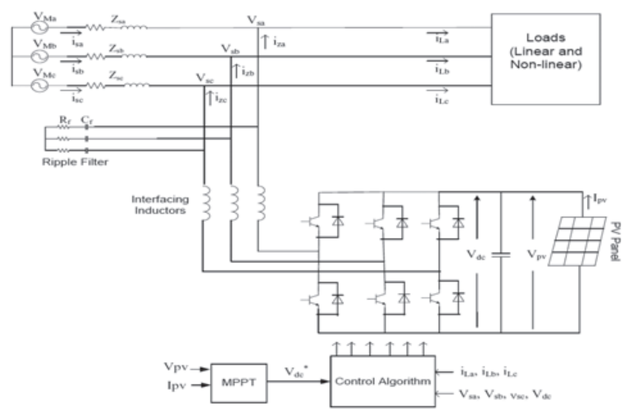

FIG.1. SINGLE STAGE TOPOLOGY OF GRID CONNECTED SPV SYSTEM

A. Selection of SPV array

The details of SPV array model chosen is shown in Table I. The SPV array used here is modelled for maximum power capacity of 6 kW connected to a 415 V, 50 Hz, 3-phase system.

The number of SPV modules connected in series are estimated

$$n_s = \frac{V_{dc}}{V_{mp}} = \frac{800}{26.3} = 30 \text{ modules} \tag{1}$$

The number of SPV modules connected in parallel are estimated as, value of Vdc is taken as 800 V.

$$n_p = \frac{P_{max}/V_{dc}}{I_{mp}} = \frac{6000/800}{7.6} = 1 \text{ module} \quad \ldots (2)$$

TABLE I					
DETAILS OF SPV ARRAY MODEL					
I_{mp}	7.6 A	I_{sc}	8.25 A	I_{pv}	8.214 A
V_{mp}	26.3 V	V_{oc}	31.7 V	R_s	0.17593 Ω
P_{max}	200 W	I_o	$8.45*10^{-8}$ A	R_p	990.84Ω

B. Selection of DC Bus Voltage

The minimum value of DC bus voltage for the VSC which has to be maintained must be more than twice the value of the peak phase voltage at the PCC (Point of Common Coupling) or the grid.

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} = \frac{2\sqrt{2}*415}{\sqrt{3}*0.95} = 713.36 \text{ V} \quad (3)$$

Where, V_{LL} is grid line voltage and m is the modulation index. (Values considered here are m=0.95 and VLL=415 V). So, the

C. Design and Selection of IGBT based VSC

Under dynamic conditions, the voltage rating (V_{sw}) of the Therefore, the SPV array with peak power capacity of 6 kW is modelled with 30 modules connected in series and 1 module connected in parallel. devices (IGBT) is computed as,

$$V_{sw} = V_{dc} + V_d = 800 + 80 = 880 \text{ V} \quad \ldots (4)$$

Where, V_d is 10% over-shoot on the DC voltage (V_{dc}) under dynamic conditions. And with appropriate factor of safety, the selected value of V_{sw} = 1200 V.

The current rating (I_{sw}) is estimated as,

$$I_{sw} = 1.25*(I_{crpp} + I_{peak}) = 1.25*(0.06*8.25 + 8.25) = 10.93 \text{ A} \quad \ldots (5)$$

Where, I_{crpp} is the ripple current value with 6% ripple. So, the selected value of I_{sw} = 50 A.

D. Design and Selection of Interfacing Inductances

$$L_f = \frac{\sqrt{3}mV_{dc}}{12*h*f_s*\Delta i} = \frac{\sqrt{3}*0.95*800}{12*1.2*10000*0.03*8.25} = 36.9 \text{ mH} \quad \ldots (6)$$

Where, h = 1.2 is the overloading factor, fs = 10 kHz is switching frequency, and Δi is ripple current that is 3% of the peak current.

E. Design and Selection of VSC-DC Link Capacitance

$$C_{dc} = \frac{P_{dc}/V_{dc}}{2*\omega*V_{dcrip}} = \frac{6000/800}{2*314*0.02*800} = 746.42 \ \mu\text{F} \quad \ldots (7)$$

Where, Vdcrip is the % ripple voltage taken as 2% of the DC link voltage and ω = 2π*50=314rad/s is the angular frequency. So, the value of VSC-DC link capacitor is selected as 1000 µF as it can stabilize the DC link voltage quickly during disturbances

F. Design and Selection of Ripple Filter

Rf = 5 Ω as designed in [19].

3.0 CONTROL OF THE PROPOSED SYSTEM

The grid connected system employs a single stage converter topology to effectively extract the maximum power from the SPV array and to regulate the DC link voltage at the VSC. The control algorithm consists of two components: MPPT algorithm and the control algorithm of VSC. The purpose of the MPPT algorithm is to extract maximum power from the SPV array at all conditions and also to provide a reference VSC-DC link voltage which is used to sustain the DC bus voltage to its desired level. On the other hand, the control algorithm of VSC focusses on generating gating signals for the appropriate switching of the VSC-IGBT's and includes control functions such as load balancing, harmonics elimination, regulating the voltage at the PCC terminals, balancing grid currents and PFC.

A. MPPT Control

Compared to various MPPT algorithms the most often used one is the P&O technique due to its simplicity. This technique is based on the fact that at the MPP (maximum power point) the derivative of power w.r.t. the voltage is zero. At any point of operation on the power vs. voltage (P-V) curve, if the voltage at that point is perturbed in any direction and the change in power is positive, then it is said that the perturbation has moved the SPV array's operating point towards the new MPP and the perturbation is then continued in same direction. Another case would be if the change in power is negative, then it is said that the perturbation has moved the SPV array's operating point away from the MPP which means the next perturbation has to be in the reversed direction. Last case is if the change in power is zero, which means the array's operating at its MPP. Here the MPPT inputs SPV array voltage (Vpv) and current (Ipv) and it processes to give DC reference voltage Vdc* as its output.

B. Control Algorithm for Switching of VSC

The control algorithm of VSC focuses on generating gating signals for the appropriate switching of the VSC-IGBT's and includes control functions such as load balancing, harmonics elimination, regulating the voltage at the PCC terminals, balancing grid currents and PFC. Synchronous Reference Frame Theory (SRF) is used for the controlling of VSCs. This theory is based on the transformation of the load currents in abc frame into synchronously rotating d-q frame. That is, it is based on the transformation of three phase quantities into two phase quantity in the d-q frame. Fig. 2. Shows the VSC control system using SRFT.

Load currents, PCC voltages and DC bus voltages are sensed as feedback signals. Load current from abc frame are converted to d-q frame by the following transformation.

$$\begin{bmatrix} i_{Lq} \\ i_{Ld} \\ i_{L0} \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (8)$$

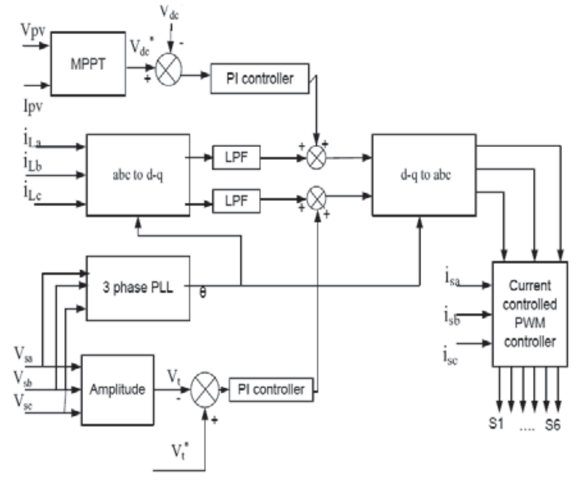

FIG. 2. BLOCK DIAGRAM OF SRF BASED CONTROL APPLIED TO THE THREE LEG

In this cos θ and sin θ are obtained using PLL over PCC voltages. Harmonics are filtered from reference signal by a low pass filter (LPF). The d axis and q axis current consists of fundamental and harmonic currents as,

$$i_{Ld} = i_{ddc} + i_{dac} \quad (9)$$

$$i_{Lq} = i_{qde} + i_{qac} \quad (10)$$

The dc and harmonic quantities are separated by SRF controller using LPF. The dc voltage from the photovoltaic is compared with a reference voltage and the error signal is given to the PI controller and it is used for active power management and also for load current balancing. The actual PCC voltage is compared with reference PCC voltage and the error signal is given to the PI controller and it is used to regulate the PCC voltage. The conversion of currents in d-q frame to abc yields the reference source currents. The actual source currents is then compared with the reference source currents using hysteresis current controller for generating different gating pulses.

4.0 MODELING AND SIMULATION

The proposed single-stage three phase SPV power generating system integrated with the grid is modeled and simulated in MATLAB/Simulink with the help of simpower system toolbox under different conditions. The SPV array which is used here is modelled for maximum power capacity of 6 kW connected to a 415 V, 50 Hz, 3 phase system. The simulation is carried out for a diode rectifier with RL load. For assessing the behaviour of the system, results involve significant signals such as grid voltages (v_{sabc}), grid currents (i_{sabc}), load currents (i_{Labc}), reference grid currents (i_s*), VSC voltages (v_{spv}), VSC currents (i_{spv}), VSC-DC link voltage (V_{dc}), SPV array DC current (I_{pv}), SPV array DC voltage (V_{pv}), and SPV array DC power (P_{pv}).

A. Steady state performance under non-linear loads

Fig. 3 and 4 depicts the steady state behavior of the grid connected SPV system under a nonlinear load. Steady state performance is carried out for an insolation of 1000 W/m^2 as shown in Fig. 3 (a). The SPV current and voltage are shown in Fig. 3 (b), (c). The power that extracted from the SPV array as shown in Fig. 3 (d). For a constant insolation the SPV current and power extracted are constant. Fig. 3 (e) shows the DC link voltage. It can be clear that the DC link voltage is regulated to the desired value. Fig. 3 (f), (g) shows source active power and reactive power. Fig. 4 (a), (b) shows the grid voltages and grid currents. It can be see that the grid currents and grid voltages are in phase. Thus power factor at source side is improved. Fig. 4 (c), (d) shows the load voltages and phase 'A' load current waveforms. It can be see that the load current is non sinusoidal, because the load used is diode rectifier with RL. Fig. 4 (e) shows the reference source current waveforms. Fig. 4 (f), (g) shows the inverter output voltages and currents. The dc link voltage is regulated to desired value.

B. Dynamic behaviour of Grid connected topology under variable insolation

Fig 5, and 6 show the dynamic behaviour of the grid connected topology when the insolation is changed from 500 W/m^2 to 1000 W/m^2 at 0.17 sec. With the increase in the solar irradiance, the level of power (P_{pv}) which can be extracted from the SPV array is increased as well as the value of SPV current (I_{pv}) as shown. And also can see that the dc link voltage is regulated to desired value. With the increase of insolation the grid current value is drops to a lower value and hence the source active power also reduced. From Fig. 6 (a), (b) it is clear that the source voltages and source currents are in phase and hence power factor at source side is improved.

C. Dynamic behaviour of the grid connected topology under unbalanced load

Fig. 7, and 8 shows the dynamic behaviour of the grid connected topology under unbalanced load from 0.12 to 0.18 sec. Even under the load unbalancing, the grid currents are maintained sinusoidal with grid voltages and the DC link voltage are regulated to desired value.

The waveforms of the PCC voltage, Ac mains current and one phase of load current along with their harmonic spectra are demonstrated in Figs 9-11 respectively. The Total Harmonic Distortion (THD) values of the grid voltage, grid current, load current as 0.10 %, 1.13 % and 19.88 % respectively. The THDs at grid side are observed to be well within limits of an IEEE-519 standard [20].

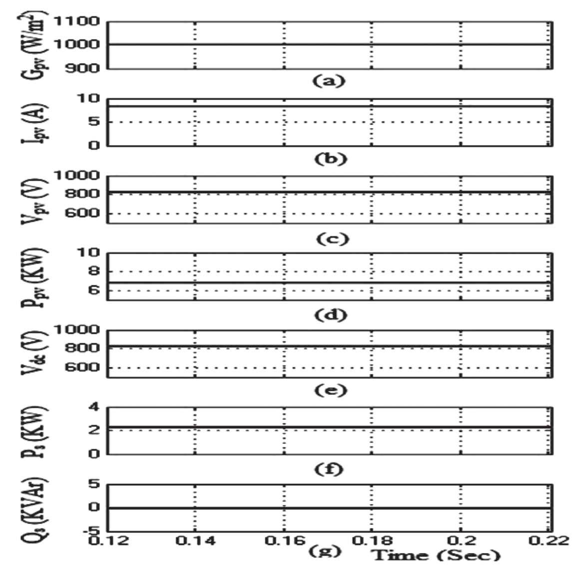

FIG. 3. STEADY STATE BEHAVIOUR OF THE GRID CONNECTED SPV SYSTEM (A) INSOLATION (B) PV CURRENT (C) PV VOLTAGE (D) PV POWER (E) DC LINK VOLTAGE (F) SOURCE REAL POWER (G) SOURCE REACTIVE POWER.

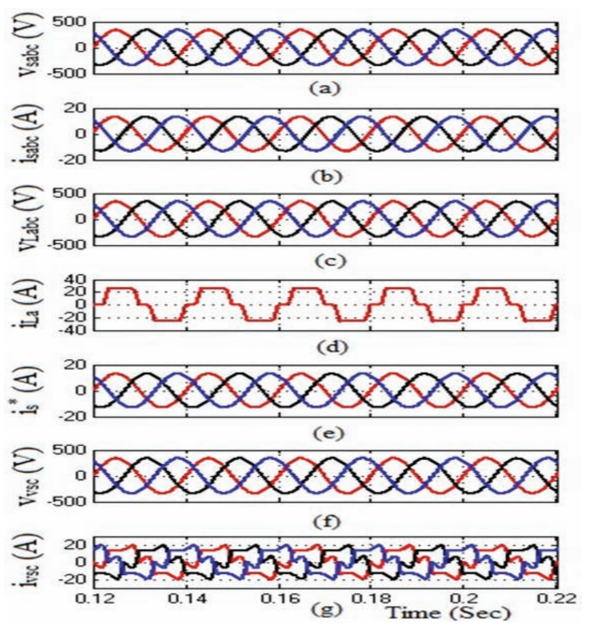

FIG. 4. STEADY STATE BEHAVIOUR UNDER NONLINEAR LOAD (A) SOURCE VOLTAGES (B) SOURCE CURRENTS (C) LOAD VOLTAGES (D) LOAD CURRENT (E) REFERENCE SOURCE CURRENTS (F) INVERTER OUTPUT VOLTAGES (G) INVERTER OUTPUT CURRENTS

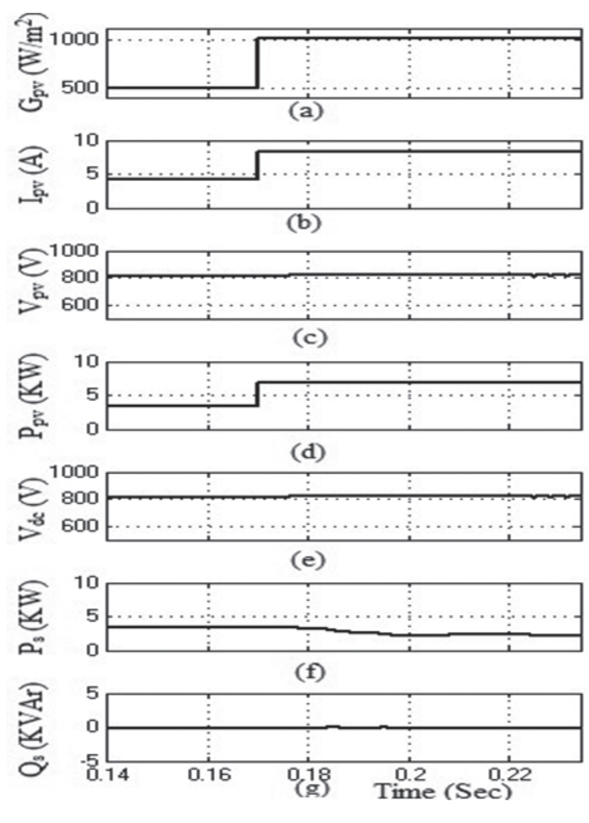

FIG. 5. DYNAMIC BEHAVIOUR OF THE GRID CONNECTED SPV SYSTEM (A) INSOLATION (B) PV CURRENT (C) PV VOLTAGE (D) PV POWER (E) DC LINK VOLTAGE (F) SOURCE REAL POWER (G) SOURCE REACTIVE POWER

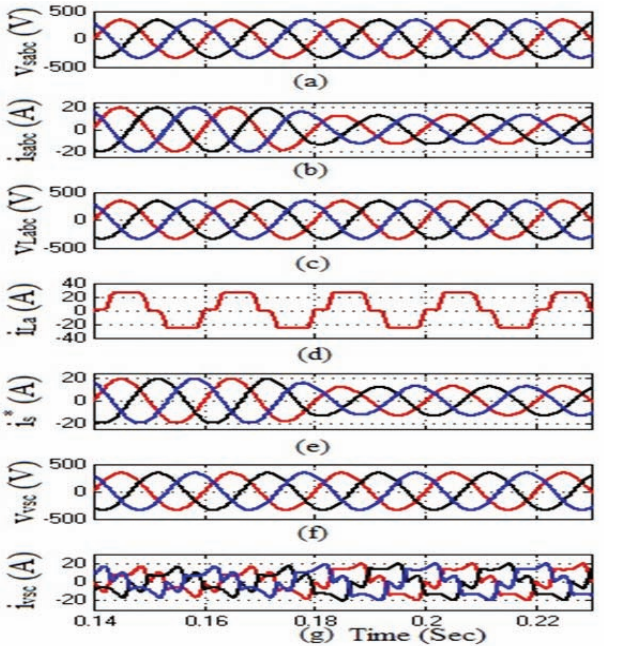

FIG. 6. RESPONSE OF SPV SYSTEM UNDER VARIABLE INSOLATION (A) SOURCE VOLTAGES (B) SOURCE CURRENTS (C) LOAD VOLTAGES (D) LOAD CURRENT (E) REFERENCE SOURCE CURRENTS (F) INVERTER OUTPUT VOLTAGES G) INVERTER OUTPUT CURRENTS

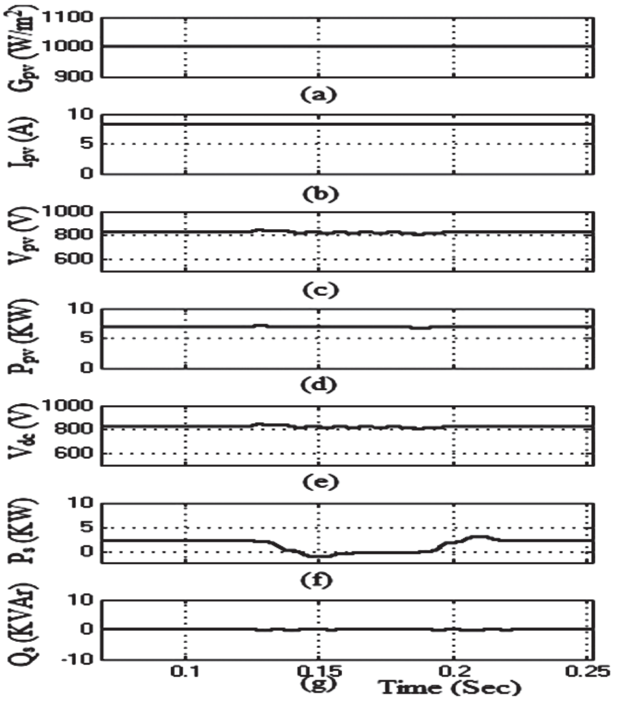

FIG. 7. DYNAMIC BEHAVIOUR OF THE GRID CONNECTED SPV SYSTEM UNDER UNBALANCED NONLINEAR LOAD (A) INSOLATION (B) PV CURRENT (C) PV VOLTAGE (D) PV POWER (E) DC LINK VOLTAGE (F) SOURCE REAL POWER (G) SOURCE REACTIVE POWER

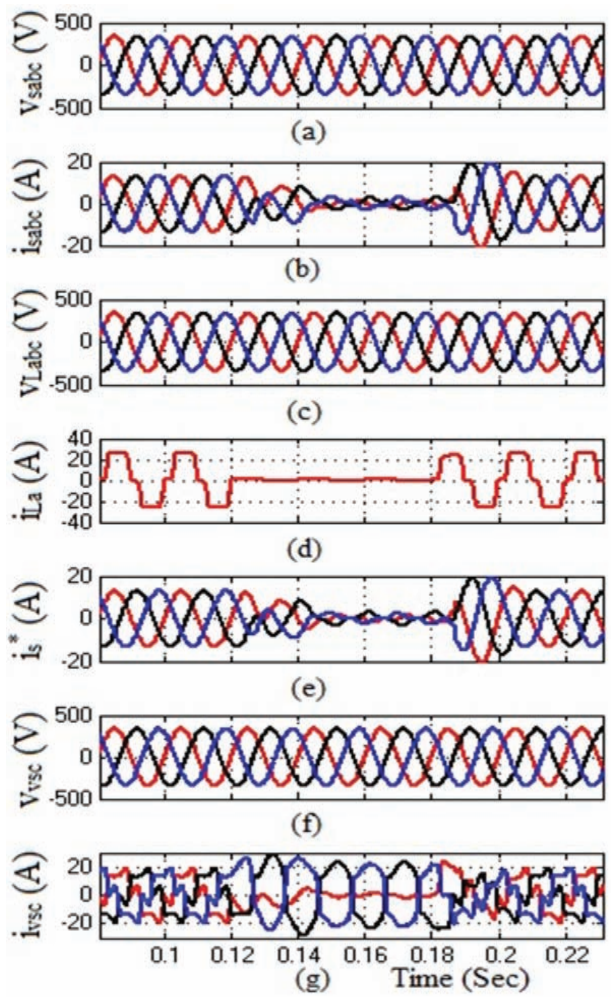

FIG. 8. DYNAMIC RESPONSE UNDER UNBALANCED NONLINEAR LOAD (A) SOURCE VOLTAGES (B) SOURCE CURRENTS (C) LOAD VOLTAGES (D) LOAD CURRENT (E) REFERENCE SOURCE CURRENTS (F) INVERTER OUTPUT VOLTAGES (G) INVERTER OUTPUT CURRENTS

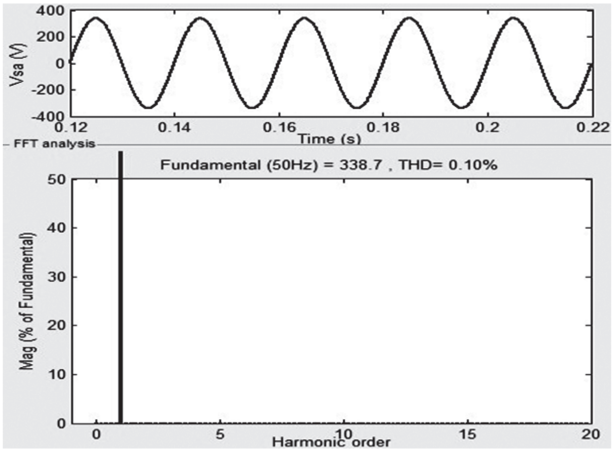

FIG. 9. VOLTAGE AT PCC AND ITS HARMONIC SPECTRUM.

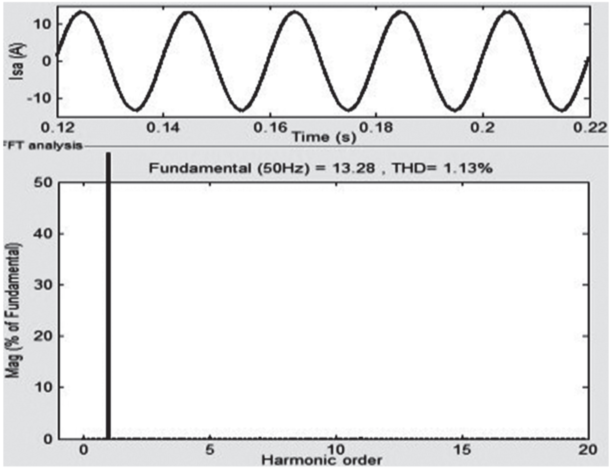

FIG. 10. SOURCE CURRENT AND THE HARMONIC SPECTRUM

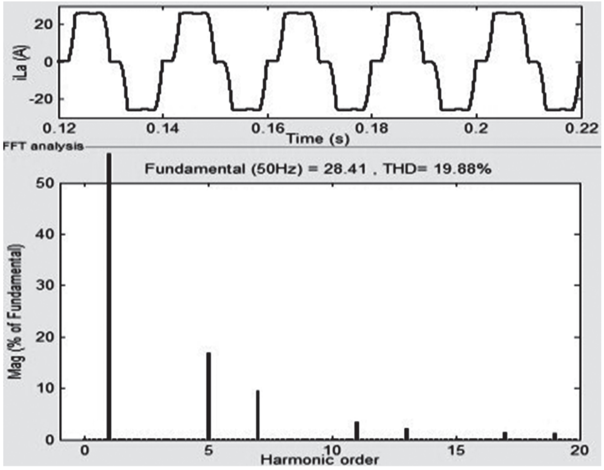

FIG. 11. LOAD CURRENT AND THE HARMONIC SPECTRUM

5.0 CONCLUSION

In this paper, a SRF (Synchronous Reference Frame) based control of a single stage dual purpose three phase grid connected SPV system is proposed. The proposed single stage system is demonstrating the two purposes and the first is the injection of real power from SPV panel with maximum power point tracking facility. As the topology is single stage, the overall efficiency of the system is high compared to a two stage system in which a dc-dc converter is also included. Secondly, the purpose of reactive power compensation, harmonic elimination and load balancing are also demonstrated. The SRF control algorithm gives the system a better dynamics because of the inherent capability of control in the stationary reference frame. The

THDs of voltages and currents at grid side are within limits of an IEEE-519 standard.

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