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Investigation of the Behavior of Active and Reactive Power in Multi-array Grid Connected Photovoltaic Systems

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Abstract: *-This paper presents a three-phase grid-connected multi-array photovoltaic generation systems with active and reactive power control for any situation of solar radiation. The modelling of the PWM inverter and a control strategy using dq0 transformation are proposed. The system operates as an active filter capable of compensate reactive power, generated by the loads connected to the grid. This paper presents a non-linear controller design for a three-phase voltage source converter (VSC). The dynamic variables adopted for the VSC are the instantaneous real and reactive power components. The control approach that interfaces the VSC between the PV system and the grid are subjected to the current-voltage based. PV system injects active power to the grid and local load while utility grid monitors the power compensation of load reactive power. The proposed topology is able to control the power between the grid and photovoltaic system, where it is intended to achieve the maximum power point operation. Simulation results are being carried out in MATLAB/SIMULINK environment and presented to validate the proposed methodology for grid connected multi-array photovoltaic generation system.*
Keywords*: Grid-connected PV system, VSC Inverter, Power quality, Active and Reactive power regulation.*

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I. INTRODUCTION

Since a decade now, in the world, a huge spread of production units fueled by renewable sources not programmable occurred. In world, there was an enormous expansion in establishment of photovoltaic frameworks because of a significant motivator strategy executed by the public authority. In a couple of years, an exceptionally quick change from incorporated age framework to dispersed age framework is happened [1]. This has caused issues hard to settle in the appropriation networks as the disintegration of voltage profiles along the lines, inadvertent detachment of the interface assurance frameworks of the inverter, issues of dependability to the electric framework. The reasons of these issues are to be discovered basically in the non-change of the circulation lines, in the pretended by lattice associated PV framework and in vulnerability of sustainable sources

Conventional PV system only supplies the instantaneous maximum power from PV array to the grid through an inverter. Distribution companies cannot directly control distributed generators, and this makes the availability of electricity produced by GD plants an unknown variable difficult to estimate the Distributed Generation (DG) can be defined as electric power generation with in the distribution networks or on the consumer side of the network. To utilize interfacing converters to compensate harmonics an enhanced current control approach is introduced in [2]. With inverter control, the active and reactive power requirement of the load can be satisfied [3]. Distributed generation (DG) units interfaced with static inverters are being applied and focused increasingly due to the fact that conventional electric power systems are being more and more stressed by expanding power demand, limit of power delivery capability, complications in building new transmission lines, and blackouts [4]. Power quality, safety and environmental concerns and commercial incentives are making alternative energy sources [5] popular. Various control techniques are presented in [6]. This paper deals with the modelling, simulation and harmonics and reactive power compensation of grid connected PV based distributed generation. In the present study, the synchronous reference frame strategy is used to generate current reference for compensation and conventional PI controllers are used for control. The synchronous reference frame strategy utilizes co-ordinate transformations to separate the reactive and harmonic content in the load current. The control techniques proposed in [7] minimizes the number of measurements and sensors.[8] presents the operation of grid connected DG system driven by dc-dc step-up converter and a dc-ac voltage source inverter and the design, modelling and control of power converters for power quality improvement in a grid-connected DG system is presented in [9].

It is widely experienced that the inductive load in the distribution system causes lagging power factor and hence under voltage in the system PV framework works at solidarity power factor. The infusion of force with the PV framework decreases the force factor. The helpless force factor puts trouble and misfortunes on the network prompting utility charged the punishment to the end client. The inverter filling in as the voltage regulator produces sounds in the resultant voltage entering the lattice coming about in to issues of standard force credits. Mushrooming utilization of sun-oriented gatherings across ventures will expand the worries about power quality and its improvement. Such issues should be settled by planning the appropriate control instrument for the inverter in the PV gathering. Many force guideline calculations are accounted for the best change among dynamic and responsive forces [10]. Producing foundations are fretted over the rising utilization of periodical environmentally friendly power sources among clients prompting helpless force quality concerns. The present study involved instantaneous reactive power theory with the grid-interfacing inverter used for the effective performance of the important functions: shifting of active power tapped from the PV system and load reactive power demand support in case of the distribution system. Additionally, effective controlling grid-interfacing inverter, the PQ constraints at the PCC are strictly maintained. The sinusoidal signal integrator and instantaneous reactive power theory with hysteresis current controller based current reference generator can be employed in the control design [11].

II. ARCHITECTURE OF PROPOSED SYSTEM

Grid connected PV based distributed multi-array generation system converts electrical energy in to same amplitude, frequency and phase with the power grid and also provide electrical energy to the local loads. The block diagram representation of the proposed system is shown in Fig. 1.

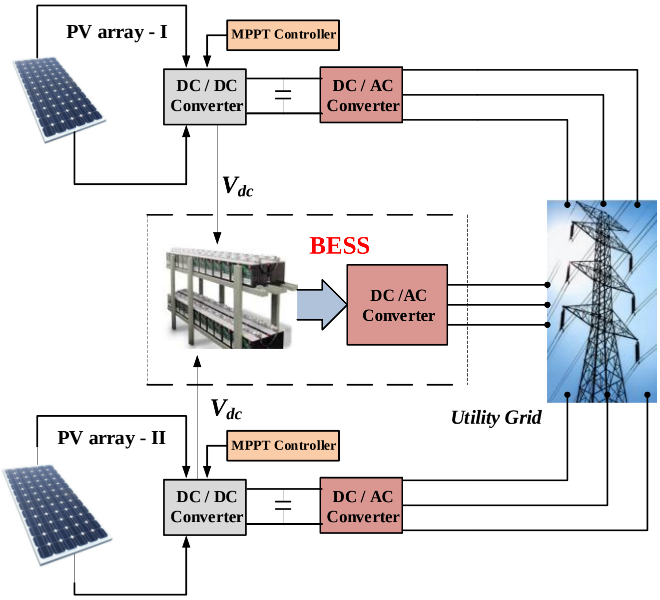

Fig. 1 Grid connected multi-array photovoltaic systems

Containing the stress of the main transmission systems using renewable energy is a topic most sought after by researchers. Employing photo-voltaic (PV) cell modules, harnessing solar power has become one of the most viable sources of renewable energy [12]. The efficiency of the PV cells can be fully trapped under myriad situations of solar intensities and temperatures incorporating altered control system using MPPT technology. Conforming to the standard power quality norms is essential while integrating renewable energy sources into the grid. Power quality issues in a grid-connected solar PV system include:
- Supply side, viz. power factor, reactive power mitigation, voltage regulations, and
- Non-linear loads on the solar power harness assembly creating sags, swell or under voltage, over voltage and dynamic momentary fluctuations.

It is widely experienced that the inductive load in the distribution system causes lagging power factor and hence under voltage in the system. PV system operates at unity power factor [13]. The injection of power with the PV system reduces the power factor. The poor power factor puts burden & losses on the grid leading to utility charged the penalty to the end user. The inverter working as the voltage controller produces harmonics in the resultant voltage entering the grid resulting in to issues of standard power attributes. Mushrooming use of solar assemblies across industries will increase the concerns about power quality and its amelioration. Such issues need to be resolved by designing the proper control mechanism for the inverter in the PV assembly. Many power regulation algorithms are reported for the ideal transformation between active and reactive powers [14]. Generating establishments are bothered about the rising use of periodical renewable energy sources amongst users leading to poor power quality concerns. The present study involved instantaneous reactive power theory with the grid-interfacing inverter used for the effective performance of the important functions: shifting of active power tapped from the PV system and load reactive power demand support in case of the distribution system. Additionally, effective controlling grid-interfacing inverter, the PQ constraints at the PCC are strictly maintained. The sinusoidal signal integrator and instantaneous reactive power theory with hysteresis current controller based current reference generator can be employed in the control design [15].

The basic element of grid connected PV system is the three-phase inverter. Inverters are an important component of the grid-connected system whose role is to convert DC into AC of the same amplitude, frequency, and in phase with the grid. In addition, the inverters should be of high validity and reliability, and ensure the security of the local loads and the power grid. With the non-linear local loads widely used, the harmonic sources are more and more, and whose impact to power quality cannot be ignored [16]. The control of mostly existent grid-connected system is to gain the unity-power factor, Voltage sag and swell, which can guarantee the efficiency of energy transfer, but ignored the need of compensating reactive power and harmonic with the principle of proximity. In this paper, based on the synchronous reference frame strategy, detection of reactive power and harmonic current, and the control strategy of inverters, a novel grid-connected system of DG is studied, which not only transfer the active power, but compensate harmonic current generated by the local loads and reactive power absorbed by them[17]-[19].

III. GRID CONNECTED SYSTEM

The basic operational principle of the grid-connected PV system is as follows:

It detects the grid voltage and current of local non-linear loads; It calculate and get command current signal including harmonic component and reactive component of load current, as well as the active component transporting to the power grid; It tracks the actual compensation current that the command current aroused, and compensate Harmonic and reactive component of the grid current, and offset harmonics and reactive component of load current and compensate the active component of grid current, and provide the active power the load and power grid [20]-[22]. This paper proposes a grid connected PV system. It mainly composed of two parts, one is the circuit of detecting harmonic and reactive component, the other is the circuit generating the compensation current. Here the load current having three components – active, reactive and harmonic. The idea is to control the voltage source inverter in such a way as to make it deliver the reactive and harmonic currents demanded by the load. Hence the controller has to generate current reference, which involves computing the reactive and harmonic current absorbed by the load.

3.1 Phase-Locked Loop

The phase-locked loop technique has been used as a common way to synthesize the phase and frequency information of the electrical system, especially when it's interfaced with power electronic devices. A simple method of obtaining the phase information is to detect the zero-crossing point of the utility voltages. However, since the zero-crossing point can be detected only at every half cycle of the utility frequency, the phase tracking is impossible between the detecting points and thus the fast dynamic performance cannot be obtained [23]. An improved method using the integral of the input waveform is proposed in the work. In the three-phase system, the dq transform of the three-phase variables has the same characteristics and the *PLL* system can be implemented using the d_q transform. The block diagram of the three-phase *PLL* system can be described in Fig. 2.

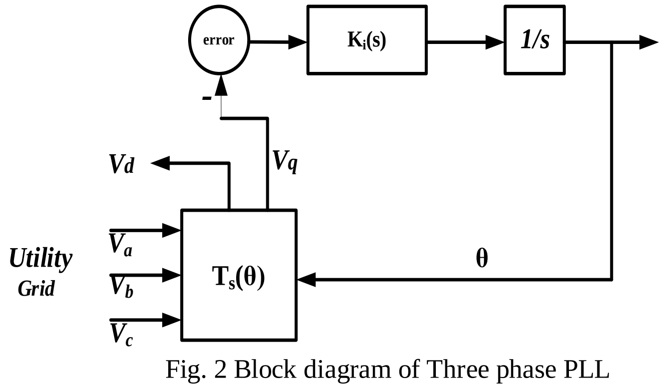

Fig. 2 Block diagram of Three phase PLL

The three-phase grid voltage can be represented in the synchronous reference frame. The transformation matrix Ts(θ) can be expressed in the following equation.

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = T_s(\theta) \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

(1)

As shown in Figure 3-5, the three-phase voltage is transformed into two DC quantities in dq axis. Then the q-axis quantity vsq is compared with the reference value zero and generates the error signal. In steady state, the reference value of q-axis is set to be zero so that only d-axis component exists to represent the AC quantity while the angular frequency becomes equal to the grid frequency. The error passes through a loop filter to derive the angular frequency. The phase shift θ is derived by integral of the angular frequency [24]. By properly designing the loop filter Ki(s), the PLL frequency ω and phase θ can be tracked accurately.

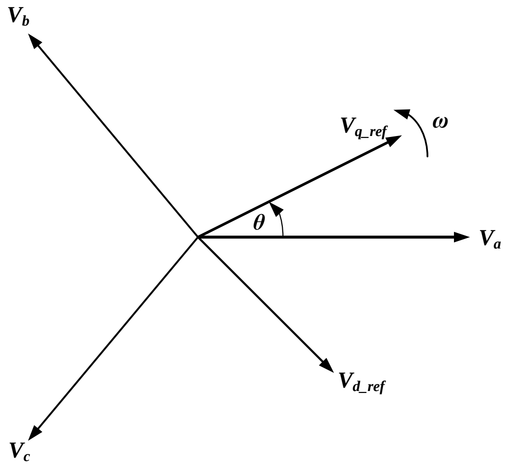

Fig. 3 Transformation to synchronous reference frame

a. VSC Current Control

As the regulation of V_{sc} has the effect that the expression for the PV system real power output is simplified to [25]:

$$P_s = \frac{3}{2} v_{sd} i_d \quad (2)$$

Equation (2) indicates that Ps is proportional to id and can be controlled by i_d. Ps is controlled to regulate the real power extracted from the PV array. Similarly, the reactive power is regulated by controlling i_q.

$$Q_s = -\frac{3}{2} v_{sd} i_q \quad (3)$$

The voltage and current from the PV module are measured and used to calculate the active power output of PV module generated. For the two string PV system, the real power can be calculated as follows:

$$P_{ref} = V_{pv\_1} I_{pv\_1} + V_{pv\_2} V_{pv\_2} \quad (4)$$

The reactive power Q_{ref} pumped into the distribution network is set to zero so that the power factor of the distribution network can be adjusted. The current references in d_q axis can be derived according to:

$$\begin{bmatrix} I_{d\_ref} \\ I_{q\_ref} \end{bmatrix} = \frac{2}{3} \frac{1}{V_{sd}^2 + V_{sq}^2} \begin{bmatrix} V_{sd} & V_{sq} \\ V_{sq} & -V_{sd} \end{bmatrix} \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix} \quad (5)$$

where *Vsd, Vsq* represent the voltage in *dq* axis at the point of common coupling (PCC). The current control algorithm is designed based on the following equations (8) and (9).

$$L\frac{di_d}{dt} = Ri_d + L\omega i_q + \frac{v_{dc}}{2}m_d - v_{sd} \quad (6)$$

$$L\frac{di_q}{dt} = Ri_q + L\omega i_d + \frac{v_{dc}}{2}m_q - v_{sq} \quad (7)$$

where id, i_q are currents flowing into the PCC, respectively, R and L represents the resistance and inductance of the LC filter connect the *VSC* and the distribution network, respectively. md and m_q are modulation index in d_q axis, respectively. Due to the factor of L_ω, the current id and i_q are coupled. To decouple the dynamic of the currents, equations (8) and (9) are written in the following way:

$$m_d = \frac{2}{v_{dc}}\left(u_d - L\omega i_q + v_{sd}\right) \quad (8)$$

$$m_q = \frac{2}{v_{dc}}\left(u_q - L\omega i_d + v_{sq}\right) \quad (9)$$

where u_d and u_q are two new inputs. Substituting m_d and m_q in equation (8) and (9), from (10) and (11), it can be obtained that:

$$L\frac{di_d}{dt} = -Ri_d + u_d \quad (10)$$

$$L\frac{di_q}{dt} = -Ri_q + u_q \quad (11)$$

Equations represent two decoupled, linear systems in which id and iq can be controlled by ud and uq, respectively. Fig. 4 demonstrates the block diagram of the dq-axis current control scheme.

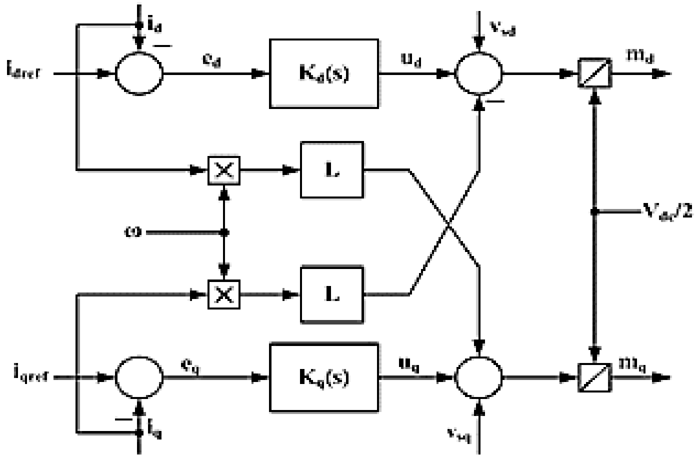

Fig. 4 Block diagram of *dq-axis* current control scheme

IV. SIMULATION AND RESULTS

To verify the feasibility of the control strategies, the simulation of three phase, 50 kW solar multi-array PV inverter is presented in this section. MATLAB Simulink platform is used for this simulation. The simulation with linear loads was done and good results were obtained to several load parameters. However, to show a better performance of the proposed system, only the results considering non-linear loads connected to the system are presented.

In Fig. 5, it can be seen that there are two different varying irradiation levels at 25º C temperature given as input to PV array 1 and 2 separately with P&O MPPT algorithm for controlling output of DC/DC boost converter for providing input to VSC Inverter for feeding the grid for controlling active and reactive power injection in it.

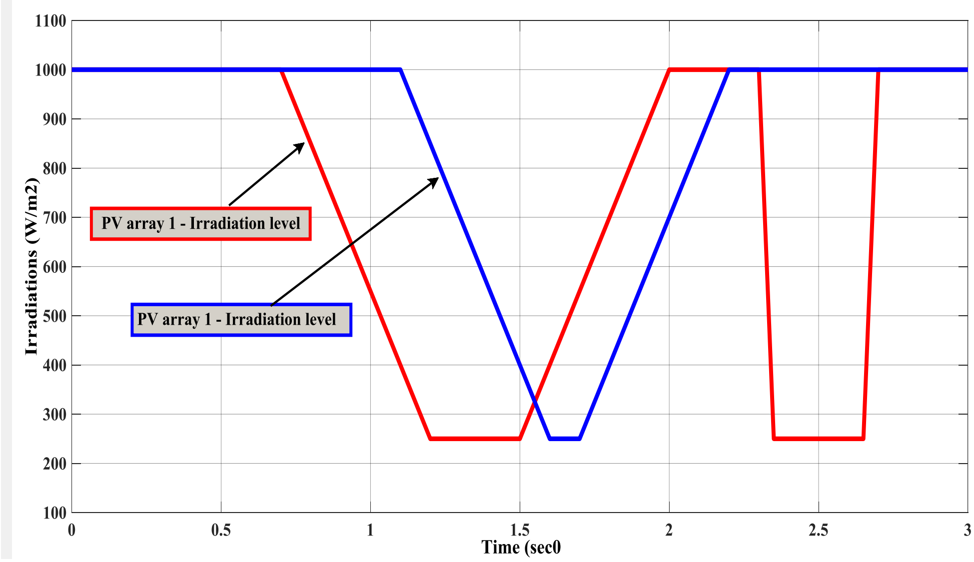

Fig. 5 Varying insolation levels to multi-array PV systems

It can easily depict from Fig. 6 that the simulation results of the output power of the multi-array PV array (input power of the DC/DC converter) and the output power of the DC/DC converter for different solar irradiances can easily trace the for power without hard injection of reactive power.

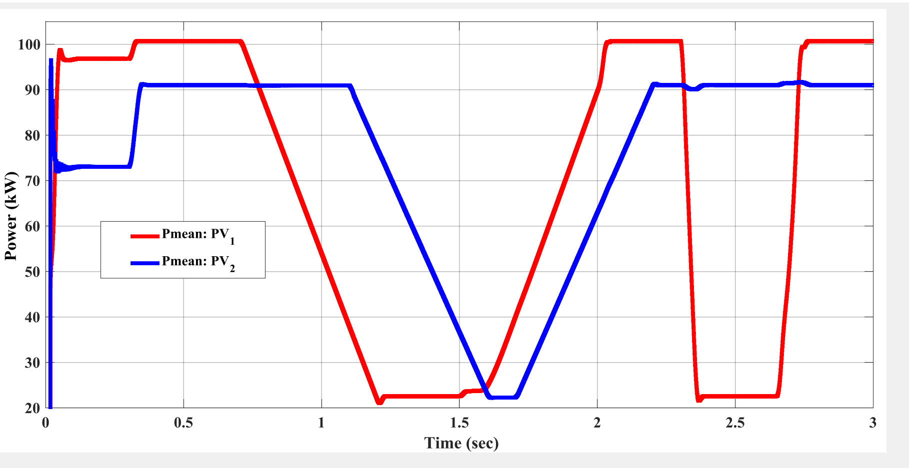

Fig. 6 DC output power from multi-array PV systems

Fig. 7 shows a one of single phase (A-phase) out of 3-ph voltage from the output VSC Inverter feeding the grid. The output of VSC Inverter shows 7-lelvel sinusoidal waveform with less harmonic rejections in the grid.

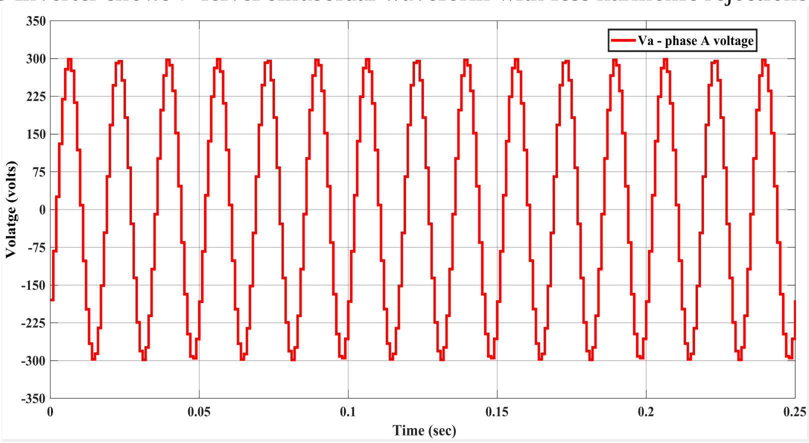

Fig. 7 Phase "a" of output voltage from 3-ph VSC Inverter

In Fig. 14, the output from VSC Inverter shows very smooth waveform as an output has very less reactive power which can be suggestified from Fig. 14 which in turn leads to lower harmonic injection to the grid for its operation.

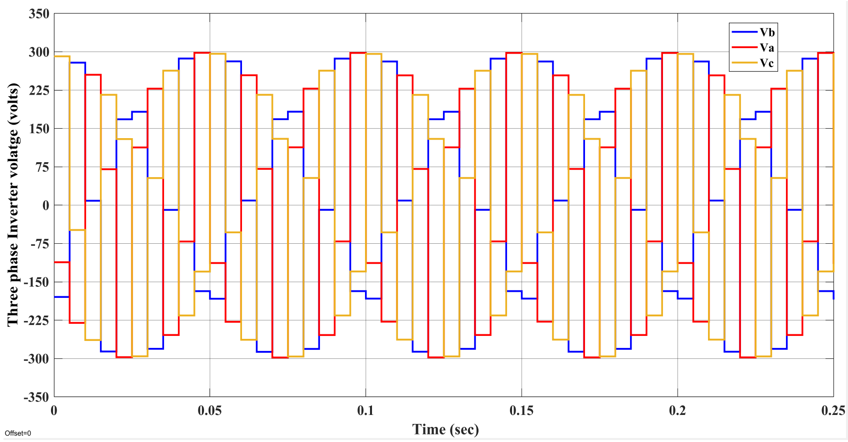

Fig. 8 3-ph output voltage of VSC Inverter

From Fig. 9 and 10 it can been seen that the inverter traces the input irradiations given to multi-array PV systems whereas in Fig. 9, phase "a" of 3-phase output of VSC Inverter and Fig. 10 depicts three phase output current. At time 1.5 sed and 2.5 sec, when insolation's levels fall drastically there is no distortion seen in the wave form as shown in Fig. 11.

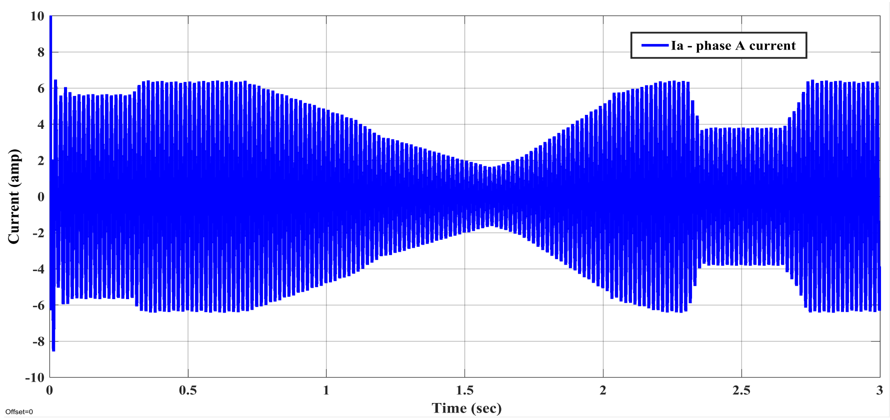

Fig. 9 Phase "a" output current waveform of 3-ph VSC Inverter

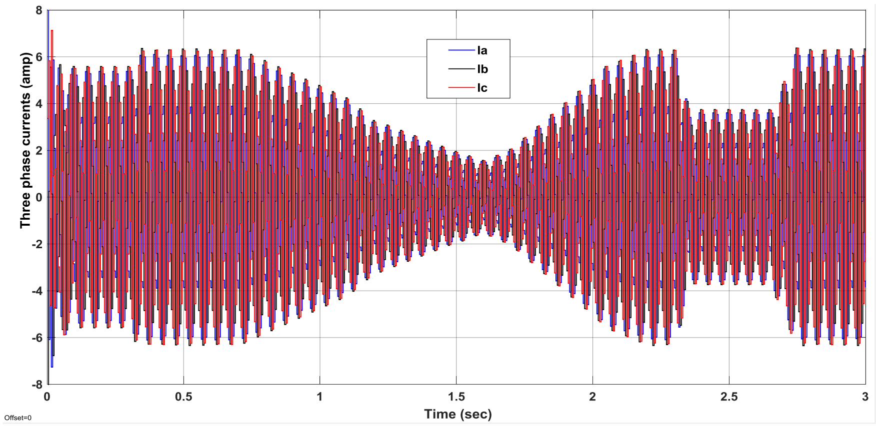

Fig. 10 3-ph output current waveform of VSC Inverter

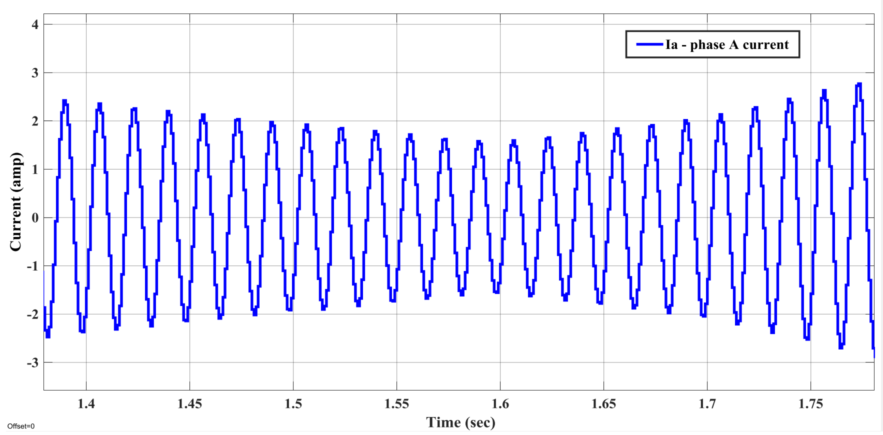

Fig. 11 Zoomed view of output waveform of current during the insolation level failure from solar

In Fig. 12 the cumulative waveforms of active and reactive injected into grid for different insolation levels fed as input to proposed multi-array grid connected PV system. It can stated that when there dynamic change in insolation levels the active power injected also falls down and reactive injections takes place which is of very low value less than1%.

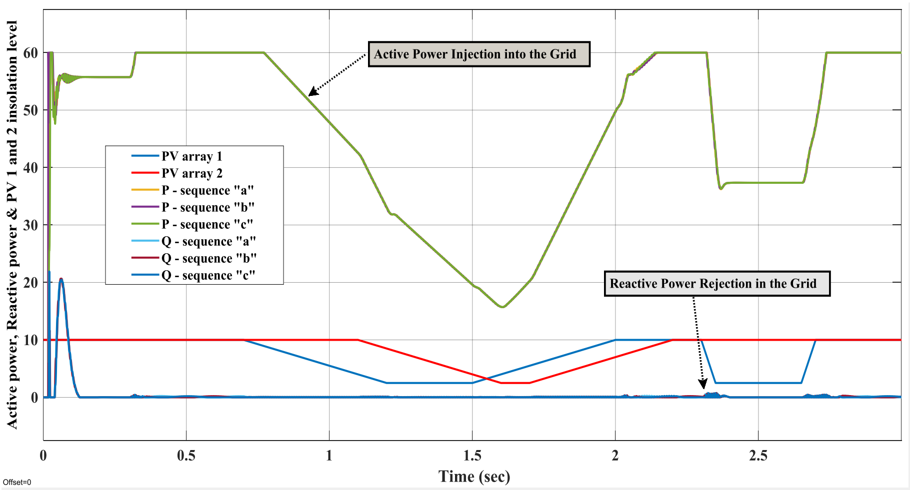

Fig. 12 Active and Reactive power with varying Insolation level to multi-array system as an input

Fig. 13 and 14 shows individual waveform of active and reactive power, it can be seen that the quantity of reactive power fed into the grid depends exclusively on the value of the active power supplied by the plant. In fact, maintaining the irradiance on the entire substring uniform and constant, it is possible to observe that when the amplitude of the mains voltage goes out of range, the system begins to deliver or absorb a quantity of reactive power proportional the active power fed into the grid as in below figures. Fig. 13 shows the active power flux in the grid, load, PV array and converter, for verifying the control strategy performance for several solar conditions. At the same figure it is possible to observe that the load active power remains constant and can be supplied by PV array or by the grid. The grid active power is negative when the grid is receiving.
energy.

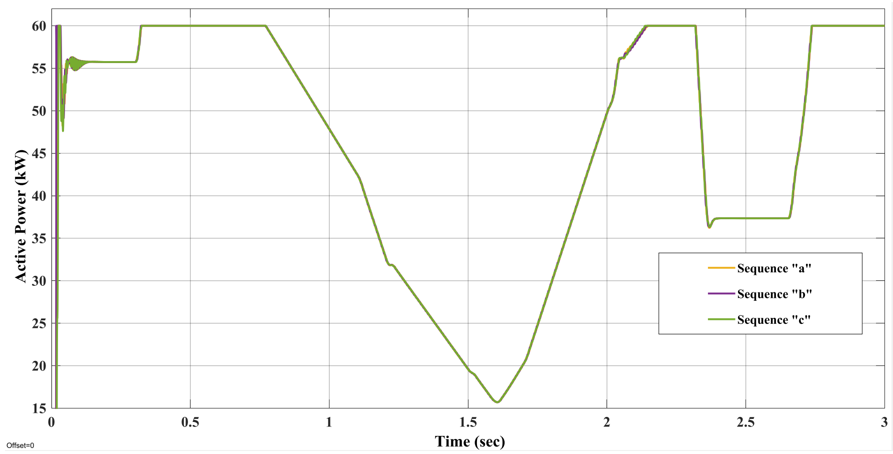

Fig. 13 Active power (P) injected into the grid

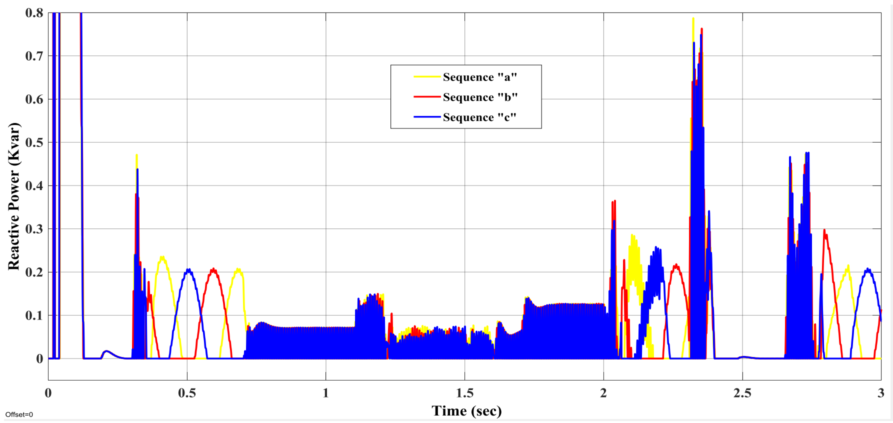

Fig. 14 Reactive power (Q) injected into the grid

Fig. 15 shows the direct-axis current (I_d) which is to be tracked by the control circuit in conjunction with reference direct-axis current (I_{d_ref}), results show that the reactive power Q (I_q) drawn from the grid is maintained at zero from t = 0.005 seconds onwards. showing the reactive power compensation of load. DC bus voltage is maintained constant. It is also seen that the grid voltage and current after compensation are in phase and the grid need not provide reactive and harmonic currents for the load.

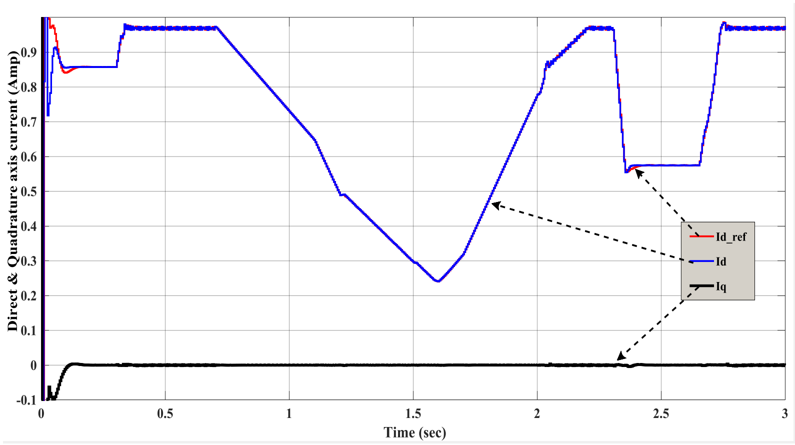

Fig. 15 Reference, Direct and Quadrature axis current for controlling active and reactive power by system

V. CONCLUSION

This paper has presented in a simple way the modelling and the control strategy using *dq0* transformation of a three-phase PWM inverter to be employed in a grid-connected photovoltaic generation system. The main focus of this work is to realize a design of a dual function PV system that would provide solar generation and works as an active power filter, compensating unbalances of power and the reactive power generated by other loads connected to the system.

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