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A Novel Technique for Voltage Regulation of PV Arrays Under Partial Shading Condition

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Abstract:

This work models a standalone PV system under partial shading condition with three converter stages, connected to two types of loads, ie., AC & DC. Two control loops, ie.,voltage control loop and current control loop are used for regulating the voltage at the load. Two loads namely, AC and DC loads can be simultaneously connected to the proposed novel work. Perturb and Observe (P&O) method, maximum power point tracking (MPPT) technique is used to draw maximum power from the PV arrays. The effectiveness of the proposed technique is checked by simulating the proposed technique using MATLAB/SIMULINK and the functionality of the proposed technique is satisfactory. The authors must follow the instructions given in the document for the papers to be published. You can use this document as both an instruction set and as a template into which you can type your own text.

Keywords —**Solar cell model, PV array, Partial shading, Stand-alone PV system, Boost converter, maximum power point tracker, Pulse- width modulation, Voltage source inverter, Proportional-Integral (PI) controller, Voltage control loop, Current control, Matlab, SIMULINK.**

I. INTRODUCTION

Round the globe, there is high concern for fossil fuels, as they are depleting at a rapid rate and also global warming is driving the researchers to quest for alternative energy sources. This lead to transformation of energy sources from non-renewable energy sources to renewable energy sources (RESs). RES like solar, wind, biomass, hydro, etc., are presented [1]. Among the various available renewable energy sources, solar energy is a promising one. Electrical energy generation by PV system is finding lot of attention, as solar energy is abundant in nature, free of cost and is available throughout the year. The main disadvantage with solar energy is, its not available during night times, its intermittent nature and seasonal effects. PV system application can be classified into standalone system and grid connected system. Standalone PV system is used as distributed generator (DG) in rural, hilly areas where power transmission is difficult, and their reliability is not guaranteed. PV systems are widely used for power generation, the main drawback of these systems is high initial cost and low conversion efficiency [2]. Solar radiation on the PV system can be uniform or non-uniform. The non-uniform radiation on the PV system condition is called as partial shading. This condition happens when any debris fall on the solar panels, or shadow of the airplane passing over, dry leaves, small sticks, birds excreta fall over the PV panel. The output power generated for the PV system mainly depends upon solar irradiance and temperature. Under uniform radiation, there exists only one peak point on IV, PV characteristics and due to partial shading effect, there exists multiple peaks called local maxima and only one global maxima. The PV system has to be operated at this global maxima to achieve maximum efficiency. To track the maximum power drawn, number of maximum power point tracker (MPPT) have been proposed [3]. MPPT technique is used along with DC-DC converter to get maximum power from PV system. MPPT helps in tracking maximum power from PV array regardless of irradiance, temperature and load deviation. In literature, a number of MPPT techniques are proposed, these methods vary from simple voltage, current, power relationships methods like perturb and observe (P&O) method, incremental conductance method, constant voltage method, short current pulse method, open voltage method, so on. P&O method is mostly used MPPT technique for solar PV applications. DC-DC converters are used for converting voltage from one level to the other level, different types of the converters are Boost, buck, Buck-Boost SEPIC, etc., converters [4].

This paper is organized as follows: section 2 deals with presentation of mathematical modelling and simulation of solar cell under uniform radiation and partial shading condition, DC-DC boost converter, Voltage source Inverter. The proposed work is presented in section 3. The simulation results of the proposed work are discussed in section 4 and finally, the conclusion is narrated in section 5.

II. MATHEMATICAL MODELLING

A. Modelling of Solar Cell

PV cells are connected in series and or parallel for attaining higher voltages, currents and power levels. Modules are obtained by interconnection of these cells in an environmentallyprotective laminate. Panel consists of one or more modules connected in series and or parallel as per the required power ratings. An array is a complete power generating unit, called as PV system. The Fig.1 shown below are the briefs of a PV cell, module, panel and an array.

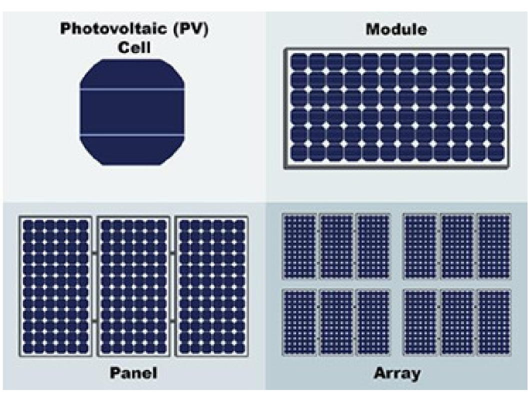


Fig.1. PV cell, Module, Panel and an Array

The voltage generated from each cell is 0.5V, number of such cells are connected in series/parallel as per the required ratings. Solar cell consists of p and n materials fabricated to form a junction. When sunlight falls on it, solar energy is converted to electrical energy. It is called as photovoltaic effect. Solar cell is electrically represented by a current source with a diode connected in anti-parallel, it is the representation of an ideal cell,and a practical cell consists of a series and a parallel resistance. R_{Se} represents the series resistance obtained due to terminals andthe R_{Sh} is the shunt resistance obtained due to leakage currents. A single diode model is taken up for simplicity [5]. The equivalent circuit of a solar cell is depicted in Fig.2. below.

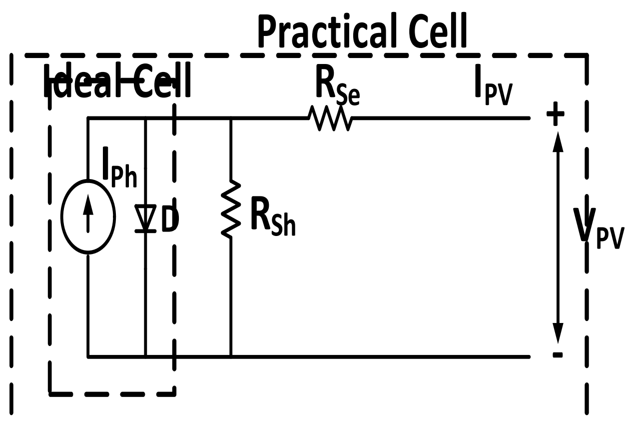


Fig. 2. Equivalent Circuit of a Solar Cell

The load current I_{pv} is given as

$$I_{PV} = I_{PH} - I_O\left[exp\left(\frac{V_{PV}+I_{PV}R_{Se}}{aV_T}\right) - 1\right] - \left(\frac{V_{PV}+I_{PV}R_{Se}}{R_{Sh}}\right) \quad (1)$$

A uniform radiated PV solar system is depicted in Fig.3, Theload current I_{pv} of the complete PV system having N_{Se} numberof cells in series and N_{Sh} number of cells in parallel is given as

$$I_{PV} = N_{Sh}I_{Ph} - N_{Sh}I_O\left[exp\left(\frac{V_{PV}/N_{Se} + R_{Se}I_{PV}/N_{Sh}}{aV_T}\right) - 1\right] - \left(\frac{V_{PV}/N_{Se} + R_{Se}I_{PV}/N_{Sh}}{R_{Sh}}\right) \quad (2)$$

The PV system shown below consists of blocking diode (D_{BL})and bypass diode (D_{BY}). D_{BL} are connected in series for everystring, they allow flow of current in one direction only, i.e., fromthe cells to the load/battery and does not allow flow of currentback from battery to the cells in the night time. D_{BY} areconnected in parallel with every solar panel to maintaincontinuity of supply, if any of the panel gets shaded, it gets opencircuited and the flow of the current produced from the otherpanels of the same string bypasses the shaded panel through thisD_{BY}, it also doesn't allow reverse flow of current from healthysolar panel.

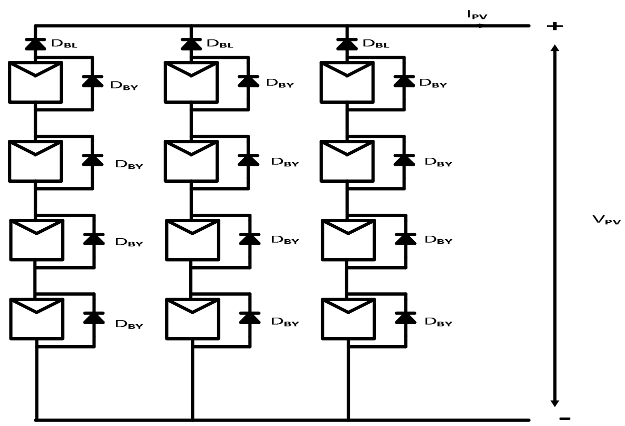


Fig. 3. Uniformly radiated PV system

I-V and P-V characteristics of uniform radiated PV system fordifferent irradiation of 200 W/m^2, 400 W/m^2, 600 W/m^2,800 W/m^2, 1000 W/m^2 at a constant temperature of 25^{0}C isshown in the Fig.4. below

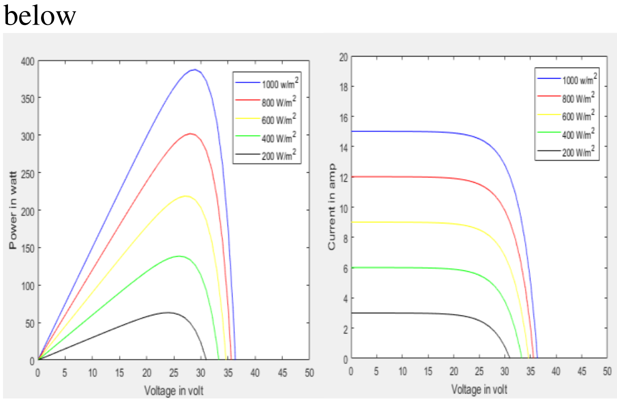


Fig. 4. I-V and P-V characteristics of uniform radiated PV system

A non-uniformly radiated or a partial shaded PVsolar system is shown in Fig.5,

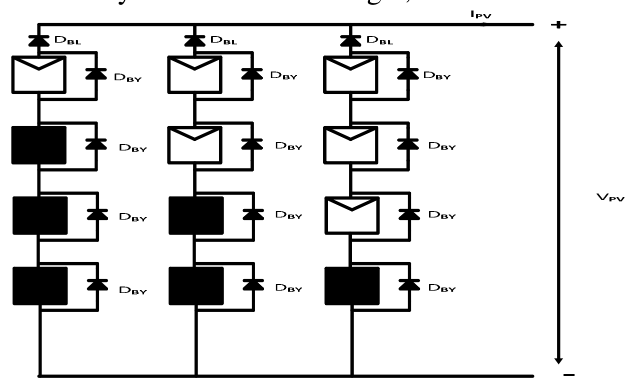


Fig. 5. A non-uniformly radiated or a partial shaded PV solar system

I-V and P-V characteristics of non-uniformly radiated (partialshaded) PV system is shown in the Fig.6. below.

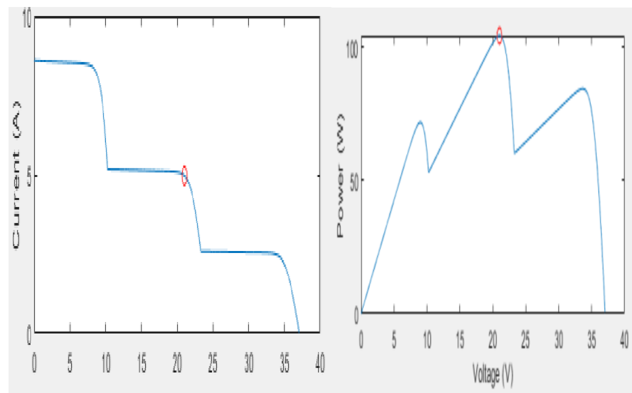


Fig. 6. I-V and P-V characteristics of partial shaded PVsystem

Three local maxima are occurring, since there are three different radiations among the three, peak one is considered as the global maxima.

B. Boost Converter

A DC-DC boost converter consists of inductor in series with the input source, a switch (IGBT or MOSFET), a capacitor and a load. It steps up the input voltage. Boost Converter helps in tracking of maximum power point (MPP). The Fig.7 . below shows the circuit of a boost converter. It operates in two modes, mode I - when switch is closed, mode II – when switch is open [6,7,8]. In the mode-I switch Q will be ON, the current flows in two loops, i.e., through voltage source (Vin), inductor (L), switch (W), voltage source (V_{in}) and through capacitor (C), loadresistor (R_L), capacitor (C). In the mode-II switch Q will beOFF, the current flows through voltage source (Vin), inductor(L), diode (D), capacitor (C), load resistor (R_L) and back tovoltage source (V_{in}).

The ratio of output to input voltage of the DC-DC converter isgiven as

$$V_{Out} = \frac{V_{in}}{(1-D)} \quad (3)$$

Max-max Inductor ripple current, ΔI_L is given as:

$$\Delta I_L = \frac{V_{in}D}{F_S L} \quad (4)$$

Capacitor output Voltage ripple, ΔVI_C is given as:

$$\Delta V_C = V_{Out} = \frac{I_O D}{F_S C} \quad (5)$$

Where D is the duty cycle, it ranges from 0 to 1, by changing itsvalue, the output voltage can be controlled.

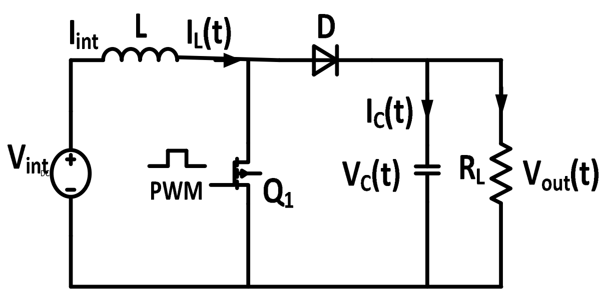


Fig. 7. Equivalent circuit of a DC-DC Boost converter

C. Inverter

Inverter converts DC voltage to AC voltage. Inverters are of two types, one is current source inverter (CSI), and the other is voltage source inverter (VSI) [9,10]. A VSI is fed by a constant DC voltage, whereas a CSI is fed by constant current source. The output of a CSI drive is adjustable 3-Φ AC current, whereasVSI drive produces 3-Φ voltage with adjustable magnitude andfrequency. The control schemes can be classified as currentcontrol inverters (CCI) and voltage control inverters (VCI). Theobjective of the current control scheme is to control active andreactive components of the current fed into the grid. A voltage source can be converted to current source by connecting ainductor in series and then varying the voltage to obtain thedesired current. The power circuit of inverter has three arms,each arm has two switches, the switch may be either an IGBT,or a MOSFET, and has a diode connected in parallel to it. Thecircuit diagram of a 3-Φ inverter is shown below in Fig.8 .

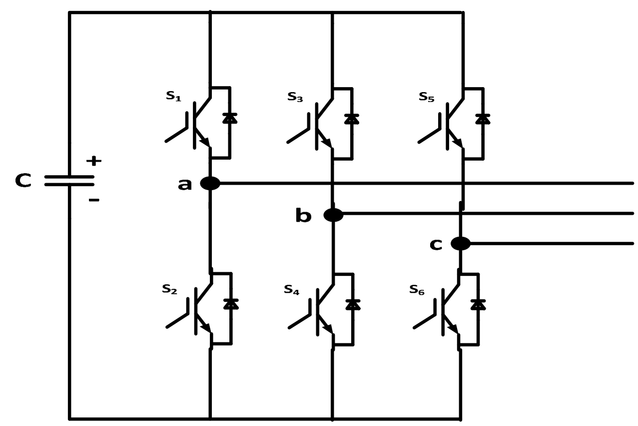


Fig.8. Circuit diagram of a 3-Φ inverter

III. PROPOSED METHODOLOGY

A. Block Diagram

The block diagram of the proposed technology is depicted in Fig.9 . below.

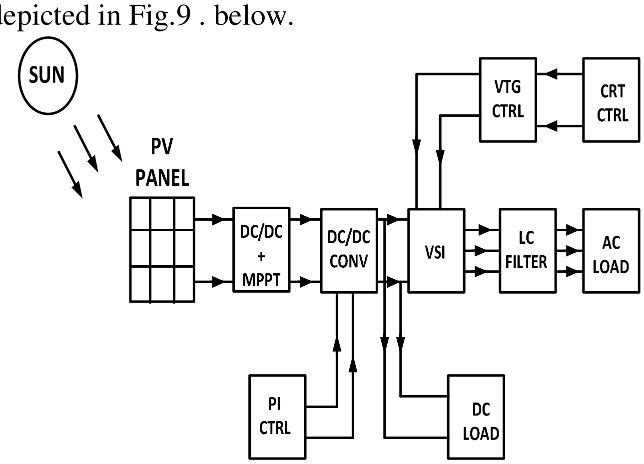


Fig.9. Block diagram of the proposed technology

When the solar radiation falls on the PV panel, electron hole pairs are generated. Hence, current start flowing into the external load circuit. The DC-DC converter used here is a boost converter; it is operated by MPPT for drawing the maximumpossible power from the solar panels by making the sourceimpedance equal to the load impedance. The second DC/DCconverter is a boost

converter, which steps up the output voltageof the first boost
converter, to a voltage level i.e., is required bythe VSI and works with a fixed duty cycle. The block diagramof DC voltage control is shown in Fig. 10. below [11,12].

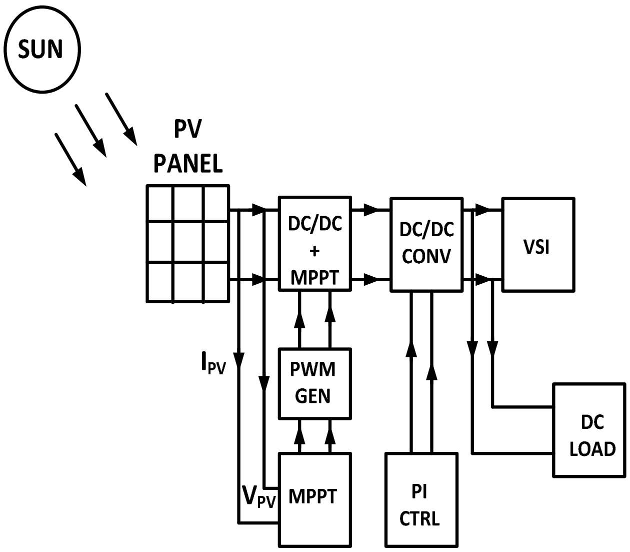


Fig. 10. Block diagram of DC voltage control

D. Invertor Controller

Inverter has an ability to maintain unity power factor by making reactive power to zero. The real and reactive power can be controlled independently by controlling decoupled and quadrature axes (d-q) currents Id and Iq as per Parkes transformation [13-15]. For a balanced 3-Φ system, instantaneous phase voltages are represented as

$$V_a = V_m Cos(\omega t + \delta_V) \quad (6)$$

$$V_b = V_m Cos\left(\omega t + \delta_V - \frac{2\pi}{3}\right) \quad (7)$$

$$V_c = V_m Cos\left(\omega t + \delta_V + \frac{2\pi}{3}\right) \quad (8)$$

Where V_m, ω, δ_v denotes the peak voltage, frequency and initial phase angle of the phase voltage V_a. The conversion of three phase voltages (V_a, V_b, V_c) to (d-q) phase can be explained by Park's Transformation as shown in Fig.11.

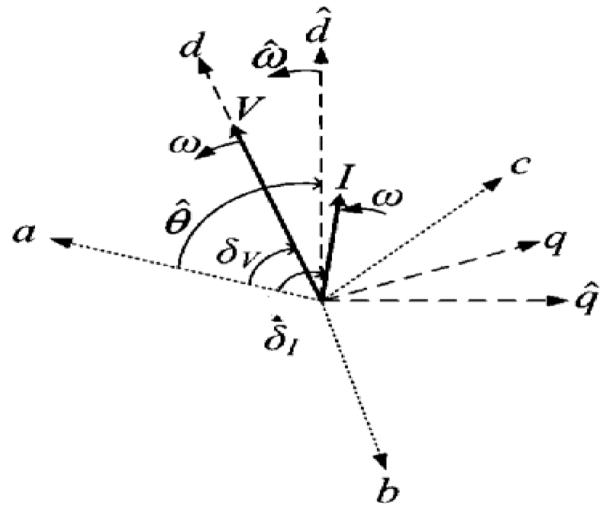


Fig. 11. Three to two phase conversion by Park's Transformation

When Phase Locked Loop (PLL) is made to operated ideally, q-axis component becomes zero, the voltage V will be on the d-axis, but there will an error between the working frequency ω and the PLL estimated frequency ω̌ the block diagram of PLL is shown in Fig.12. below

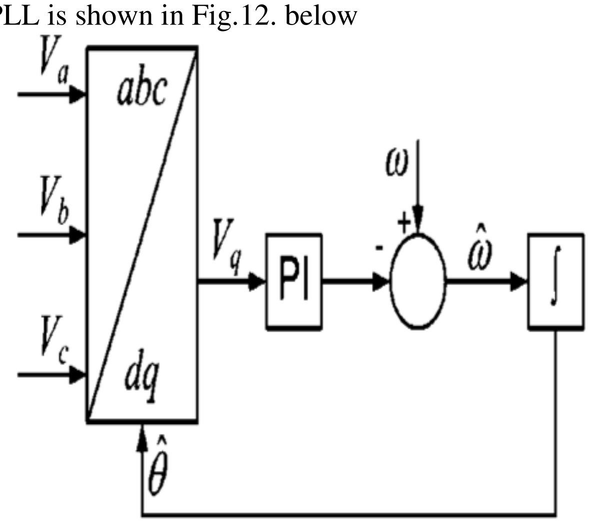


Fig. 12. Block diagram of PLL

As PLL uses an integrator and PI controller, it cannot correct the error, the estimated d-q axes are different from the original ones as shown in Fig. 11. The real and reactive power are obtained from V_d, I_d, V_q, I_q from Park's Transformation and are given as

$$P = \frac{3}{2}\left(V_d I_d + V_q I_q\right) \quad (9)$$

$$Q = \frac{3}{2}\left(V_d I_q - V_q I_d\right) \quad (10)$$

By controlling voltages and currents, active and reactive powers can't be controlled independently, by controlling the current, both active and reactive powers can be controlled. Hence, one of the component voltages V_d and V_q should be made zero to control active and reactive powers. When d' axis is synchronized to V, ie., d' axis becomes same as d axis, and Vq component becomes zero. The active and reactive power becomes

$$P = \frac{3}{2}(V_d I_d) \tag{11}$$

$$Q = \frac{3}{2}(V_d I_q) \tag{12}$$

The block diagram of operation of a VSI is shown in Fig. 13

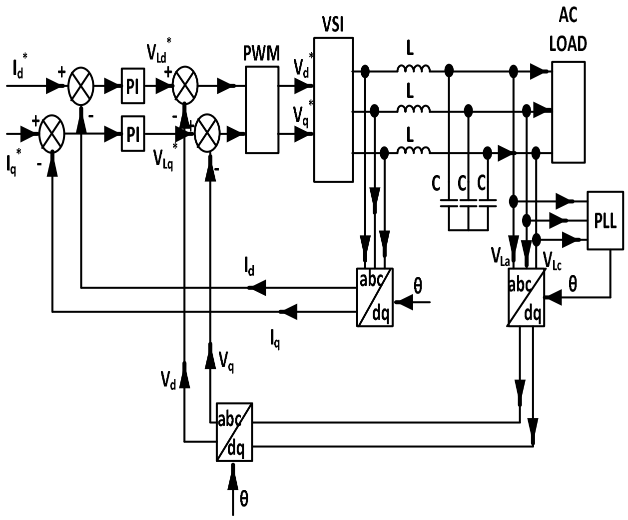


Fig. 13. Block diagram of operation of a VSI

C. LC Filter

A filter is connected at the output terminals of a semiconductor converter to reduce the harmonics and also the effects which are caused by switching of semiconductor devices. LC filter is one of the important filter topology to reduce for a 3-Φ inverter. The output current produced is sinusoidal in nature with THD less than 5%. The design of LC filter [16,17] is such that its cut off frequency, FC is higher than load current frequency and voltage frequency and less than inverter switching frequency, the cut-off frequency is given as

$$F_c = \frac{1}{2\pi\sqrt{L_F C_F}} \tag{13}$$

IV. SIMULATION RESULTS

The proposed technique is modelled to a PV system consisting of four PV arrays at different irradiation and temperatures and they are connected in series. The output of the four arrays is connected to a capacitor through DC-DC boost converter and MPPT, which acts like a battery. The voltage is further stepped up using a DC-DC converter fed though PI controller. This output is fed to the inverter then to the LCL filter, transmission line and to the load. The gate pulses are fed to the inverter through voltage and current control loop. Both AC and DC load can be connected to the proposed system. The Matlab simulation figure is shown in the Fig.14. below.

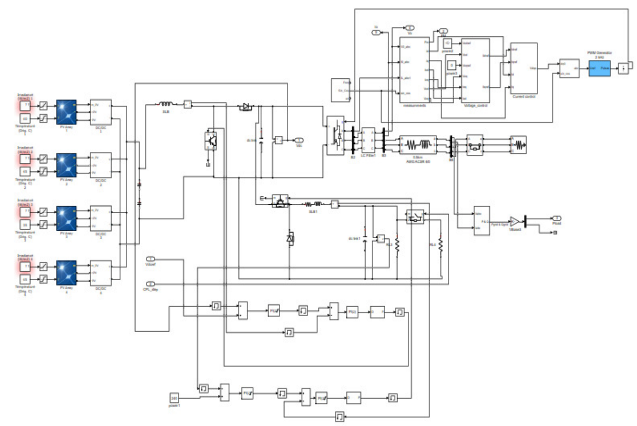


Fig.14. Matlab sim file of the proposed system

The output voltage V_{dc} from the PV arrays and voltage V_{dc} ref is shown in Fig.15

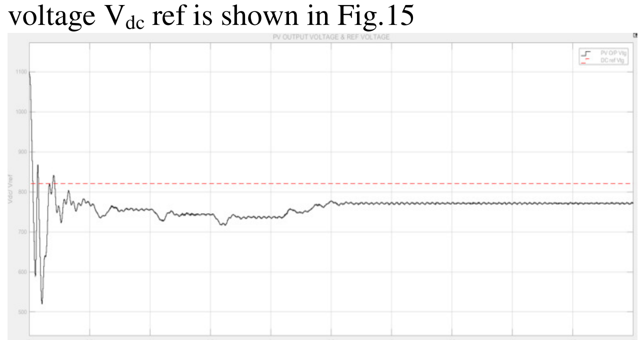
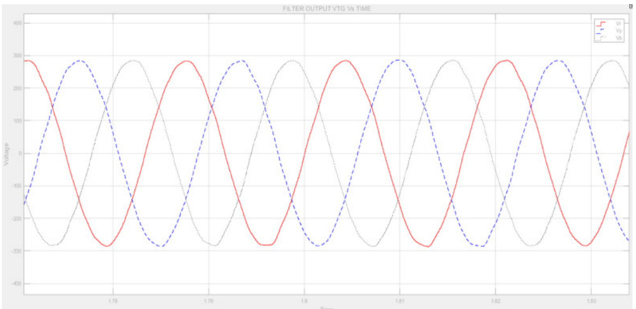


Fig.15. PV arrays output voltage Vdc and ref voltage Vdc ref

The LC filter output voltage and current is shown in Fig. 16



(a)

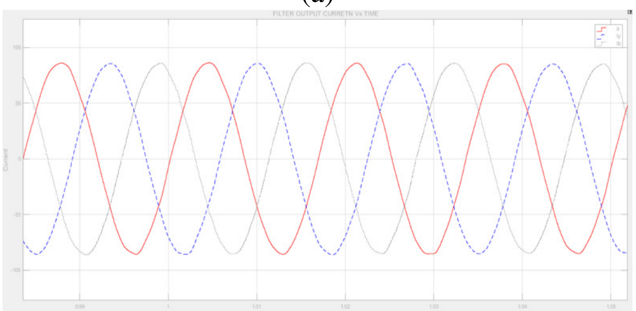


Fig.16. (a) LC filter output voltage (b) LC filter output current

The AC output power at the load terminals is shown in Fig. 17

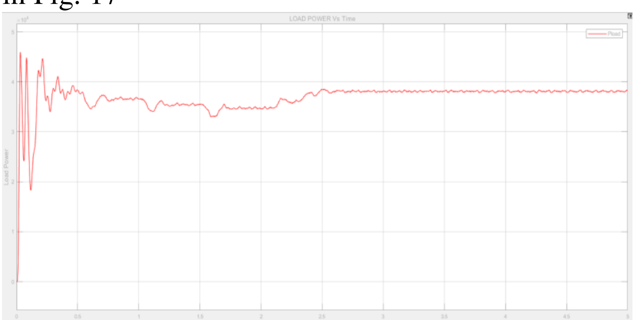


Fig.17. AC output power at the load terminals

V. CONCLUSION

In this paper, a new technique for voltage regulation of PV arrays under partial shading condition was proposed and analysed. The main feature of the presented system is novel loading of both AC & DC loads simultaneously. A model of partial shading PV module was simulated in the beginning. Inverter modelling was later done. A 3-ϕ inverter was controlled using voltage and current controller. Finally the results show the effectiveness of the proposed method.

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