

# Analysis of Single Phase Inverter for Standalone Residential Load Using Solar Photovoltaic Arrays

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**ABSTRACT:** The Paper proposes the use of a single phase inverter for remote residential loads using Solar photovoltaic arrays for household energy requirements. The analysis includes the study of effects of source and load variation for the stand alone systems by simulation of the entire system. The study also discusses the role of PI controller in the proposed model for stand-alone systems to mitigate the effect of the variations by tuning the controller manually. The paper discusses the essentials of photovoltaic system operation, the resultant changes in output of photovoltaic array with changing condition, power conversion using inverter, the study of Sinusoidal Pulse Width Modulation (SPWM), analysis of proposed model and finally scope of further development of this complete analysis.

**KEYWORDS:** Sinusoidal Pulse Width Modulation, photovoltaic system, DC-DC Converter, DC-AC Inverter.

## I. INTRODUCTION

With fast depleting conventional energy resources, the future of industrial development and human life sustainability is moving more towards the use of resources which are non-conventional and capable of supporting human existence. Renewable energy can be defined as the energy that is collected from resources which are naturally regenerated in short time on a human time scale, such as sunlight, wind, tides and geothermal heat. Therefore, for all practical purposes, these resources can be considered to be inexhaustible, unlike fossil fuels. Out of these major resources Solar energy is the most readily available throughout the world though its distribution is uneven. The solar form of energy relies on the nuclear fusion power from the core of the Sun. Solar energy can be utilized in two ways. First, the captured heat can be used as solar thermal energy, with applications in heating. Secondly, the conversion of energy from incident solar radiation into electrical energy using Solar PV systems.

The solar energy produced from Photo Voltaic (PV) arrays is around 180 GW which contributes about 1% of the total energy production of the world. In India, currently the total installed capacity is 298 GW. Out of which, solar energy production contributes 6.7 GW, nearing 2.2 % of total energy. Government of India has planned to increase solar energy production to 10 GW by 2017 and to 100 GW by 2022. Photovoltaic system for residential application found to be very useful where conventional grid fails to supply power. PV alone can act like distributed generator (DG) or act like one of distributed energy source (DER) forming Micro-grid. Many studies reported in literature about designing, modelling, optimization and simulation of hybrid energy systems [1-3]. Different inverter configurations for residential PV grid connected system discussed in [4]. Design control of residential off grid PV system discussed in [5]. The analysis elaborated here is a simulation study for stand-alone residential loads located in remote regions.

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## III. PHOTOVOLTAIC ARRAYS AND PV MODULES

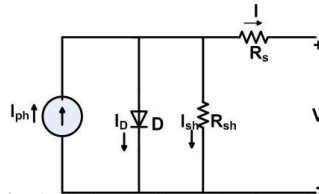


Fig.1: Solar Cell Equivalent Circuit

To understand the electronic behaviour of the solar cell, it is useful to consider an equivalent circuit based on electrical components as shown in fig.1, where behaviours are as expected. Solar cells have non-linear properties as they are made by using P-N junction

In few cases, approximation is helpful to create equivalent circuit of a solar cell. This cell is represented by a current source in parallel with diode having negligible resistances. Considering, parallel resistance equal to infinity and series resistance equal to zero. There is no such ideal solar cell existing in practise. The circuit determines current-voltage relationship at output terminals. Expression for the solar cell equivalent circuit is given by Kirchhoff's current law,

$$I_{sc} = I_d + I_p + I \quad \dots(1)$$

Where,  $I$ ,  $I_p$  and  $I_d$  are the output current, shunt resistance current and diode current. The current through each element is influenced by the voltage across them. The current across diode is given by,

$$I_d = I_o(\exp(qV_d/KT) - 1) \quad \dots(2)$$

$$V_d = V + IR_s \quad \dots(3)$$

Where,  $I_o$  is the reverse saturation current for diode,  $K$  is Boltzmann's constant,  $q$  is the electron charge and  $T$  is the Temperature. By substituting equations (2) and (3) into (1) and re-arranging, a solar cell characteristic equation can be derived as in (4),

$$I = I_{sc} - I_o(\exp(qV_d/KT) - 1) - V_d/R_p \quad \dots(4)$$

The solar cell is distinguished by  $I_{sc}$  its short circuit current at zero output voltage and  $V_{oc}$  which is maximum open circuit voltage at zero current. In case of short-circuit or open-circuit no power is generated. The cell delivers maximum power when operating at a point on the characteristic where the product of the two quantities that are current and voltage, has a maximum value. The position of the maximum power point represents the largest area of the rectangle as shown in Fig.2. The figure shows the maximum output power at particular voltage and current on the I-V curve.

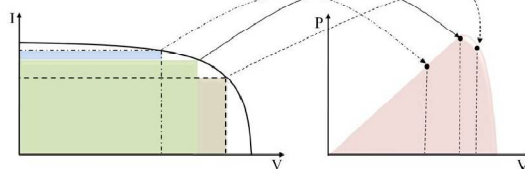


Fig.2: Maximum Power Points on I-V and P-V curves

The power  $P_{max}$  supplied by the cell at the maximum power point under standard conditions, divided by the power of the radiation incident upon it gives the cells efficiency. The most common conditions used are irradiance of  $1000 \text{ W/m}^2$ , standard spectrum, and temperature  $25^\circ\text{C}$ [6].

To get a desired value for voltage and current, modules are wired in series and parallel in PV Array. The number of series cells indicates the voltage of the panel, whereas the number of parallel cells indicates it's current. If cells are

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connected in series, shading of individual cells can destroy the shaded cell or of the lamination material. To avoid such a condition, Bypass diodes are connected anti-parallel to the solar cells as shown in Fig.3 As a result, voltage differences are avoided in the reversecurrent direction of the cells. In practice, one bypass diode is connected for every 15-20 cells. Bypass diodes also allow current to flow through the PV module when it is partially shaded, even if at a reduced voltage and power, Bypass diodes do not cause any losses.

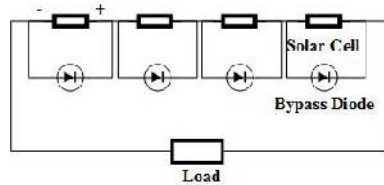


FIG.3: SERIES PV CELLS WITH BY-PASS DIODES

## IV. EFFECTS OF ATMOSPHERIC CONDITIONS ON SOLAR PV SYSTEM

1) Effect of Irradiation: In case of irradiation level increase, maximum power that could be obtained increases linearly but the voltage at which Maximum Power Point occurs remains almost constant as shown in fig.4. The figure shows the output current and power at  $1\text{kW/m}^2$  and  $0.6\text{kW/m}^2$  irradiation. The point on the curve shows the maximum power points.

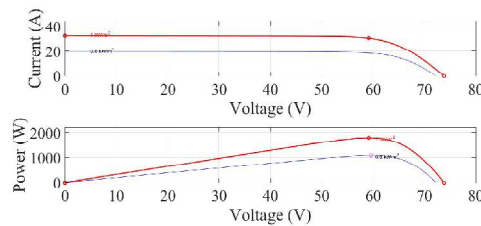


FIG.4: I-V AND P-V CHARACTERISTICS

2) Effect of Temperature: As temperature increases, the exponential term in cell current equation reduces. The net effect of increasing temperature is to reduce the open circuit voltage( $V_{oc}$ ) linearly. The magnitude of this reduction is inversely proportional to  $V_{oc}$  and  $I_{sc}$  increases slightly with increasing temperature because of an increase in heat generated carriers in the cell. The changes shown in fig.5 also depend on how the cell is made. However, the overall effect on efficiency seems to be similar to that on voltage. The fig.5 shows the curve at  $45^\circ\text{C}$  and  $25^\circ\text{C}$ . The points on the curve indicate the maximum power point at the two different temperatures.

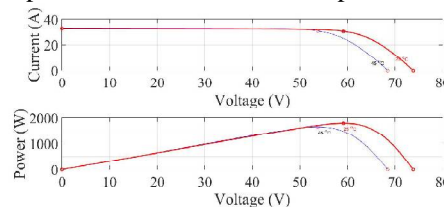


Fig.5: I-V and P-V Characteristics at different Temperature conditions

3) Shading and dirt: When a portion of array is shaded, the output falls drastically due to internal short-circuiting. If the current drawn from the series string of cells is lesser than the current that can be produced by the shaded cell, the current developed by the string is restricted to a certain value. In case of voltage available from the rest of the cells in a string is greater, current will continue to flow through the cells in the shaded portion. Power is absorbed in the shaded cell, converting and losing it in the form of heat energy. The breakdown voltage for common cells is between 10 to 30 volts. Usually the reverse voltage of a shaded cell is greater than the forward voltage of an illuminated cell, hence one shaded cell is able to absorb the power of many other cells in the same string, abruptly affecting panel output.

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## V. SINGLE PHASE FULL BRIDGE INVERTER

A single phase full-bridge inverter is shown in fig.6. From the given figure, the full-bridge circuit has two legs of switching devices, which are Insulated Gate Bipolar Transistor (IGBT) in this case. Each leg has two IGBTs and the load is connected between the two legs. This is also known as H-bridge inverter. Free-wheeling diodes are connected in parallel of each IGBT for circulating current, considering inductive loads.

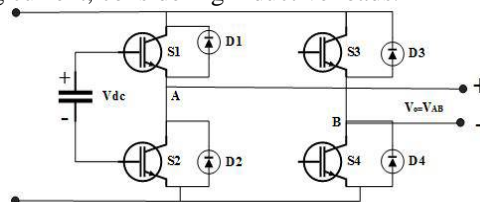


FIG.6: SINGLE PHASE FULL BRIDGE INVERTER

When S1 and S2 are turned ON, output voltage  $V_{AB}$  is equal to  $V_d$ . When S3 and S4 are turned ON, output voltage  $V_{AB}$  is equal to  $-V_d$ . When all the four switches or IGBT's are turned ON, zero output voltage is obtained. The upper and lower switch of a leg of the H-bridge works in alternating manner such that when one switch is ON, the other is OFF. This inverter is usually used as PWM inverter.[7]

## VI. SINE PWM WITH UNIPOLAR SWITCHING TECHNIQUE

In unipolar PWM technique, two completely out of phase sine waves are taken as reference signals. The signal waves have same amplitude and frequency. These sine waves are compared with the common carrier wave, which can be taken as a high frequency triangular wave. From the Fig.7 it can be observed that a high frequency triangular wave acts as a carrier signal and a low frequency sinusoid is reference signal in this case. The gate pulse  $V_{g1}$  applied at the S1 is obtained from comparison of upper sine wave w.r.t. carrier wave whereas, gate pulse  $V_{g3}$  applied at the S3 is obtained from comparing lower sine wave with carrier.

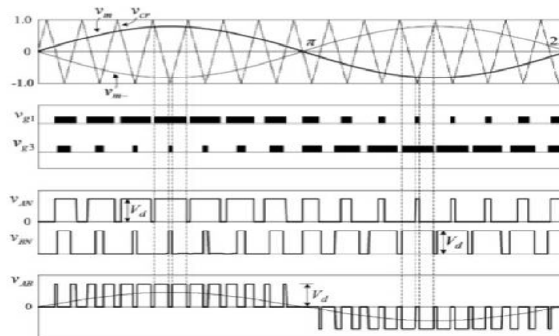


Fig 7: Unipolar Switching PWM Waveforms[8]

$V_{g1}$  and  $V_{g3}$  are not applied simultaneously. There exists a phase difference between them. Whenever the reference signal 1 has higher magnitude than carrier signal,  $V_{g1}$  is high and  $V_d$  appears as  $V_{AN}$  Otherwise,  $V_{AN} = 0$ . Similarly, whenever the reference signal 2 has higher magnitude than carrier signal,  $V_{g3}$  is high and  $V_d$  appears as  $V_{BN}$  or  $V_{BN} = 0$ . For the complete cycle of reference signal,  $V_{AB} = V_{AN} - V_{BN}$  The inverter output voltage switches between either between zero and  $+V_d$  during positive half cycle or between zero and  $-V_d$  during negative half cycle of the fundamental frequency. The unipolar switched inverter offers reduced switching losses and generates less Electromagnetic interference. The harmonic content of the output voltage waveform is reduced as compared to bipolar switching. Thus, Unipolar switching is better and is preferable to use when desired output is pure sine wave[8].

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## VII. DC TO DC CONVERTER

A DC to DC converter is a device that accepts a DC input voltage and produces a variable DC output voltage. The output voltage is usually at different voltage level than the input provided to the circuit. DC to DC converters can be used to play important roles in power system such as to provide noise isolation, power bus regulation, etc.

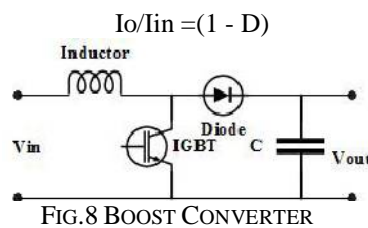
A. Boost Converter:fig.8 shows a Boost converter circuit which is used when a voltage at higher level than the input voltage is desired. The figure shows an IGBT in parallel with a capacitor. When the transistor is in the ON state  $V_x = V_{in}$ , and in the OFF state  $V_x = V_o$  the inductor current travels through the diode. The average inductor voltage must be zero for the average current to remain in steady state as shown in Fig.9.The analysis assumes continuous conduction provided by inductor.

$$(V_{in} - V_o) * t_{off} + V_{in} * t_{on} = 0 \dots(5)$$

This can be rearranged as,

$$V_o/V_{in} = T/t_{off} = 1/(1 - D) \dots(6)$$

and for a lossless circuit,  $T = t_{on} + t_{off}$  and  $D = t_{on}/T$  .assuming constant power gives,



The negative sign indicates a reversal in the direction of the output voltage [9].The duty ratio D stays between 0 and 1 the output voltage will always be greater in magnitude than the input voltage. Fig.9 shows the output of the boost converter for improved output. The waveform indicates the on and off time of the transistor and the inductor current.

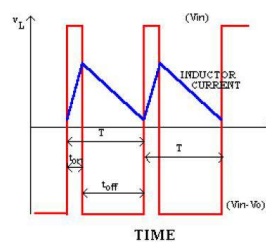


Fig.9 Boost Converter Output[9]

## VIII. MODEL FOR RESIDENTIAL LOAD STAND-ALONE PV SYSTEM

The basic model for the residential load PV system is described in fig.10. Basic components are PV array or PV panel, DC-DC converter, DC-AC inverter, low pass filter, transformer, PI controller, and finally AC load[10]. The figure shows the PV cell output given to converter circuit and the optimisation is done by using a PI controller.

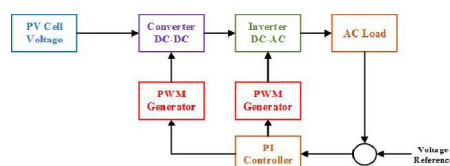


Fig.10 Schematic of stand-alone PV system for Residential Load

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**PV Array:** A standard PV module has 36 PV cells which has 0.5 V as output voltage of each cell. Thus, a PV module has 18 V as its open circuit output voltage. A number of PV panels thus can be arranged in series or parallel to get desired current or voltage rating [11]. In the model presented, 8 modules are connected, 2 in a series string and 4 such parallel strings in PV array.

**DC-DC Converter:** Any of the DC-DC converters can be used for changing the DC power obtained from PV array. A boost converter has been used in the presented model. A reason of using boost converter is that it increases the voltage level at inputs of inverter, or reduces current through the inverter, which gives reduced losses and low current rating for apparatus used. [9]

**DC-AC Inverter:** A single phase sine PWM inverter has been used for obtaining AC power from converters. Control of output voltage can be easily be obtained by varying pulse width of inverters. Varying the modulation index of inverter varies the output voltage or output power. Thus, a unipolar switched sine PWM inverter is used in the proposed model [12].

**Low pass filter:** A low pass filter is necessary to filter the harmonic content from the PWM inverter output. An almost pure sine wave is obtained when the output of sine PWM inverter is passed through a low pass filter. Hence, an L-C low pass filter is used.

**Transformer:** A single phase transformer is used to change the output voltage level efficiently and it helps to vary modulation index.

**AC Loads:** Loads connected are residential loads which mainly comprise of tube lights, fans, bulbs, refrigerator, etc. These loads are thus considered as resistive loads only as the power factor for all these loads is very high, close to unity.

**PI Controller:** A Proportional-integral controller can be used for the regulation of output voltage. As shown from Fig.11 the block diagram of PI controller, it processes on the error between reference and the output. Proportional control gives output proportional to instantaneous error and integral control gives output proportional to integral of the error.

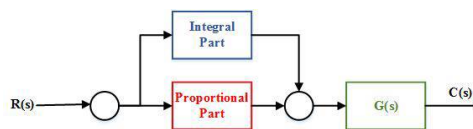


Fig.11 Block Diagram of PI Controller

Transfer function of PI controller is:

$$G(s) = K_p + K_i/s$$

Where,

K<sub>p</sub> - proportional gain and K<sub>i</sub> - integral gain.

When K<sub>p</sub> increases, the rise time and steady state error decreases while there is an increase in overshoot and minor changes are seen in settling time. In case of increase in K<sub>i</sub> there is a considerable decrease in rise time, while steady state error is completely eliminated. Settling time and overshoot increases with increase in K<sub>i</sub>. PI controller is used very widely in industries as it has the ability to reduce steady state error to zero [13]. For the presented model, voltage regulation is required as per the requirements of residential loads. A reference of 230 V Root Mean Square (RMS) value is given to PI controller. Output at load terminals is compared with reference and the error is fed back to PI controller. As the controlling variable of output voltage is modulation index for PWM inverter, the PI controller output is fed to reference signal generator of PWM generator, thereby varying the modulation index. PI controller can also be used to achieve the same purpose but in a different manner, by controlling the duty cycle of boost converter. In this manner, PI controller has been utilized to regulate the output voltage.

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## IX. OUTPUT WAVEFORMS AND RESULTS

Two conditions with corresponding output waveforms discussed here are: Simulink model without PI controller and Simulink model with PI controller.

Before going into details of the models, parameters of various components which are found out manually and are common to both the models (e.g. inductor and capacitor values in low pass LC filter) are specified. Parameters of various components and assumptions:

PV Array: 2 modules in a series, 4 parallel strings, Irradiation=1000W/m<sup>2</sup>, temperature=25°C, Voc =73 v, Isc= 32.4 A.  
Boost Converter: L= 0.463 mH, C= 2mF, Switching frequency=2000 Hz, Duty Cycle =0.6. Single phase Transformer: primary turn to secondary turn ratio, N = 1:4, Rm = 250 ohm, and Xm = 1.2732 H, r1=0.005ohm, r2=0.025ohm, x1=0.159mH, x2=0.795mH.

Low Pass LC Filter: L=15mH,C=50 micro Farad.

For practical purposes, irradiation is considered to vary from 600 W/m<sup>2</sup> to 900 W/m<sup>2</sup>. Similarly, temperature is considered to vary in between 25°C and 45°C. Pertaining to the above conditions, maximum load on the system is assumed to be 1kW, which can be fed by PV array at 600 W/m<sup>2</sup> and 45°C.

### A. MODEL WITHOUT PI CONTROLLER:

The model is shown in following fig.12. A constant modulation index m=0.8 is assumed here. The model consists of a boost converter connected to the PV array and the converter output is further given to PWM inverter. The output of inverter is given to a filter circuit which is later supplied to load through a linear transformer.

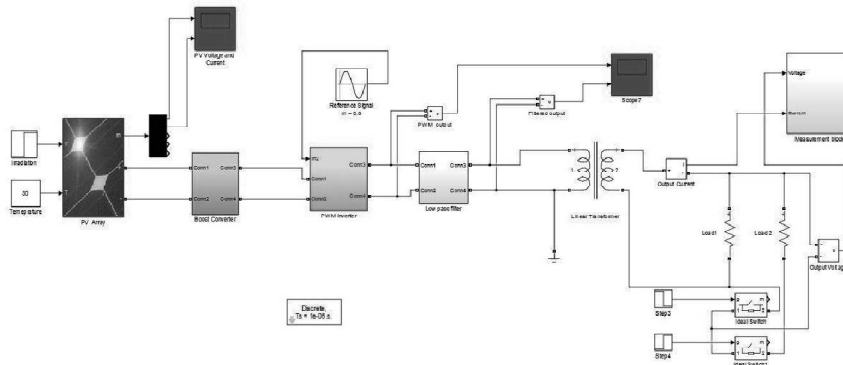


Fig.12 model without PI controller

1) Effect of irradiance and load disturbance on output parameters:

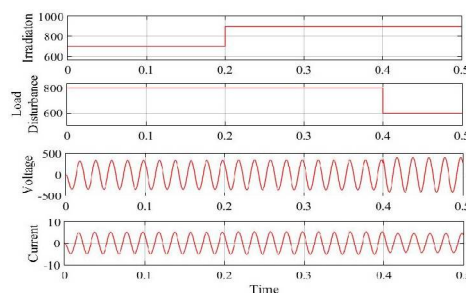


Fig.13 Output voltage and current w.r.t. change in load and irradiation

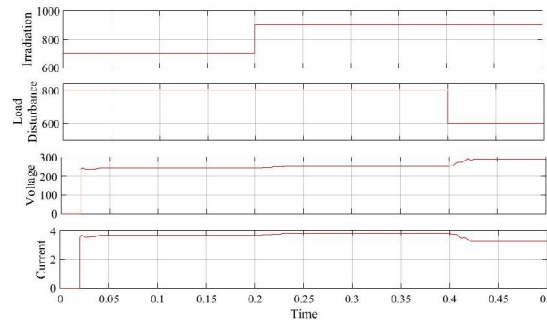


Fig.14 RMS Output voltage and current w.r.t. change in load and irradiation

From Fig.13 and Fig.14 it is observed that at first with increase in irradiation, voltage and current increase to higher values. After sudden decrease in load, voltage increases and reaches a steady RMS value while current decreases and reaches a steady value and to meet the required power output. Thus, the output voltage is displaced from its required value which is undesired. Therefore, PI controller is used.

### B. MODEL WITH PI CONTROLLER:

By manually tuning i.e. changing values of gains and observing outputs till satisfactory output is obtained, gains of PI controllers were found. Fig.15 shows model with a PI controller block connected to PWM inverter for tuning. The model circuit consist of a PV module connected to boost converter which provides its output to PWM inverter. In this circuit the PI controller block is connected to the PWM inverter and a reference voltage is given to the PI controller block for regulating the output voltage.

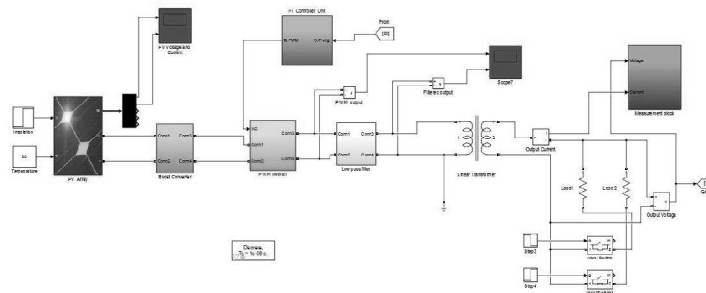


Fig.15 Model with PI controller

Values of controller gains are:  $K_p = 0.004$ ,  $K_i = 0.3$  The model is shown in fig. below

#### 1) Effect of irradiation and load disturbance on output parameters:

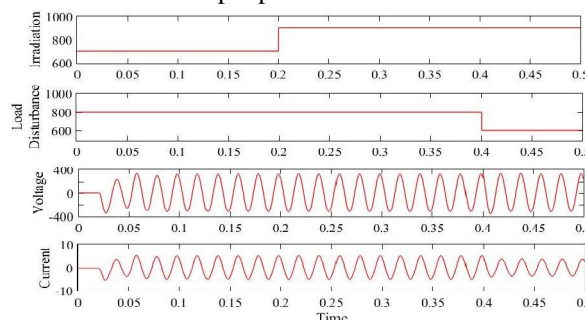


Fig.16 Output voltage and current w.r.t change in irradiation and load



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As fig.16 shows the current and voltage output of the model with change in irradiation at 0.2 seconds and the change in the load at 0.4 seconds. There is a slight change in the expected voltage and current, rather a unnoticeable one.

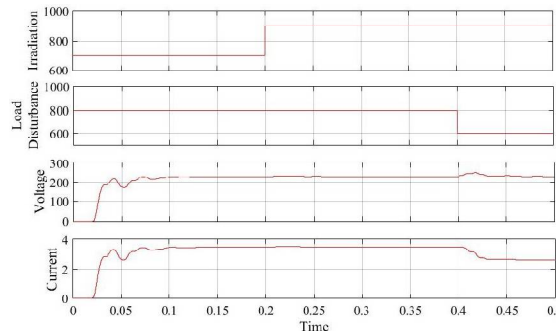


Fig.17 RMS Output voltage and current w.r.t. change in load and irradiation

As in fig.17 irradiation is increased at 0.2 sec, RMS voltage and current both are increased but return to the previous value in about 2 cycles. At 0.4 sec, when load is decreased suddenly, voltage goes up and current decreases. After 2 cycles, voltage regains its original value due to PI action and current remains steady to meet the required power. Thus, PI controller acts as a voltage regulator and maintains the voltage level constant, which is required by residential loads.

## X. CONCLUSION

The paper deals with study of single phase sine PWM inverter and its switching techniques. Moreover, implementation of unipolar switched PWM inverter in residential load PV system is studied. PI controller is used in regulating the output voltage for variations in source and load conditions. P-V and I-V curves for different irradianations and temperatures have been plotted. Model with PI controller and without PI controller has been developed and simulation results are observed. The simulation results suggest that the changes in current and voltage are very minute or of negligible magnitude. After going through this phase of change the current and voltage return to their previous values. Use of PI controller along with PWM inverter was found to satisfactorily regulate the output voltage regardless of source as well as load variations. The future work in this project includes improving the system performance by implementing Maximum Power Point Tracking controller and including a battery to store the energy. A battery charge controller is required to keep batteries properly fed and safe for the long term. Use of MPPT in the PV system shall enable use of minimum number of PV panels to meet the load requirement.

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