IRACST – Engineering Science and Technology: An International Journal (ESTIJ), ISSN: 2250-3498,
Vol.2, No. 5, October 2012

Performance Improvement of PV Module at Higher Temperature Operation

Mr. Pandiarajan Natarajan, Associate Professor (corresponding author)
pandiarajann@ssn.edu.in
Dr. Rangnath Muthu, Professor,
ranganathm@ssn.edu.in
Department of Electrical & Electronics Engineering,
SSN College of Engineering, Kalavakkam 603110, India

Abstract— **Photovoltaic (PV) modules operate in high ambient temperatures. This paper focuses on power grid-offs in grid connected PV power plants at higher ambient temperatures. Detailed analysis on performance of PV module at higher temperatures using circuit model of PV module is made. The performance improvement through circuit modifications is presented through simulation studies.**

Keywords-Circuit Model; grid-offs; higher temoerature;PV Module

I. Introduction

The use of renewable-energy generating systems has recently increased dramatically due to the exhaustion of fossil fuels and their impact on the environment. The market for PV systems is one of the most stable and fastest growing in the world.

The PV power source is the current source continuously varies with solar irradiation and temperature, where as power grid needs the power sources with constant voltage and frequency. The effect of temperature variation of the PV module can be described as follows.

Module energy rating (MER) procedure, which was developed at the US National Renewable Energy Laboratory (NREL) for five reference days such as ‘‘hotsunny”,‘‘cold-sunny”, ‘‘hot-cloudy”, ‘‘cold-cloudy”, and ‘‘nice day”that represent different climatic conditions.[1] The comparative energy output of a PV module for the reference five days in Table 1.

TABLE I.
COMPARISON OF PV MODULE RATING UNDER DIFFERENT CLIMATIC CONDITIONS

Climate	MPPT	Battery Charging
Average - Nice day	400Wh	15 Ah
Sunny - cold day	452Wh	17Ah
Sunny - hot day	334Wh	13Ah
Cloudy - cold day	224Wh	8Ah
Cloudy - hot day	276Wh	10Ah

A. Present Status of PV PowerPlant operation in India

In India, the operation of PV power plant is facing the grid offs [2] due to higher ambient temperature as explained in the Annexure-I.

The general discussions on variation of electrical efficiency due to variations of irradiation and temperature are available at present.[3]Various studies on regulation of wide variation of photovoltaic voltage [4] are not with respect to particular temperature range especially higher temperature.

Hence the problem of higher temperature operation of PV modules is studied extensively and possible methods of improving the performance are presented in this paper through simulation studies. In section 2, modeling of PV devices is discussed in detail and formation of circuit model of PV module is briefly explained. The detailed study on higher temperature performance of PV module is made in section 3. The need and nature of improvement is presented with Proportional-Integral (PI) controller circuit and improved waveforms in section 4. In section 5 results and discussion is presented and conclusion is made in section 6.

II. Circuit model of PV module

A. How A PV Cell Works

PV system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells may be grouped to form panels or arrays. The voltage and current available at the terminals of a PV device may directly feed small loads such as lighting systems. More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid-connected systems, and mainly to track the maximum power point (MPPT) of the device.

B. Equivalent Circuit.

For simplified modeling and the single diode model of Figure1is used.[5] This model offers a good compromise between simplicity and accuracy with the basic structure consisting of a current source and a parallel diode.

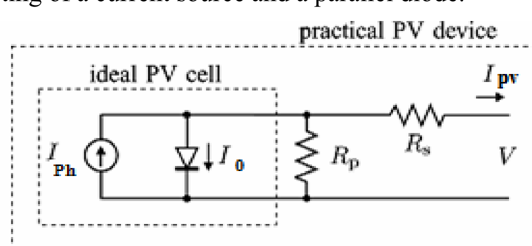

Figure 1. PV cell modeled as diode circuit

In Figure 1 the current source I_{ph} represents the cell photocurrent. R_{sh} and R_s are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of R_{sh} is very large and that of R_s is very small, hence they may be neglected to simplify the analysis.

C. Equation of PV Module

PV cells are grouped in larger units called PV modules, which are further interconnected in a series-parallel configuration to form PV arrays.

The following are the basic equations (1) - (4) from the theory of semiconductors and photovoltaic [6] that mathematically describe the I-V characteristic of the photovoltaic cell and module.

Module photo-current is

$$I_{ph} = [I_{SCr} + K_i(T - 298)] * \lambda / 1000 \qquad (1)$$

Where, I_{ph} is the light generated current in a PV module (A), I_{SCr} is the PV module short-circuit current at 25 °C and 1000W/m^2 = 2.55A as per the name plate details of reference model, K_i is the short-circuit current temperature co-efficient at I_{SCr} = 0.0017A / °C, T is the module operating temperature in Kelvin, λ is the PV module illumination (W/m^2) = 1000W/m^2

Module reverse saturation current , I_{rs}, is given by

$$I_{rs} = I_{SCr} / [\exp(qV_{OC} / N_S kAT) - 1] \qquad (2)$$

Where V_{OC} is Open circuit voltage of the reference model=21.24 V, q is Electron charge = 1.6 ×10^{-19} C, k is Boltzman constant = 1.3805 × 10^{-23} J/K, A = B is an ideality factor = 1.6

The module saturation current I_0 varies with the cell temperature, which is given by

$$I_0 = I_{rs}[\frac{T}{T_r}]^3 \exp[\frac{q * E_{g0}}{Bk}\left\{\frac{1}{T_r} - \frac{1}{T}\right\}] \qquad (3)$$

Where E_{go} is the band gap for silicon = 1.1 eV.

The current output of PV module is

$$I_{PV} = N_P * I_{ph} - N_P * I_0[\exp\left\{\frac{q * (V_{PV} + I_{PV}R_s)}{N_S AkT}\right\} - 1] \qquad (4)$$

Where $V_{pv} = V_{oc}$, N_p = 1 and N_s = 36

D. Reference Model

Solkar make, 36 Wp, PV module is taken as the reference module for simulation and the name-plate details are given in Table 2.

TABLE 2: ELECTRICAL CHARACTERISTICS DATA OF SOLKAR 36W PV MODULE

Rated Power	37.08 W
Voltage at Maximum power (V_{mp})	16.56 V
Current at Maximum power (I_{mp})	2.25 A
Open circuit voltage (V_{OC})	21.24 V
Short circuit current (I_{SCr})	2.55 A
Total number of cells in series (N_s)	36
Total number of cells in parallel (N_p)	1

Note: The electrical specifications are under test conditions of irradiance of 1 kW/m^2, spectrum of 1.5 air mass and cell temperature of 25 °C.

E. SIMULINK Model I_{pv}

The combination of MTALAB/SIMULINK models of all above four equations gives SIMULINK model I_{pv} of the reference module is as given in Figure 2 through subsystem combination. Detailed modeling procedure is available in [7].

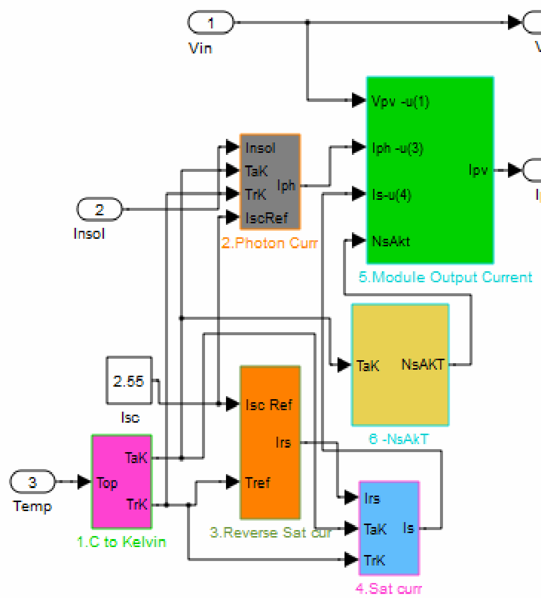

Figure 2. I_{PV} SIMULINK model with sub systems of each equation

Simulation set up for getting I-V & P-V output characteristics using I_{PV} SIMULINK model is shown in Figure 3.

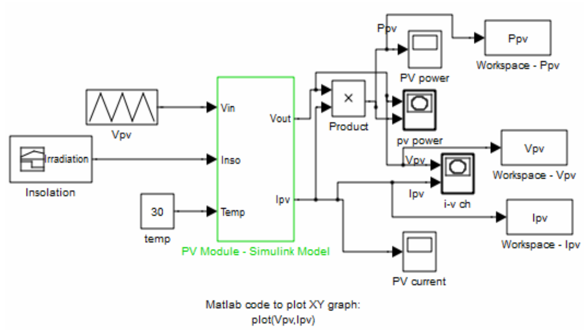

Figure 3. Simulation set up for getting I-V & P-V output characteristics from I_{PV} Simulink Model

Irradiation, temperature and voltage are given as input. The voltage is required for curve plotting hence it is given as additional input.

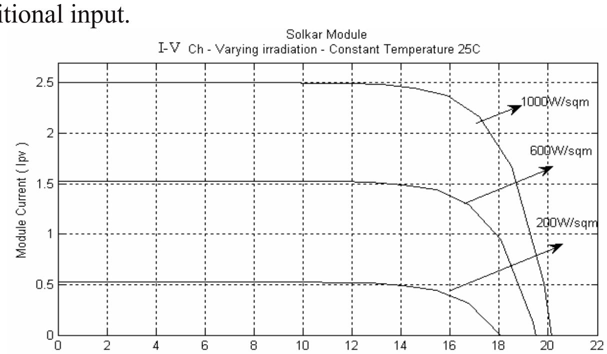

Figure 4. Output I-V characteristics with varying irradiation

The Output I-V characteristics with varying irradiation are shown in Figure 4, varying temperature as shown in Figure 5 are obtained through the above simulation setup.

The results are verified and found matching with the manufacturer's data sheet output curves.

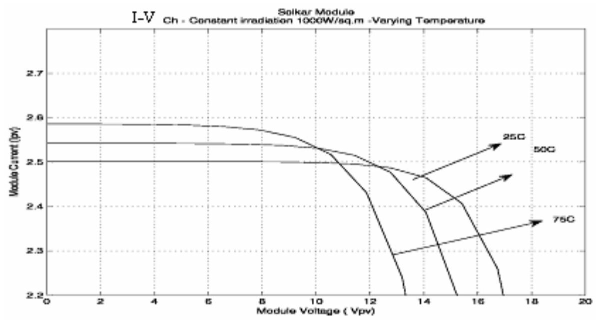

Figure 5. Output – I-V characteristics with varying temperature

F. Circuit Model of PV Module

In the equivalent circuit of a PV cell, shown in Figure 1, the voltage available across the PV cell is nothing but the PN junction forward bias voltage of 0.6V. The open-circuit voltage of the PV module is 21.24 V/36 cells = 0.594V ≈ 0.6V.

SIMULINK model, I_{PV}, developed above, provides the module current I_{PV}. This PV current is calculated from irradiation and temperature and is the input to be used directly in the circuit model. The voltage at the output terminal of the model is fed back as the voltage input V_{in} for SIMULINK model of I_{PV}. [5]

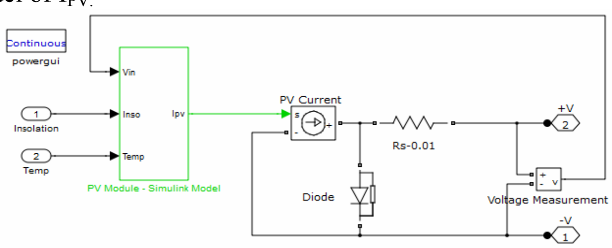

Figure 6.Detailed Circuit model of PV module.

A small resistance of 0.01Ω is added to the circuit to aid the charging of capacitor normally used with the current source. The detailed circuit model of PV module is shown in Figure 6.

Further, the forward bias voltage of the diode shown in Figure 6 is taken as 19V (as it represents the series connection of 36 PV cells) which is the higher value of useful voltage level. Here, a voltage value is chosen initially and the iteration of power equation is carried out as done in normal functional PV model as it involves the algebraic loop problem.

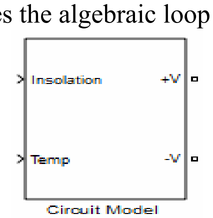

Figure 7.Circuit model block of PV module

The circuit model block of PV module is given in Figure 7.

Details of circuit modeling and its experimental verification are available authors paper. [8].

III. STUDY OF HIGHER TEMPERATURE PERFORMANCE OF PV MODULE

When the comparison is made between the output I-V characteristics with varying irradiation as shown in Figure 4 and Output I-V characteristics with varying temperature as shown in Figure 5, the variation in maximum power point voltage is within 0.5V for varying irradiation, and more than 3V for varying temperature operations.

This type of PV module output characteristics are available in wide variety of existing literature and this work also confirms with it.

A. Nominal cell operating temperature

The electrical specifications and ratings of PV module are given under test conditions of irradiance of 1kW/m^2, spectrum of 1.5 air mass and cell temperature of 25ºC. But these conditions never exist under outdoor operation. This specified temperature is Nominal Operating Cell Temperature (NOCT) and is to be found out from environmental conditions.

By definition, the NOCT is the temperature of the cells at a solar irradiance of 800 W/m^2, an ambient temperature of 20ºC, and a wind speed of 1 m/s.

The heat transfer from PV module depends on panel cover material, insulation back sheet and convection depends on panel mounting methods, radiation depends on tilting of panels. So it needs extensive data to determine exact NOCT. Normally NOCT was taken as 5ºC higher than the ambient temperature. [3]Our maximum ambient temperature recorded as above is around 52ºC. So our Nominal Operating Cell Temperature is about 60ºC. Hence the analysis has to be carried out to 65ºC.

B. MPPT Control Simulation Circuit for Higher Temperature Performance

The circuit model is used to find higher temperature performance of PV module.

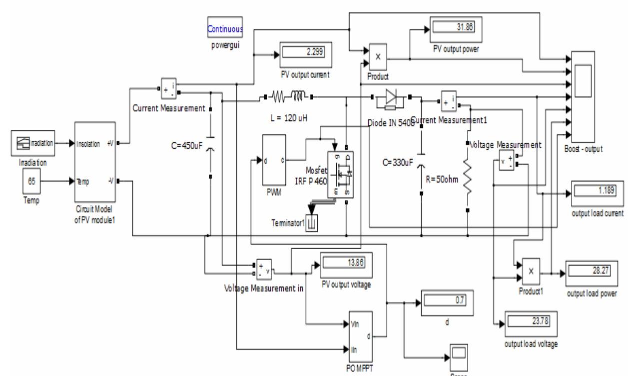

Figure 8. MPPT Control simulation circuit

The MPPT Control simulation circuit with maximum powerpoint (MPPT) control unit [8] and developed circuit model of PV module is shown in Figure 8. The V_{in} and I_{in}, are taken as input to MPPT unit, duty cycle is obtained as output. The simulation is done with irradiation of 1000W/m^2 and various temperatures 25ºC, 35ºC, 45ºC ,55ºC and 65ºC.

C. PV Input and Converter Output Value at Different Temperatures

The PV input and converter output values at different temperatures are tabulated in Table 3.

TABLE.3
PV INPUT AND CONVERTER OUTPUT AT 1000W/m^2
Insolation: 1000w/m^2

Temp ºC	Pv Input			Converter Output		
	V	I	P	V	I	P
25	15.58	2.412	37.57	18.65	1.865	34.78
35	15.44	2.371	36.61	18.48	1.848	34.13
45	15.23	2.31	35.18	27.75	1.11	30.8
55	14.19	2.357	33.43	27.71	1.109	30.72
65	13.86	2.299	31.86	23.78	1.189	28.27

In PV input and converter output values, the current variation with respect to temperature is all most nil. The power output due voltage variation from the converter shows is around 15%

The input output waveforms for various temperatures are shown in diagrams Figure 9 to 13.

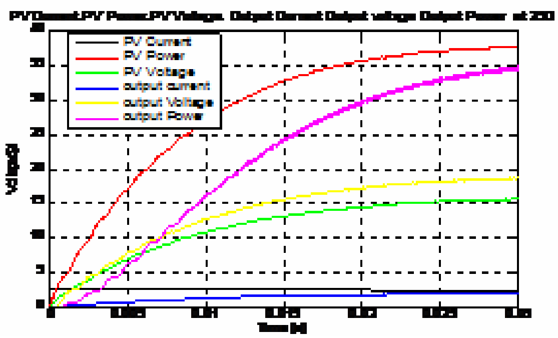

Figure 9. Variation of voltage, current, power for temperature of 25ºC

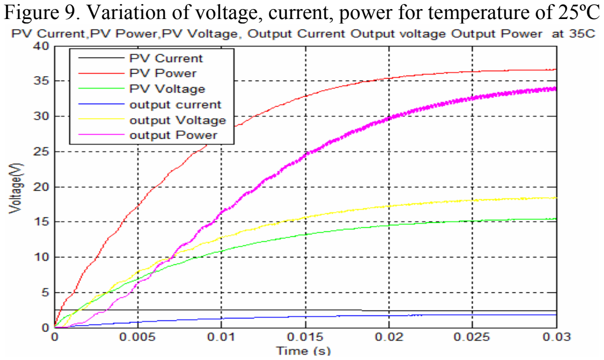

Figure 10. Variation of voltage, current, power for temperature of 35ºC

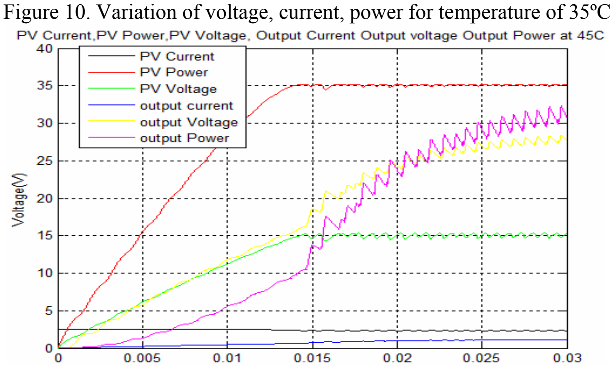

Figure 11. Variation of voltage, current, power for temperature of 45ºC

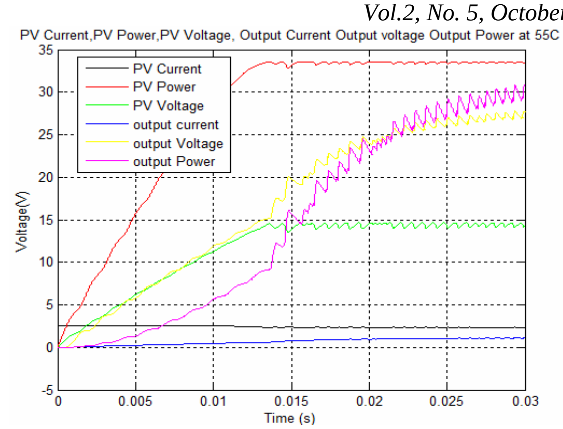

Figure 12. Variation of voltage, current, power for temperature of 55ºC

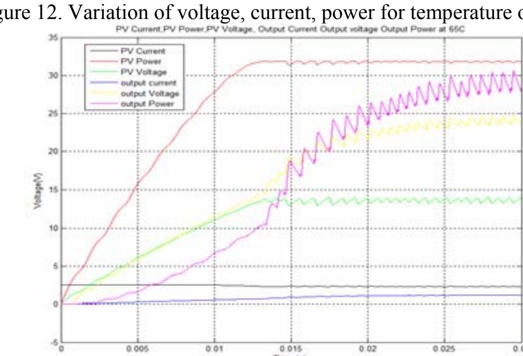

Figure 13. Variation of voltage, current, power for temperature of 65ºC

In existing literature only low output of PV module at higher temperature is generally discussed where as this type of waveform analysis is new work that is possible with this type of simplified circuit model.

D. Analysis of higher temperature wave forms

The current, voltage and power wave forms at 25ºC and 35ºC were very smooth and without ripples. At 45ºC input current to the converter is normal input voltage waveform is with ripples and was amplified in the output voltage wave form. The resultant power wave form at 45ºC was distorted with ripples due to the voltage waveform. At 55ºC and 65ºC situation was worsened that both input and output waveforms were full of ripples. These ripples are due to the sudden changes in module voltages due to higher temperature operation and boost converter may enter into discontinuous conduction mode (DCM) of operation.

When such a poor quality of discontinuous DC wave form were fed to the grid tied inverter used to get tripped off and this is the reason for the grid-offs occurred the mainly during the peak hours (11.30 am – 2 pm), that is, when the availability of solar insolation is maximal in peak grid-connected solar photovoltaic power plant of Kolar district of Karnataka, given in Annexure - I

IV. NEED AND NATURE OF IMPROVEMENTS

Even though the power output reduction from PV module at higher temperature is common, the need for the improvement in quality of the voltage output from the PV module needs immediate attention. When improved quality of the DC voltage is fed to grid connected voltage source inverter(VSI) at higher temperature the grid-offs experienced by the Indian PV power plants could be avoided.

1. The input filter capacitor must be increased enough so that the operation of boost converter in discontinuous conduction mode (DCM) may be avoided and to handle the ripple voltage and current of the boost converter [9]
2. Femia .N et al [10] studied the oscillation due to PO algorithm and presented the need for the control circuit. To arrest the higher order ripples as well as oscillations in higher temperatures we need a control and smoothen the output voltage waveform.
3. To have the simple and effective control, PI controller is included in our circuit shown in Figure 8.
4. The controller input needs the input without ripples the filter should be very effective. Hence the output capacitor size has be increased
5. Hence it is needed to increase the input and output capacitor in the boost converter shown in Figure 8.

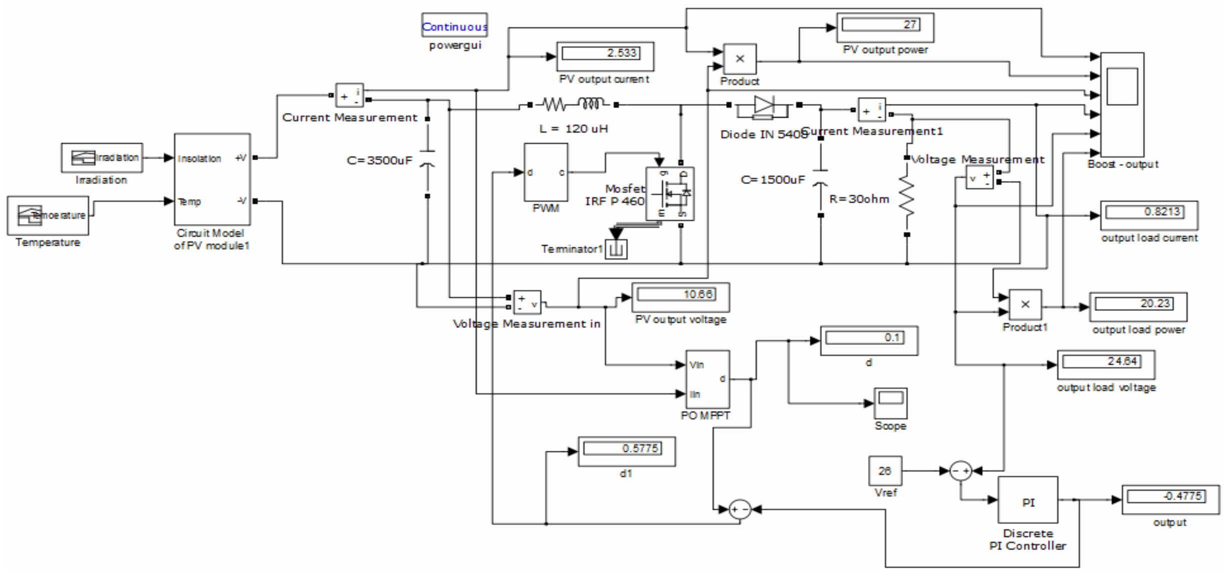

Figure 14. Closed loop control circuit with MPPT and PI controller - 65ºC

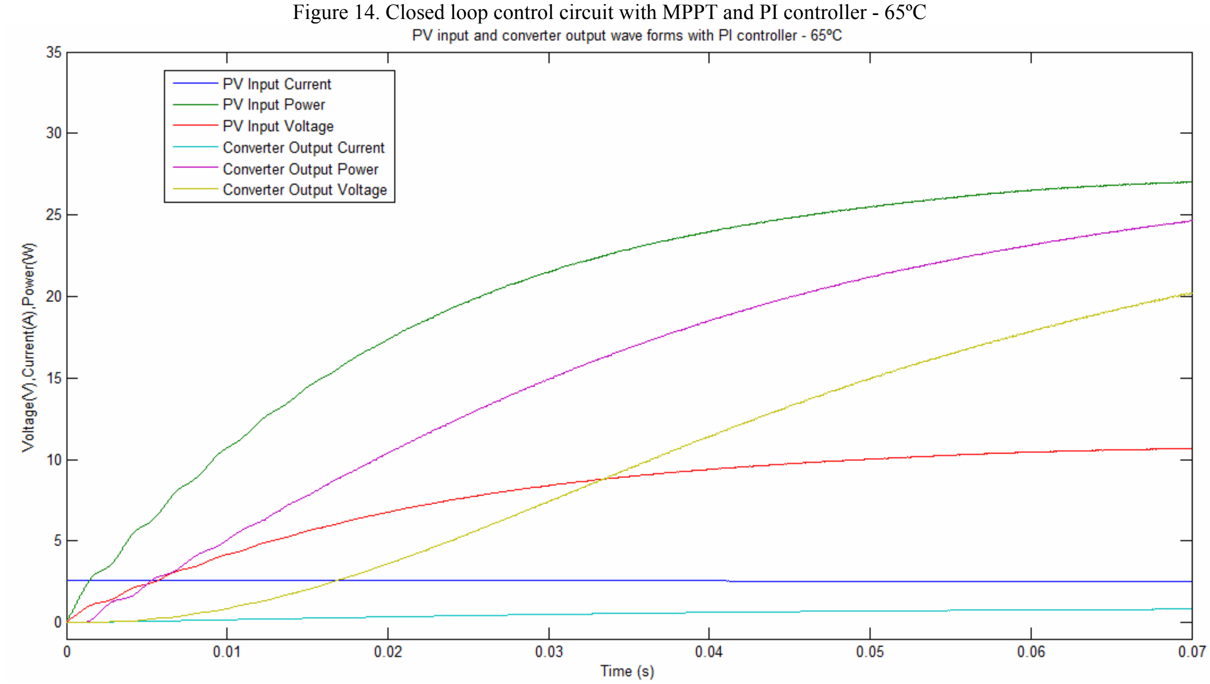

Figure 15. PV input and converter output wave forms with PI controller - 65ºC

6. The error between the output voltage and reference is fed to PI controller with proportional gain (Kp) = 0.0027, Integral gain (Ki) = 0.62.
7. The main function is wave form improvement and continuous operation of the power converter, around 10 to 15% output voltage variation is allowed .
8. The values of the increase in capacitor values are arrived with iterative simulation studies to improve the waveform output of the converter.

The increase of input capacitor value from 450µF to 2500µF and output capacitor value 330µF to 1000µF and adding the simple PI controller proportional gain (Kp) = 0.0027, Integral gain (Ki) = 0.62 the closed loop control with MPPT unit and PI controller is shown in Figure 14.

The circuit is simulated for constant irradiation 1000W/m^2 and constant higher temperature of 65ºC. The simulation output is shown in Table 4 and PV and converter wave forms are shown in Figure 15.

TABLE. 4
PV INPUT AND CONVERTER OUTPUT WITH PI CONTROLLER
Insolation: 1000w/m^2 Temperature :25 to 65ºC

Temp ºC	PV Input			Converter Output		
	Voltage	Current	Power	Voltage	Current	Power
25	14.33	2.464	35.22	35.64	0.7128	25.4
35	14.62	2.435	35.6	35.85	0.717	25.7
45	14.29	2.465	35.24	33.52	0.6704	22.47
55	13.71	2.403	33.09	28.59	0.8662	24.76
65	10.66	2.533	27	24.64	0.8213	20.23

V. RESULT AND DISCUSSION

The graph shows that the PV input values are settled at 0.04 Seconds and show slight incremental values thereafter with increased temperatures. But the converter output values are not properly settled with lower efficiency due to higher capacitor values and PI controller. But the wave forms are better with PI controller.

The above technique of employing the capacitors of higher values and boost converter for solving temperature issue is in line with solution of grid power fluctuation with higher DC link capacitor. The effect of these elements under normal temperatures is also presented in Table 4.

VI. CONCLUSION

In this paper the practical problems experienced by the Indian PV power plants with a case study is presented. The detailed study on higher temperature was made using the circuit model is done. With this closer waveform analysis, the solution to the higher temperature issue is made through simulation studies.

ACKNOWLEDGMENT

The authors wish to thank the management of SSN College of Engineering, Chennai for providing experimental and computational facilities to carry out this work at SSNCE EEE Department Solar Photovoltaic Research Laboratory.

ANNEXURE -I
PRESENT STATUS OF
PV POWER PLANT OPERATION IN INDIA

H. Mitavachan et al reported on 3 MW capacity peak grid-connected solar photovoltaic power plant near Yalesandra village in Kolar district of Karnataka established by Karnataka Power Corporation Limited (KPCL) The plant was fully commissioned on 27 December 2009. [2]

- ❖ The total electrical energy generated by the Yaleasandra plant during 2010 was 3.34 million kWh and 3.30 million units were sold to the grid.
- ❖ It is observed that the efficiency of the plant is more sensitive to temperature than the solar insolation.
- ❖ Solar cell material used at the plant is mono-crystalline silicon.
- ❖ The highest power generation achieved was 11812.4 kWh on 5th February 2010, with recorded insolation, average module temperature and plant efficiency of 6663 Wh/sqm/day, 42ºC and 12.24% respectively.
- ❖ **It was observed that the grid-offs occurred the mainly during the peak hours (11.30 am – 2 pm), that is, when the availability of solar insolation is maximal.**
- ❖ The daily efficiency of the 2MW plant ranged from 5% to 13.41% depending on the performance of arrays, inverters, average module temperature and the solar insolation.
- ❖ Figure 16 shows the daily average temperature of PV modules for the year 2010. It ranged from a minimum of 24.65ºC (on 6th Dec) to a maximum of 51.9ºC (on 23rd April).
- ❖ Although the solar insolation level is more in March compared to January, the efficiency during March is low. This may be due to increase in the daily average temperature of PV modules during that month.

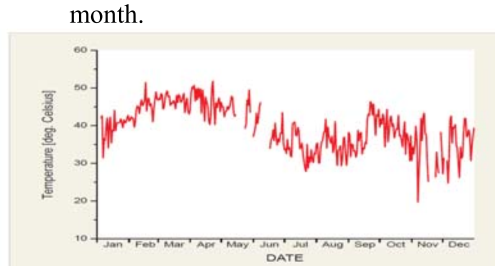

Figure 16. Daily average temperature of PV modules (day time) – 2010

REFERENCES

[1] Kroposki, B., Myers, D., Emery, K., Mrig, L., Whitaker, C., Newmiller,J., 1996. Photovoltaic module energy rating methodology development. In: Proceedings of 25th IEEE Photovoltaic Specialists Conference, May 13–17, Washington DC, pp.1311–1314.

[2] H. Mitavachan, Anandhi Gokhale and J. Srinivasan, "Renewable Energy Systems Reports - A case study of 3-MW scale grid-connected solar

photovoltaic power plant at Kolar, Karnataka Performance assessment & recommendations" Divecha Centre for Climate Change, Indian Institute of Science, 2011.

[3] E. Skoplaki, J.A. Palyvos "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations"Solar Energy, www.elsevier.com/locate/solener,Science Direct, October 2008.

[4] Weidong Xiao, William G. Dunford, Patrick R. Palmer, Antoine Capel "Regulation of Photovoltaic Voltage" IEEE Transactions On Industrial Electronics, VOL. 54, NO. 3, June, 2007

[5] Marcelo Gradella Villalva, Jonas Rafael Gazoli, and Ernesto Ruppert Filho "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays" IEEE Transactions on power electronics, VOL. 24, NO. 5, MAY 2009.

[6] Aeronautics and Space Administration, (NASA-CR-149364) National, Solar Cell Array Design Handbook, vol. 1, Jet Propulsion Lab, 1976.

[7] N. Pandiarajan and Muthu R, "Mathematical Modeling of Photovoltaic Module with Simulink" Proceeding of International Conference on Electrical Energy System (ICEES 2011), 3-5 Jan 2011.

[8] Pandiarajan N, Ramaprabha.R,Muthu R," Application of Circuit Model for Photovoltaic Energy Conversion System", International Journal of Photoenergy, Article ID 410401, Volume 2012.

[9] Walker G.R and Sernia P.C "Cascaded dc–dc converter connection of photovoltaic modules" IEEE transactions on power electronics, vol. 19, no. 4, July, 2004.

[10] Femia .N, Petrone .G, Spagnuolo .G, and Vitelli .M "Optimization of perturb and observe maximum power point tracking method" IEEE transactions on power electronics, vol. 20, no. 4, July 2005