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# UNCONVENTIONAL AND OPTIMIZED MEASUREMENT OF SOLAR IRRADIANCE IN BENGALURU USING PHOTOVOLTAIC TECHNIQUES

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***Abstract***

***Field solar radiation measurement is very essential to estimate the conversion efficiency of the solar photovoltaic (PV) system. Pyranometers, instrument used for solar radiation measurement are very expensive and require regular calibration and increasing maintenance cost. This paper provides an alternative low cost solution to estimate the solar radiation received on field. The paper addresses the design and development of MSP430G2553 microcontroller based data logger for measurement of the solar panel voltage and current output. The design is based on maximum power point tracking technique using 16-bit microcontroller to measure, analyse and compute the instantaneous maximum power of solar PV panel. The data is communicated through RS485 onto storage device for future analysis. The experimental analysis is carried out in Bengaluru co-ordinates. The estimated solar radiation is compared with recordings from a calibrated pyranometer. The loggers required very low power requirement and can be powered by the parent panel on which they are mounted thus avoiding requirement of grid. This feature makes it ideal for use in rural side field PV analysis. The developed SPV logger gives accurate measurement of solar PV output and aide in estimation of incoming solar irradiance.***

***Keywords:***

***Solar Photovoltaic (SPV), Irradiation Calculation, Pyranometer, Optimized Power Measurement, Microcontroller***

## 1. INTRODUCTION

A lot of emphasis is given on solar green energy generation to meet increasing energy generation demands. Solar photovoltaic (SPV) cells are used for electrical energy (in terms of voltage and current) generation through solar photovoltaic conversion process. Commercially available SPV modules have conversion efficiency of 10-12% of incoming solar radiation. In order to analyse the conversion efficiency of the SPV panels, it is important to measure the incoming solar radiation and the output power from SPV modules at any geographic location where SPV installation is planned [1, 2]. To carryout research work in any field it is very essential to have sufficient data from reliable source. Though solar energy is available freely, the instruments used for measurement are expensive. These instruments cannot be put up everywhere since additional manpower or surveillance will be required which will add to expense. Only few agencies put up such instruments with funding from other sources. The recorded solar data have to be procured by paying nominal charges for required duration. The work in this paper deals with a less expensive solution for recording solar data. These meters can be installed everywhere and have low or zero maintenance cost. Proposed work focuses on maximum power point tracking (MPPT) based solar parameter measurement and data logging.

Solar radiation received in earth's atmosphere is divided over wide spectral range. Maximum solar energy is carried in visible spectrum followed by IR spectrum [3]. Solar radiation can be represented in two terms: solar radiation power (Irradiance) and solar radiation energy (Insolation).

Solar radiation power is the amount of energy received by a unit surface. It is also known as solar irradiance and represented in terms of W/m². Solar radiation energy is rate of energy received by surface over a period of time. It is also termed as solar insolation and represented in terms of W-Hr/m². The SPV device used for photovoltaic conversion is a current controlled device. The current generated in device is proportional to the amount of light (in form of photons) incident on it [4, 5]. This can be represented in Eq.(1), and thus the device output power varies throughout the day and w.r.t the surrounding conditions as shown in Fig.1.

$$I = I_{ph} - \left\{ \exp\left( \frac{(V + IR_s)}{k_0} \right) - 1 \right\} - \left( \frac{(V + IR_s)}{R_s} \right) \quad (1)$$

where, $k_0 = \frac{\Delta kT}{q}$

| | | |
|---|---|---|
| $I$, $V$ | - | cell output current (A) and voltage (V) |
| $I_{ph}$ | - | light generated current (A) |
| $I_{sat}$ | - | cell reverse saturation current (A) |
| $A$ | - | ideality factor ( = 1) |
| $K$ | - | Boltzmann's constant (=1.3805 x $10^{-23}$ N.m/K) |
| $T$ | - | cell temperature (°C) |
| $Q$ | - | electronic charge (=1.6 x $10^{-19}$ C) |
| $R_s$ | - | Series resistance (Ω) |
| $R_{sh}$ | - | shunt resistance (Ω) |

For optimal electrical power yield from SPV device, it is required to operate system at its maximum power point (MPP). MPPT is a technique which involves automatic calculation of instantaneous maximum power ($M_p$) of SPV panel from panel parameters: voltage and current ($V_{mp}$ and $I_{mp}$) for varying atmospheric conditions. MPPT techniques are prevalent from early 1960s' [6] – [10]. Selection of MPPT technique depends on various factors such as response time to detect MPP under varying and shading conditions, complexity of algorithm and its implementation, number of sensors required, cost etc.

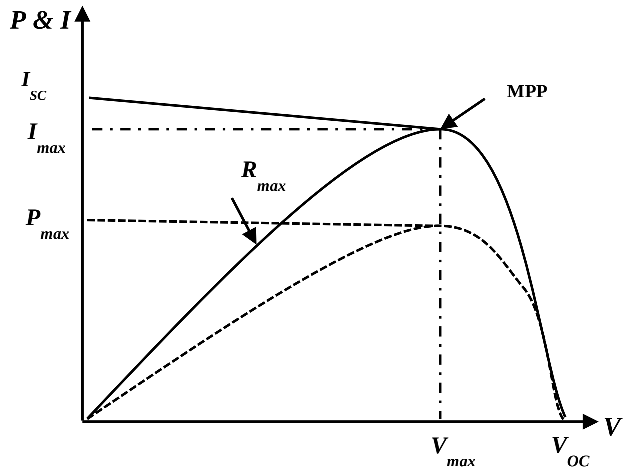


Fig.1. General Characteristic Curves of Solar Array

## 2. MAXIMUM POWER POINT TRACKING TECHNIQUE: INC CONDUCTANCE TECHNIQUE

Solar radiation received within the earth's atmosphere can be classified as global, diffuse and beam (direct) radiation. Each of the radiation can be measured using different instruments. Pyranometer can be used for measurement of global and diffuse radiation. Similarly, pyrheliometer can be used to measure beam (direct) radiation. Another instrument called sunshine recorder is used to measure the period of bright sunshine available per day at a location.

In pyranometer and pyrheliometer, photo diodes and temperature sensors are used which generate signals proportional to received light intensity falling on sensor. In case of sunshine recorder, a solid glass sphere is used. A light sensitive standard trace recorder paper is used to record the number of sunshine hours in a day. These instruments are very expensive and complex. The measurement by these instruments involves solar radiation over wide spectral range. These instruments need to be calibrated regularly and it is also expensive. Thus a low cost and complex alternative solution to measure irradiance received on a surface accurately is required.

An alternative solution to estimate incoming solar irradiance received on surface by measuring the maximum power generated from SPV collector is analysed in this paper. INC conductance MPP technique states that at MPP point the slope of *p-v* curve is zero, is negative on the right side of MPP and positive on left side of MPP [7] [8].

$$\frac{dp}{dv} > 0 \quad (2)$$

$$\frac{dp}{dv} < 0 \quad (3)$$

$$\frac{dp}{dv} = 0 \quad (4)$$

$$\frac{dp}{dv} = \frac{d(vi)}{dv} = i + v\frac{di}{dv} = \frac{i}{v} + \frac{di}{dv} = 0 \quad (5)$$

$$\Delta i = i(z) - i(z-1) \quad (6)$$

$$\Delta v = v(z) - v(z-1) \quad (7)$$

In this technique, instantaneous SPV panels generated maximum voltage and current are measured and maximum power is calculated. As we move along the power curve, the sign of slope ($dp/dv$) in *p-v* curve is checked. If slope is negative or positive, perturbation value has to be reduced or added.

When the slope is zero, indicates the MPP as shown in Fig.2. Equations governing INC conductance MPPT are given from Eq.(2) to Eq.(7).

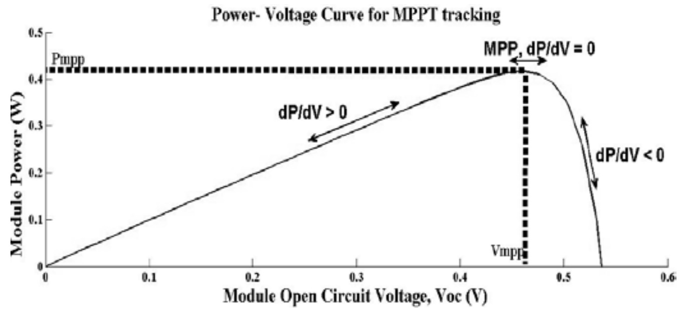


Fig.2. INC Conductance MPPT

## 3. PROPOSED ARCHITECTURE

The analysis involves calculation of incoming irradiance by measuring the maximum power generated by the SPV collectors. Simple and low cost solution architecture to measure instantaneous maximum power generated by SPV panel is shown in Fig.4. The irradiance is calculated by Eq.(8). The calculated irradiance data are correlated with the measured irradiance data by a standard pyranometer measurement. This work involves reasoning of cause for deviations if any between the calculated and measured irradiance.

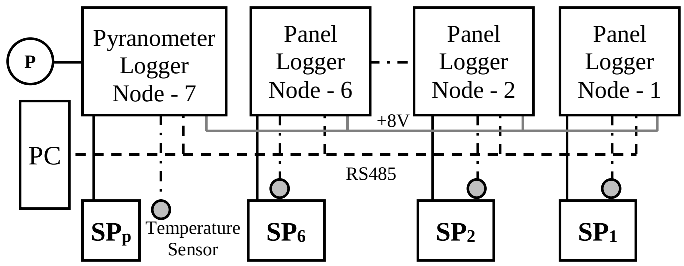


Fig.3. Solar Parameter Measurement System Block Diagram

The solar parameters measured by solar parameter data logger are solar radiation (in terms of W/m²), SPV module power ($V_{oc}$, $I_{sc}$, $V_{mp}$, $I_{mp}$, $M_{pp}$) and temperature (ambient and SPV module temperature in °C). The Fig.3 shows solar parameter measurement system block diagram and Fig.4 shows block diagram of proposed architecture of solar parameter measurement.

In Fig.3, seven panels are there and each panel is mounted with respective panel logger. The loggers are powered by parent panel on which they are mounted on. Out of the seven panels loggers, 6 measure the panel parameters (voltage, current and temperature). The 7$^{th}$ logger also powered by its SPV panel, converts the solar irradiance as sensed by pyranometer and measures ambient temperature. The 7$^{th}$ SPV panel also act as power source of +8V for all the temperature sensors in the system.

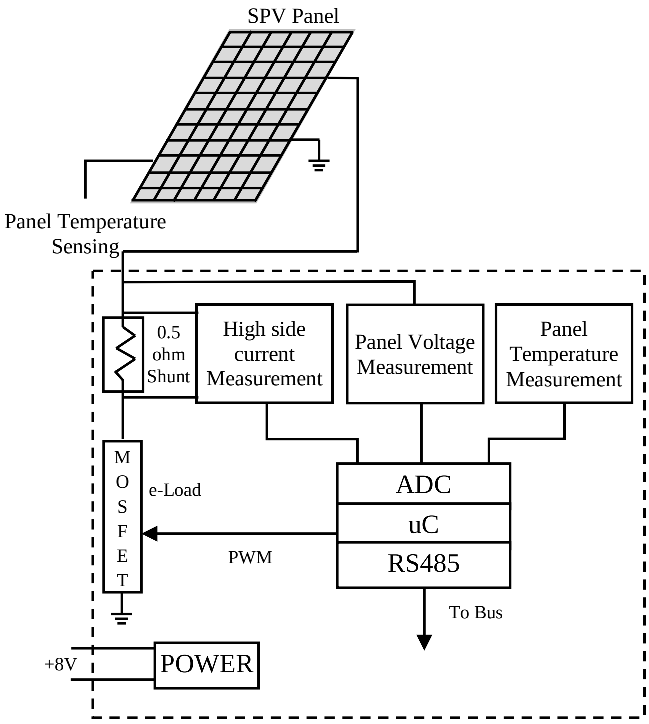


Fig.4. Proposed Measurement System Block Diagram

The Fig.4 shows proposed solar parameter measurement system block diagram. The solar parameter logger is powered by an external power supply of 8V. The measured data is analog form. Analog to digital converter (ADC) is used to convert the measured analog information to digital or microcontroller usable form. The output from ADC is 16-bit data which will be processed by 16-bit microcontroller (MSP430X). The processed data from microcontroller is communicated with the information logger system to be stored for further data analysis. RS485 is used for fast communication with PC and other meters connected in series. Data logging interval is pre-programmable for 15s-3600s. LM35 is used as temperature sensor to measure the ambient and panel temperature.

The system consists of MOSFETs as switching devices operating as electronic load (e-load) as seen in Fig.4. Pulse width modulated (PWM) signals are generated for the MOSFET switches from the microcontroller. Thus use of expensive battery load is avoided in this analysis.

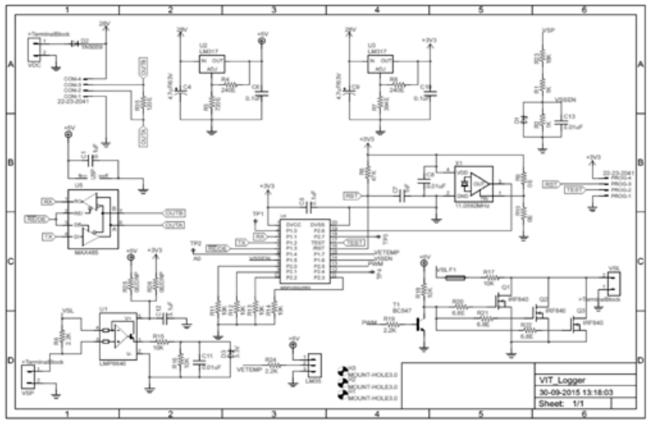

Fig.5. Circuit Diagram of the Logger

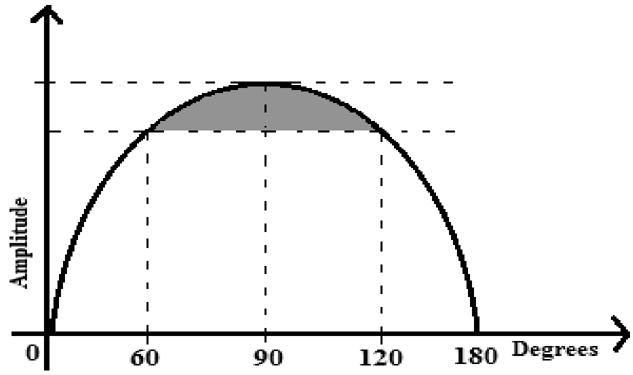


Fig.6. Sine Correction

Solar radiation received on earth's surface is for 12 hours and it follows sine wave pattern as shown in Fig.6. The starting point of incoming solar irradiance can be equated to sin(0°) and ending point equated to sin(180°) as shown in Fig.6. However effective solar radiation for electrical energy generation can be received for 8 hours which is approximated to range sin(60°) to sin(120°). It can be assumed that maximum peak power for a day can be achieved at sin(90°). To approximately calculate solar irradiance for clear sky from measured peak power for given active SPV cell area applying sine correction is given in Eq.(8).

$$Irradiance_{(theoretical)} = \frac{\left(\dfrac{M_p}{Active\ cell\ area}\right) * \eta * \sin\left(60 + \left(0.125 * M\right)\right)}{C} \quad (8)$$

where, $M_p$- measured instantaneous maximum peak power for given active cell area (active cell area considered from manufacturer's data sheet).

$\eta$ – instantaneous efficiency of SPV device

$M$ – minutes at which peak power is measured and recorded

$C$ – sine correction factor (depends upon the efficiency specified in manufacturer's data sheet)

Graphical display window indicating the measured solar parameters (received radiation, SPV panel output), ambient and SPV panel temperature and programmable logging interval is as shown in Fig.7.

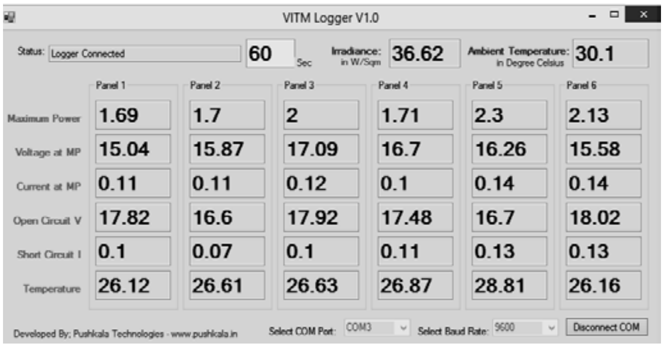


Fig.7. Graphical Display Window for MPPT Based Solar Logger

## 4. RESULTS AND DISCUSSION

For the experiment, a 40W polycrystalline SPV panel of WAREE make, with 10% conversion efficiency (as specified in manufacturer's data sheet) is used. The complete solar structure is oriented towards true south. Both the pyranometer and the SPV panel are held at same tilt angles while measuring. The Fig.12 and Fig.13 shows the graphs of theoretically calculated and measured irradiance for clear sky condition. The Fig.12 is result for arrangement at 55° tilt angle and recorded on 27$^{th}$ November 2015. Fig.13 is result of arrangement at 90° tilt angle recorded on 17$^{th}$ December 2015.

Co-ordinates for the Bangalore is 12.96666°N latitude and 77.566667°E longitude. Since India is located in the eastern hemisphere, the orientation of SPV panel is towards true south for maximizing solar irradiance received on surface. The data is recorded for approximately 8 hours a day, starting from morning 9 am to evening 5 pm. All the irradiance measurement is in terms of W/m².

A pyranometer is usually calibrated for many factors since it measures global and diffuse radiation over wide spectral range. Clear sky irradiance is the measure of maximum power for given active surface area of panel and panel conversion efficiency. After applying the sine correction factor, the theoretical irradiance level is nearly same as that of pyranometer measured irradiance level with minimum tolerance level. Sine correction factor depends on the conversion efficiency of SPV panel (as per the manufacturer's data sheet).

The Fig.8 shows the experimental setup with SPV panel and pyranometer. The structure of the SPV panel and pyranometer could be adjusted to desirable tilt angle. The Fig.9 shows the modular solar parameter logger, which is mounted to respective SPV panel. Another aspect of the solar logger is that it is powered by the SPV panel to which it is connected, thus eliminating the need for additional power supply to power up the logger. The solar parameter loggers powered by additional 12W panel. The hardware and software specifications of solar parameter logger are as shown in Table.1.

The Fig.10 and Fig.11 shows the SPV panel conversion efficiencies achieved on 2 different clear sky days and cloudy days. On clear sky days the measured conversion efficiency varies from 8-10% depending on the incident irradiance level as seen in Fig.10. On cloudy and rainy days, the efficiency varies rapidly with sudden peak overshoots in between due to the passing clouds.

The Fig.14 and Fig.15 shows irradiance output of both theoretical and measured output on two different cloudy days. Calculation of irradiance on given day depends upon the clearness index also and on cloudy or rainy days, it is difficult to calculate irradiance due to the passing clouds. Thus this analysis holds good only for clear sky days. The data of efficiency curves in Fig.11 for cloudy days is being analysed to identify the reason for sudden overshoots.

Table.1. Hardware and Software Specifications of Data Logger

| **Specifications** | |
|---|---|
| Communication | RS485 |
| Baud rate | 9600bps |
| Operating System compatibility | Windows XP and above. |
| Development platform | Microsoft Visual studio |
| Programming language | VC++ |
| Data file type | CSV |
| Microcontroller | MSP430G2553 |
| Voltage measurement range | 0-30V with step size of 50mV |
| Current measurement range | 10mA to 2.5A with step size of 5mA |
| Temperature sensor | LM35 |
| Temperature measurement range | 0°C to 80°C with step size of 0.5° C |
| **Irradiance measuring Pyranometer** | |
| Measuring and logging radiation range | 0 – 1500W/m$^2$ |
| Measuring and logging temperature | 0-60°C |
| Percent reading | ≤ 3% (0-70° incident angle) |

Table.2. Calculated Irradiance (W/m$^2$)

| **Parameter** | **Clear Sky Days** | | **Cloudy days** | |
|---|---|---|---|---|
| Measured Irradiance Data | 27$^{th}$ Nov 2015 | 17$^{th}$ Dec. 2015 | 4$^{th}$ Dec 2015 | 11$^{th}$ Dec. 2016 |
| Irradiance received in a Day | 548.67 | 399.66 | 582.88 | 338.22 |
| Incoming Solar Irradiance Range | 344.35 to 652.47 | 27.17 to 566.18 | 68.27 to 738.65 | 39.57 to 624.71 |

The Table.2 indicates the calculated irradiance values with sine correction factor and Table.3 gives measure of the incoming solar irradiance as measured by calibrated pyranometer on clear and cloudy days. All irradiance values are in W/m$^2$. The deviation in calculated and measurement on clear sky days is less than 30%.

Deviation between calculated and measured irradiance is as tabulated in Table.4.

Table.3. Measured Irradiance (W/m$^2$)

| **Parameter** | **Clear sky days** | | **Cloudy days** | |
|---|---|---|---|---|
| Measured Irradiance Data | 27$^{th}$ Nov 2015 | 17$^{th}$ Dec. 2015 | 4$^{th}$ Dec 2015 | 11$^{th}$ Dec. 2016 |
| Irradiance received in a Day | 455.56 | 360.35 | 527.34 | 355.95 |
| Incoming Solar Irradiance Range | 241.69 to 468.75 | 188.96 to 372.07 | 123.04 to 596.19 | 77.63 to 383.78 |

Table.4. Percentage Deviation (%)

| **Date** | **Clear sky days** | | **Cloudy days** | |
|---|---|---|---|---|
| | **27$^{th}$ Nov 2015** | **17$^{th}$ Dec. 2015** | **4$^{th}$ Dec 2015** | **11$^{th}$ Dec. 2016** |
| Deviation (%) | -28.05 | -20.79 | -24.4 | -20.22 |

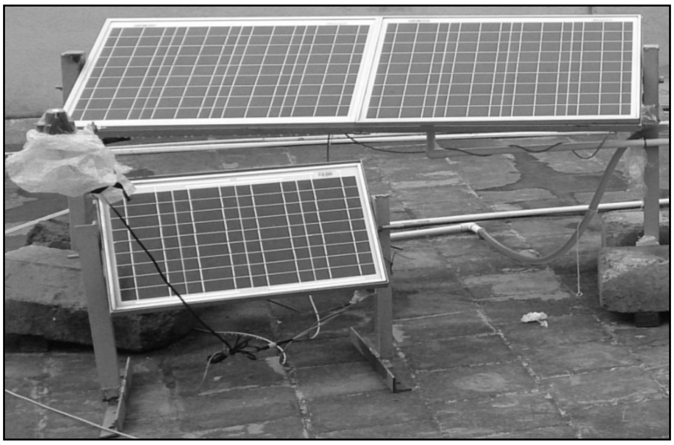

Fig.8. Experimental Setup

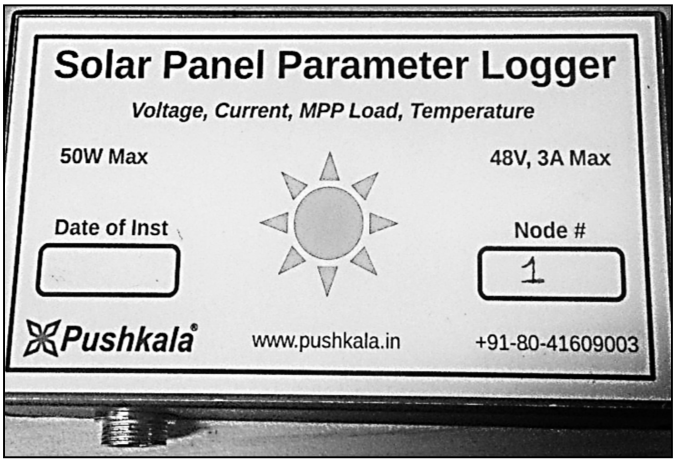


Fig.9. Solar Parameter Data Logger

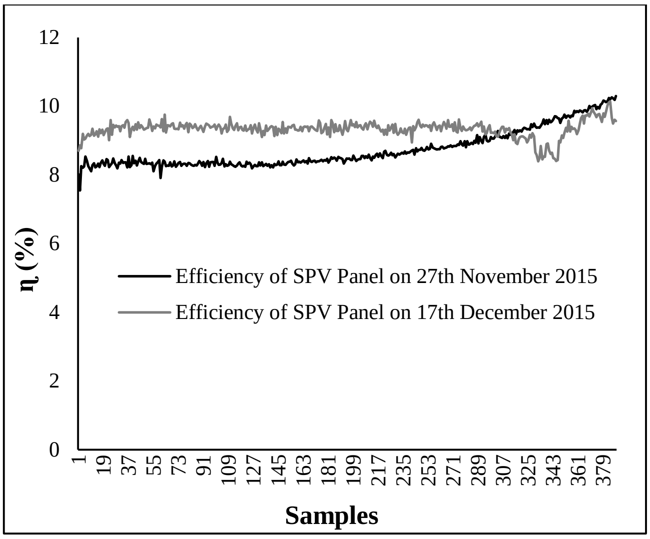


Fig.10. Panel Conversion Efficiencies on Clear Sky

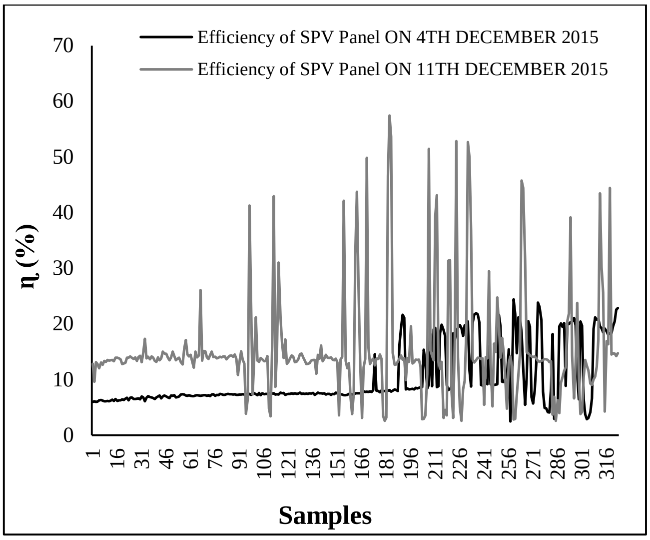


Fig.11. Panel Conversion Efficiencies on Cloudy Day

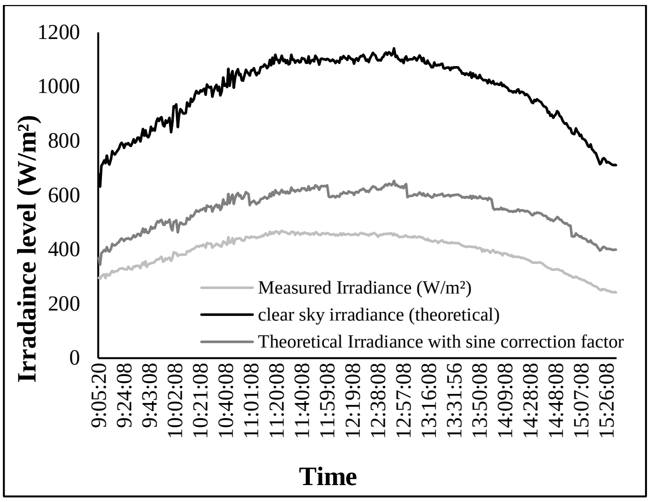


Fig.12. Output on 27$^{th}$ November 2015

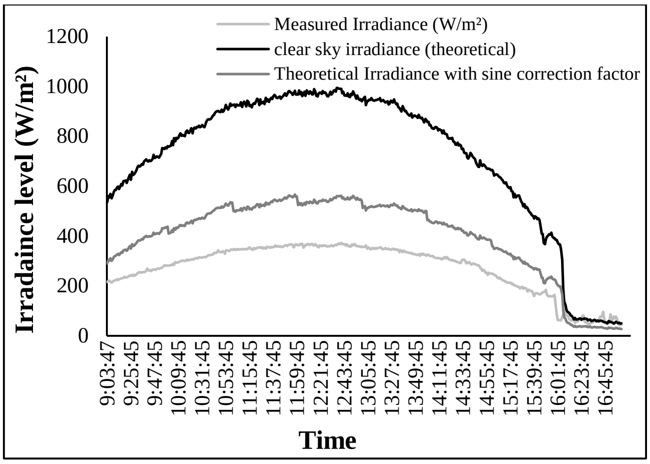


Fig.13. Output on 17th December 2015

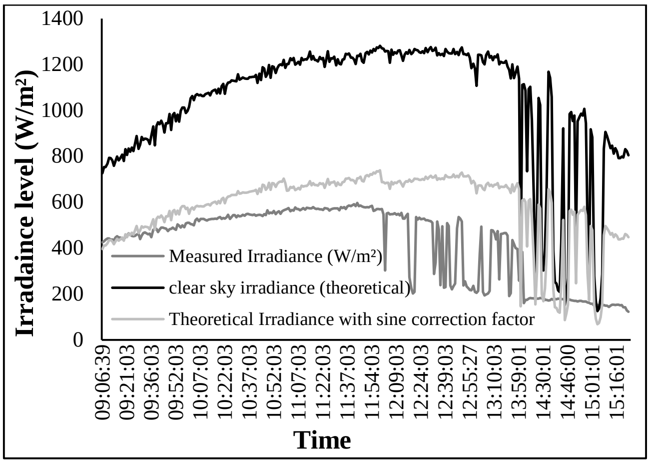


Fig.14 Output on 4th December 2015 Cloudy Day

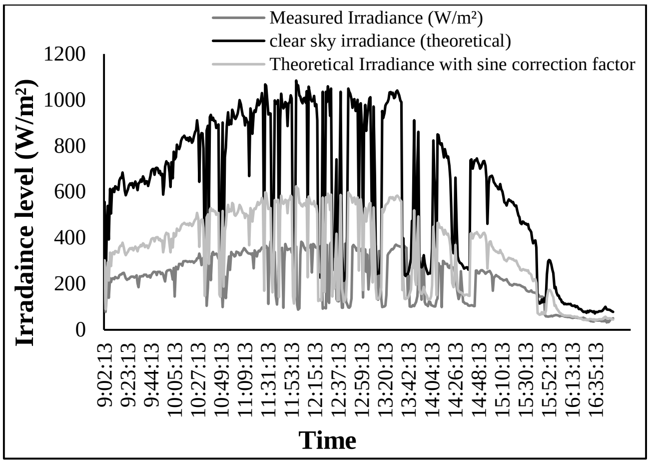


Fig.15. Output on 11th December 2015 Cloudy Day

## 5. CONCLUSIONS AND FUTURE WORK

A low cost MPPT based solar power measurement technique is designed and developed. The measured maximum power is used to estimate the incoming solar irradiance. The results are reasonably close to actual irradiance measurement. The deviation between calculated and pyranometer measured irradiance is found to be less than -30%. This deviation is due to variation in the spectral response of each measurement technique. Findings are relevant only during clear sky days. The solution measures the maximum power accurately at any given location. The logger is modular and compact, requiring low power.

The loggers are powered by the SPV panels on which it is mounted, thus avoiding any requirement of additional power supply. This reduces the stress on grid. It also includes internal electronic load, thus battery requirement which is costly can be avoided in day time. The measured data is logged on to PC environment directly and it could be published live on internet for use of interested researchers in field of organic solar cells to analyse data. It involves less transportation and installation cost and its wiring is simple. This solar parameter logger is very economical which can be installed in rural areas as an alternative for costly pyranometers since its maintenance is easy and in case of theft loss will be very low. Further work is in progress with 5 more nodes totalling 6 measurement sets at various tilt angles which will be published in future.

## ACKNOWLEDGEMENT

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## REFERENCES


[1] T. Shivalingaswamy and B.A. Kagali, “Determination of the Declination of the Sun on a Given Day”, *European Journal of Physics Education*, Vol. 3, No. 1, pp. 17-22, 2012.

[2] Iqbal Reda and Afshin Andreas, “Solar Position Algorithm for Solar Radiation Applications”, NREL Technical Report, pp. 1-34, 2008.

[3] Chetan Singh Solanki, “*Solar Photovoltaics, Fundamentals, Technologies and Applications*”, 2nd Edition, Prentice-Hall of India, 2011.

[4] Tarak Salmi, Mounir Bouzguenda, Adel Gastli and Ahmed Masmoudi, “MATLAB/Simulink Based Modelling of Solar Photovoltaic Cell”, *International Journal of Renewable Energy Research*, Vol. 2, No. 2, pp. 213-218, 2012.

[5] Hiren Patel and Vivek Agarwal, “MATLAB-Based Modelling to Study the Effects of Partial Shading on PV Array Characteristics”, *IEEE Transactions on Energy Conversion*, Vol. 23, No. 1, pp. 302-310, 2008.

[6] Chris Glaser, “Easy Solar Panel Maximum Power Point Tracking for Pulsed Load Applications”, *Analog Application Journal*, Vol. 3, pp. 5-7, 2012.

[7] V. Salas, E. Olais, A. Barrado and A. Lazaro, “Review of the Maximum Power Point Tracking Algorithms for Stand-Alone Photovoltaic Systems”, *Solar Energy Materials and Solar Cells*, Vol. 90, No. 11, pp. 1555-1578, 2006.

[8] S. Jain and V. Agarwal, “Comparison of the Performance of Maximum Power Point Tracking Schemes Applied to Single-Stage Grid-Connected Photovoltaic Systems”, *IET*

*Electric Power Applications*, Vol. 1, No. 5, pp. 753-762, 2007.

[9] K.J. Shruthi, P. Giridhar Kini, C. Viswanatha and Rajashekar P Mandi, "Design and Analysis of Perturb and Observe MPPT Technique for Inverter in Photovoltaic System", *CPRI Journal*, Vol. 10, No. 1, pp. 125-130, 2014.

[10] Bidyadhar Subudhi and Raseswari Pradhan, "A Comparative Study on Maximum Power Point Techniques for Photovoltaic Power Systems", *IEEE Transactions on Sustainable Energy*, Vol. 4, No. 1, pp. 89-98, 2013.