# Field Trials and Performance Monitoring of Distributed Solar Panels Using a Low-Cost Wireless Sensors Network for Domestic Applications

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***Abstract*—Use of solar panels is gaining an ever increasing foothold in society, especially on the roof of the houses for feeding domestic electrical appliances in recent times. In many situations, the expensive solar panels stop working due to some external nuisances which goes unnoticed to the users. There is a need of a low-cost monitoring system to get information of the defected solar panels for timely repair and maintenance. The design, development, and trial work of a performance monitoring system of distributed solar panels along with automated data logging based on a low-cost wireless sensors network has been reported to help the current situation. The developed system can be used up to 146 V and 15.5 A solar cell systems with automatic selection of best resolutions. The system can be extended for wide range of solar cells for material research and development activities. The fabricated system has been used for field trials and very satisfactory results are obtained.**

***Index Terms*—Defect of solar panels, I-V-P curve tracer, maintenance, maximum power tracker, performance monitoring, solar panels, wireless communication, Zigbee.**

## I. Introduction

IN RECENT times, Photovoltaic (PV) Solar cells have found a multitude of applications in society, especially on the roof of the houses for feeding domestic electrical appliances. In the past, predominately the main uses of it has been for a reliable, low maintenance, environmentally safe, and sound power source for remote sensing and communication applications. However, for isolated dwellings where it would not be geographically possible nor financially viable to use or access existing electrical utility networks. PV also has been integrated into many small portable commercial and consumer electronic devices in which regular battery replacement can be alleviated. With the cost of PV coming down as is shown in Fig. 1 and approaching grid parity in some countries, along with the focus on environmentally sustainable energy production; many new technologies are being developed and showcased now that can be affordably integrated into general domestic home and utility power systems. Though, the technologies are getting smart, still the failure rate of the PV modules are not zero, as is shown in Fig. 1 [1]. There is a need of continuous monitoring of the behavior of the solar panels.

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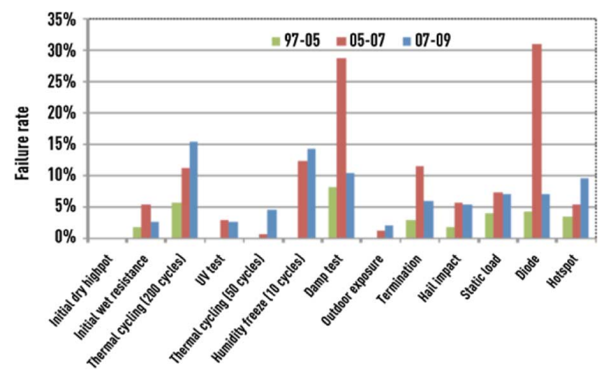



Fig. 1. Failure rate comparisons of PV modules (source: http://www.tuv.com/).

To extract the maximum power from a panel or an array of panels, it is important to understand the characteristics of a particular panel under different light conditions. Usually, this is accomplished by tracing the I–V characteristics of the panels or arrays under different real-world atmospheric conditions. The most immediate solution is to find the maximum power point of the solar panel and make sure the solar panel always provides the maximum power it can produce. A substantial amount of research works have been carried out for the measurement of I–V–P curve and then to track the maximum power point [4]–[12]. There are also many other parameters of a system that one may be interested in, i.e., effects of panel shading, temperature, etc. A good amount of research has also been reported on the measurement of performance of solar panels in the outdoors and using the remote monitoring method [13], [14]. A microcontroller-based standalone PV cell monitoring system has been reported in [15], which can supply power to the wireless sensor node. The use of efficient solar cells for providing power to a wireless smart camera has been reported in [16]. A remote data acquisition system of laboratory scale has been developed based on a solar powered wireless monitoring system [17]. A wireless remote monitoring system using multiple wireless sensors and wireless communication has been proposed [18]. An implementation of a system based on wireless sensor network to monitor the activities of a salt-farm has been reported [19]. A proposal of environmental monitoring framework based on a wireless sensor network technology characterized by energy harvesting, robustness, and solar powered has been reported in [20] and [21].

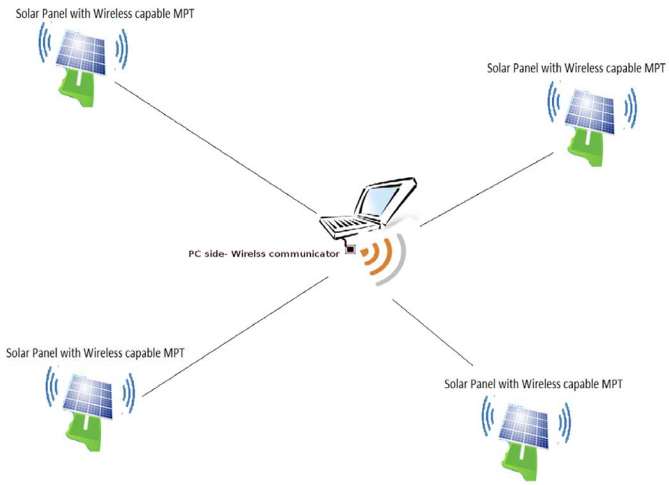



Fig. 2. The concept of wireless monitoring of performance of solar panel networks.

The existing or reported wireless-based monitoring system still falls short of addressing one or more of the following concerns; economic, capacity, range, efficiency, and reliability. Therefore, there is a motivation to explore and to develop a performance monitoring system of distributed solar panels based on low-cost wireless sensors network.

## II. Background of the Project

When generating the idea for this project, the likely future scenario is considered where power companies or communities have placed a network of solar panels to provide electricity to households. They would like to control and monitor the solar panels network from the work base. Making the control and monitoring system capable of communicating through a wireless medium adds the flexibility that the technician does not have to be in the actual area where solar panels are located to monitor the solar panel networks.

In the current study, a system has been developed which can track and monitor the performance of the solar panel, can set the maximum power point of solar panels, monitor its instantaneous power output, and send and receive data and commands from a operator who is based on a remote location using wireless medium. The system will also be able to monitor whether there is any operational problem of the solar panel, such as not generating any output even in the presence of sunlight. The problem can be due to a cell problem itself or may be due to shading (a branch of a fallen tree might have created the shading). The system can give a warning sound by which the household people may physically observe it to know the problem. The conceptual diagram is shown in Fig. 2. All the parameters are measured by the local measurement circuit and then transferred using the Zigbee communication protocol. The reasons for using Zigbee are that it matched the data rate, distance and power consumption and cost compared to other communication protocols available. The important information are the open circuit voltage ($V_{oc}$), short circuit current ($I_{sc}$), and the maximum power point (MPP, $P_m$), and the associated voltage and current at this maximum power point ($V_{mp}$ and $I_{mp}$, respectively). The MPP and associated values can vary significantly, depending on solar irradiance intensity, cell type, temperature, shading, etc. This type of measurement is also invaluable in PV system maintenance, where it is necessary to detect faulty cells and panels (a single faulty or shaded cell can significantly destroy the output of an entire panel or array), and also useful for insuring panels in arrays are matched so as to get maximum power.

TABLE I
Some Current Portable Commercial I–V Curve Tracers for PV

| Model | Price $NZD | General Specifications | Cell Loading |
|---|---|---|---|
| Prova 200 | $1620 | 60V, 6A | Electronic |
| Vision Tec VS-6810 | $6,190 | 200V, 10A | Electronic |
| EKO MP-170 | $10,900 | 10-1000V, 1-20A | Capacitive |
| PVMPM2540C | $11,000 | 250V, 40A | Capacitive |
| Celtis PV-CTF1 | $19,700 | 250V, 20A | Electronic |
| Daystar's DS-100C | $32,100 | 600V, 100A | Capacitive |

Many commercial I–V curve tracers exist, some being purposely designed for PV market or the adaptation of common I–V curve tracer equipment as is shown in Table I. These range in price from NZ $1620 for the Prova 200 to NZ $32 100 for the Daystar DS-100C. Generally, these have PC link for control and data download, and have inputs for or come with irradiance and temperature sensors. Usually, most of the available commercial I–V–P curve tracer are designed for desktop applications and can monitor the performance of one solar panel at a time. The purpose of the work is to design and develop wireless sensor network which can monitor performances of a few solar panels simultaneously with the help of switching arrangement and provide valuable information about failure and/or maintenance data. The challenge was to develop each wireless remote sensing and monitoring unit under NZ $200.00 for a 150 V, 15 A solar panel system including communication devices. The design and fabrication of each remote system has been carried out within the price.

## III. Design Methodology of the Performance Monitoring System

While there are numerous circuit schematics for solar cell I–V–P measuring circuits in the literature based around DAQ devices, and I–V curve tracers for discrete components, very few seem to have included a loading circuit with sufficient capacity to handle larger currents and voltages associated with larger solar cell modules.

The initial device setup and requirements were identified as follows.

- Large dynamic current range 0–15 A with 1 mA resolution and low insertion loss (0.01 ohm max).
- Voc of 100 V.
- Simple and light in construction so that can be used at roof of the house along with the panel.
- Adjustable scan time, ideally down to 1 s or less so accurate scans can be completed under changeable atmospheric conditions.

TABLE II
DETAILS OF SILICON SOLAR PV MODULE

| | |
|---|---|
| Model | SR-5S |
| Pm | 5 W |
| Voc | 21.0 V |
| Isc | 0.38 A |
| Vmp | 16.8 V |
| Imp | 0.30 A |
| Dimension | 254 mm * 294 mm * 23 mm |
| TEST CONDITION | AM 1.5 1000 W/m$^2$ 25°C |

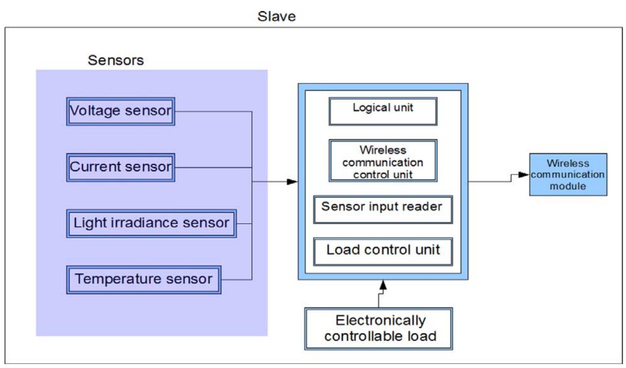



Fig. 3. The functional block diagram representation of the remote unit.

- Integration of a budget pyranometer, so panel efficiency can be calculated.
- Portable.

To do this, suitable methods and signal conditioning for both voltage and current measurements and a controllable load were investigated and developed. For the purpose of development, a solar panel used the details of which are given in Table II. The functional block diagram representation of each remote unit is shown in Fig. 3.

In this project, we investigate and evaluate a number of ways to measure the I–V characteristics and load of a PV module, both from a device and software perspective. The designed and fabricated circuit for the remote monitoring unit is shown in Fig. 4. Four remote wireless monitoring units are placed under the roof having solar panels for field trial, as shown in Fig. 5.

Breaking down into the three main areas of consideration are as follows.

### A. Voltage Measurement

A voltage sensor uses simple voltage divider arrangements to bring the input voltage level to a measurable voltage, as is shown in Fig. 6. The voltage division level is adjusted to get the best resolution for the input voltage level with the help of a few switching resistors. There are four different voltage resolution levels. The maximum measurable voltage is 146 V.

The output equation of the circuit in Fig. 6 can be written as

$$\frac{V_{\mathrm{out}}}{V_{\mathrm{cell}}} = 1 + \frac{R_1 + R_{\mathrm{DS(ON)}}}{R_2} \tag{1}$$

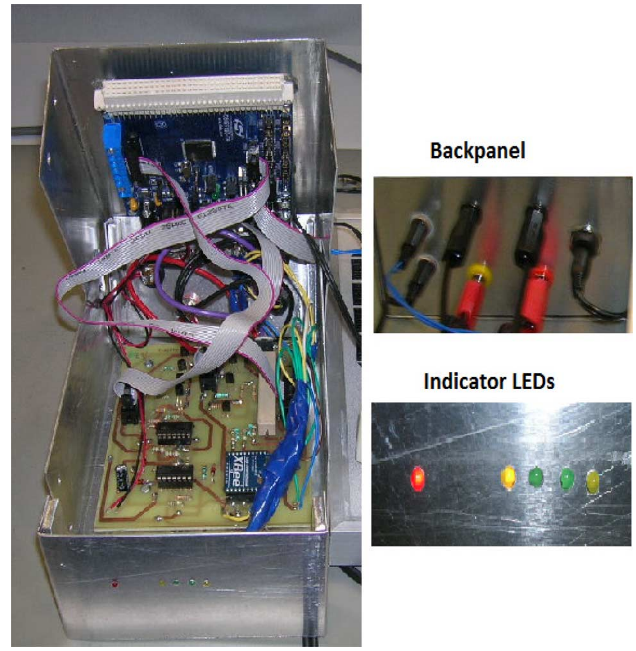



Fig. 4. The developed electronic system for performance measurement of solar panel and wireless communication.

Fig. 5. The field trail of the developed and fabricated remote performance monitoring unit.

where $R_1$ is the resistance in series with the MOSFET and $R_{\mathrm{DS(ON)}}$ is the on-state resistance of the MOSFET. The resistance $R_2$ is connected in series with cell. The different values of resistance $R_1$ are used to measure different cell voltages.

The comparison of measured characteristics with respect to the actual values for two different voltage settings is shown in Fig. 7.

### B. Current Measurement

This involves using a MOSFET to operate as a variable voltage dissipating device and it allows more voltage to drop across it as in input gate voltage changes as is shown in Fig. 8. A MOSFET was chosen as it can switch faster than a transistor. The current sensor uses low ohm current sensing resistor (0.05 Ω) to measure the current. The voltage across the current sensing resistor is amplified and fed into the Analogue to Digital Converter of the microcontroller. The gain of the amplification

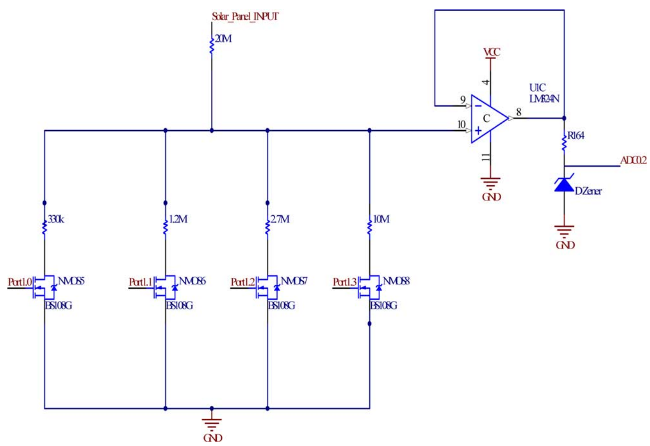
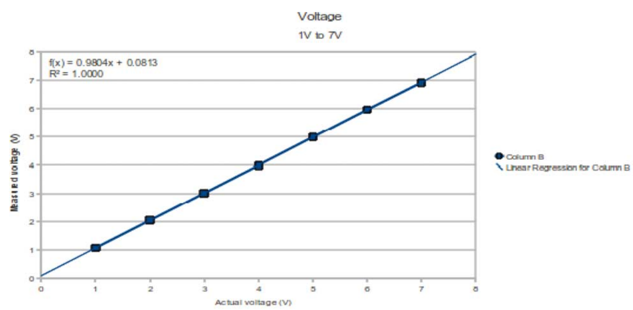
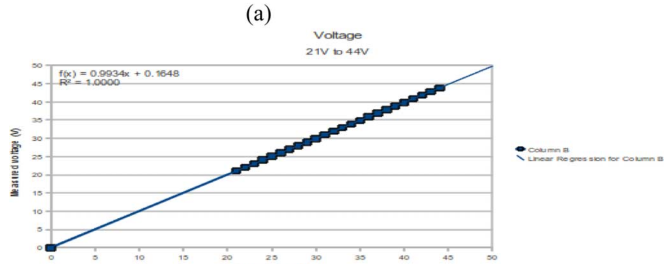



Fig. 6. Voltage divider arrangements to measure cell voltage.




(a)




(b)

Fig. 7. Measured voltage characteristics. (a) Voltage resolution up to 7 V. (b) Voltage resolution from 8 to 20 V.

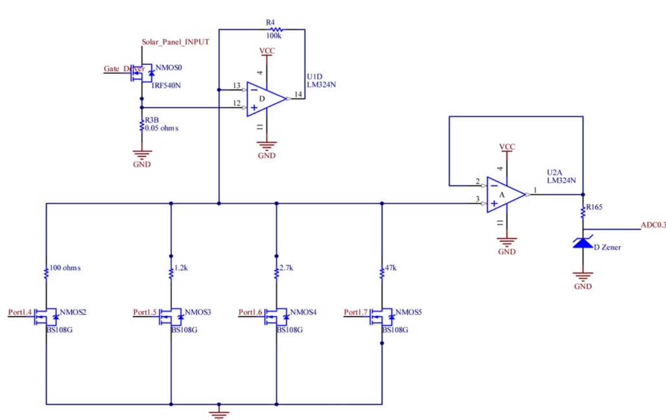



Fig. 8. Loading arrangements to measure current delivering capability of the cell.

of the circuitry is adjusted to get the best resolution for the sensor with the help of a few switching resistors. There are four different current resolution levels. The maximum measurable

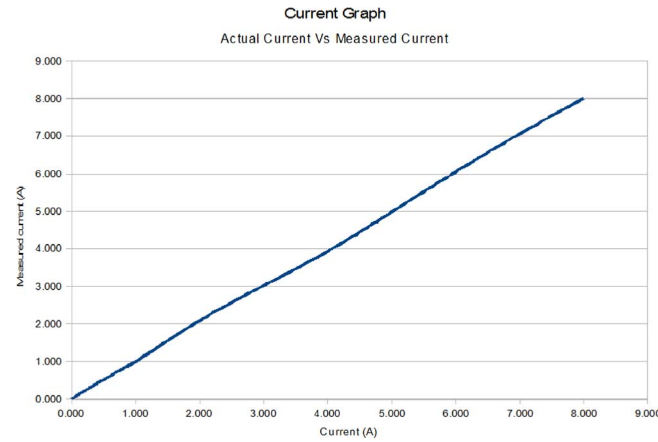



Fig. 9. Measured current characteristics.

Fig. 10. PDB-C139 photodiode.

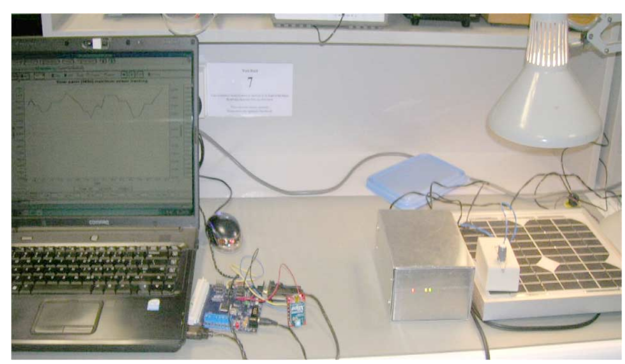


Fig. 11. The setup for calibration and testing of light.

current is 15.5 A. The measured current characteristic for one range is shown in Fig. 9.

## C. *Measurement of Light Irradiance*

The photodiode (PDB-C139) as is shown in Fig. 10 has been used as the sensor. Although the photodiode is not the ideal choice, but due to cost and other considerations, it is used for the measurement of light irradiance. The photodiode is placed parallel with a 470 $\Omega$ resistor which is smaller than the shunt resistance of the photodiode. This arrangement allows the photodiode to act as a linear current generate for the given light irradiance. The output of the photodiode is amplified and fed into the Analogue to Digital Converter of the microcontroller. The maximum measurable light irradiance is 2550 W/m$^2$. Fig. 11 shows the setup for calibration and testing of light irradiance and Fig. 12 shows the electronic circuit for

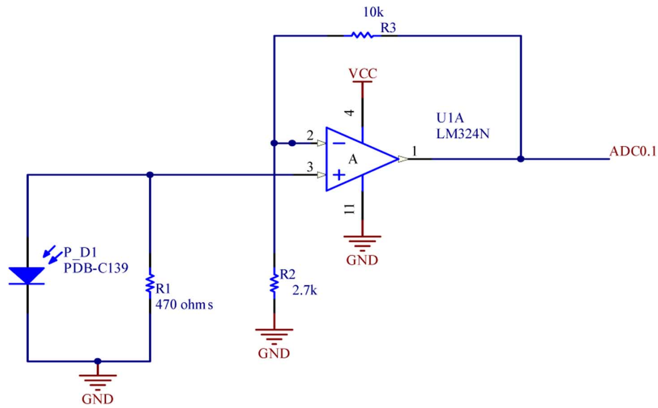



Fig. 12. The circuit for light irradiance measurement.

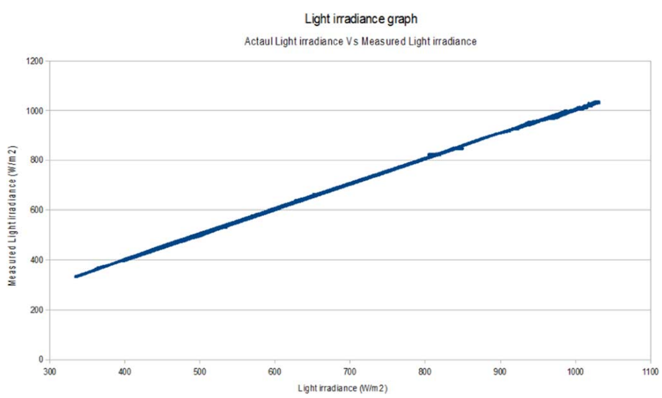



Fig. 13. Measured light irradiance characteristics.

Fig. 14. B57164K472J NTC-Thermistor.

measurement. Fig. 13 shows the comparison of measured light irradiance characteristics.

### D. Ambient Temperature Measurement

A NTC thermistor (B57164K472J) as is shown in Fig. 14 is used as the sensor. The thermistor is placed in series with 560 Ω and 3.2 V reference voltage is supplied to the thermistor. The voltage across the 560 Ω resistor is fed into the Analogue to Digital Converter of the microcontroller and is used to find the thermistor resistance. Thermistor resistance is converted to temperature reading using the Steinhart–Hart equation. The maximum measurable temperature is 122 °C.

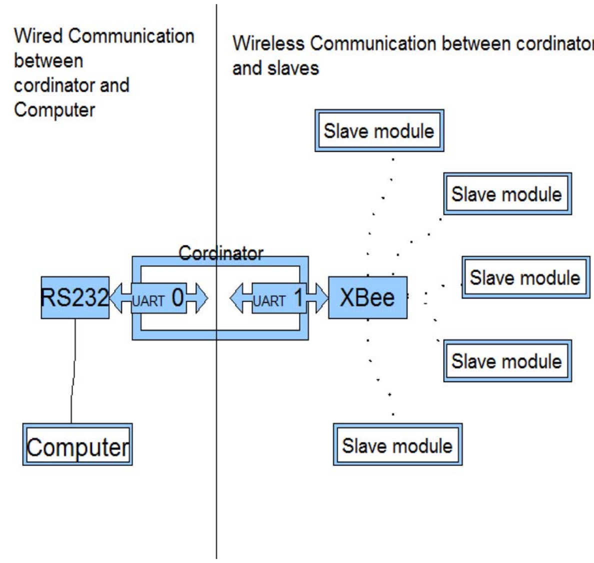



Fig. 15. The functional arrangement of communication of performance monitoring data.

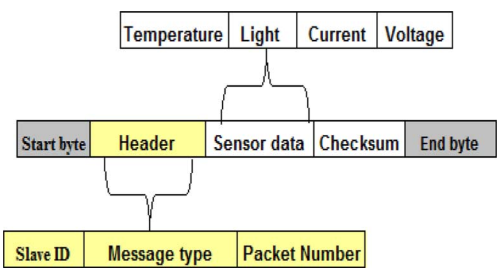



Fig. 16. Formation of performance data packet for wireless communication.

## IV. Wireless Data Collection for Performance Monitoring

All performance data are collected by the microcontroller and are formed in a format to send them wirelessly to the coordinator using Zigbee communication. Each slave module has their own unique IDs. The communication between the coordinator and the computer is done via a USB to serial cable. The functional description of the arrangement for data communication is shown in Fig. 15.

The maximum power point tracking data packet contains slave ID, Message byte indicating the data packet contains MPT data, and the packet number followed by the ADC readings of temperature, light, current and voltage sensors followed by the checksum. The data formation is shown in Fig. 16.

Data is saved in a Database as well as text files. Every slave module has their own entry in the database, as shown in Table III.

The data is communicated using the Zigbee protocol, the low-cost Xbee has been used for the purpose. Zigbee protocol has been used as it matched the data rate, distance and power consumption and cost that are aimed for. During this experimental stage, the reliability and efficiency of the communications are tested for various conditions. By considering various factors like reflections due to walls, noise caused by household appliance,

TABLE III
DETAILS OF DATA FORMAT

| Name | Purpose |
|---|---|
| Slave_ID | Holds the unique ID of the slave module |
| Category | Indicate what type of slave this is |
| Area | If this slave is a performance tracking unit for solar panels, area of the solar panel this slave is connected to. |
| Samples | The averaging index of this slave module data |
| Last_found | When this slave was last seen online |
| Last_MPT | When is the last time this slave did the maximum power point tracking |
| Last_Monitor | When is the last time this slave did the performance tracking |

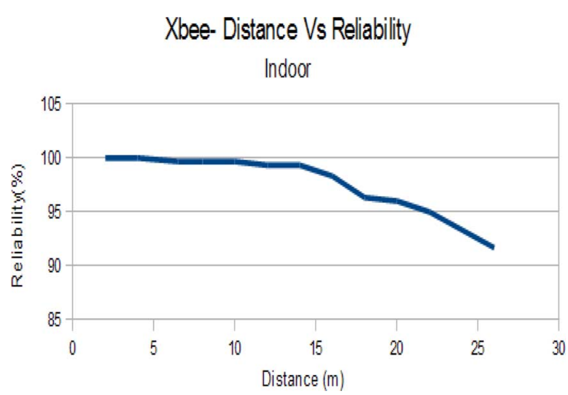



Fig. 17. The reliability of communication as a function of distance.

the sensor node RF communication reliability was also tested and the results obtained are satisfactory. Fig. 17 shows the reliability of communication as a function of distance in a home environment. The range achieved by the Xbee is sufficient for normal household application. If higher range is required, the Xbee can be simply replaced by Xbee-Pro without changing any electronic circuits.

Maximum power point tracking data is automatically logged in the computer. Each slave module has its own folder and all the logged data is saved inside this folder. Data files are named in such a way to indicate when the MPT is run. Fig. 18 shows the screenshot of the format of the saved data. Fig. 19 shows the actual data saved in a file.

Once the performance data are stored, it is possible to plot different performance characteristics of the particular solar panel. Fig. 20 shows the measured voltage-current and power as a function of voltage characteristics of a typical solar panel. Fig. 21 shows the measured voltage-current and power as a function of current characteristics of a typical solar panel. Fig. 22 shows the measured characteristics of voltage, power, temperature, and light irradiance characteristics as a function of time.

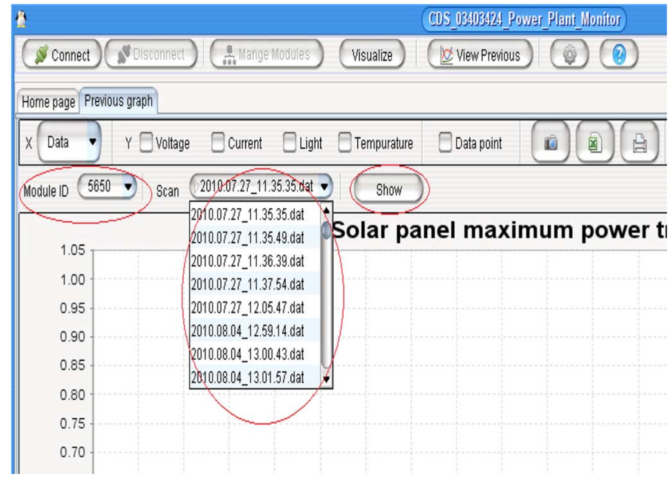



Fig. 18. The screenshot of GUI for storage of data.

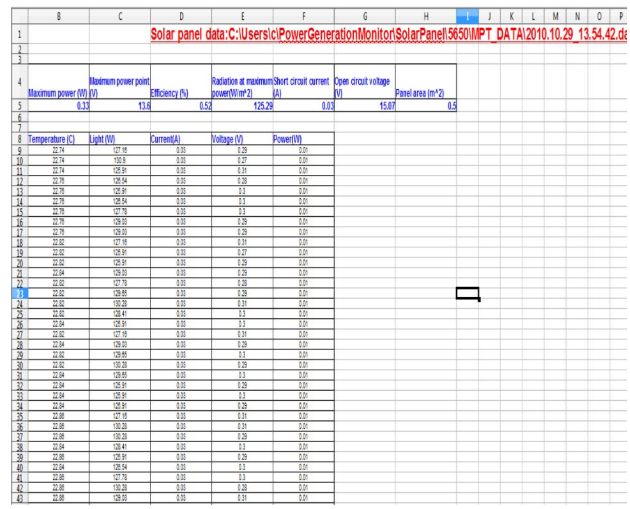


Fig. 19. The performance data of solar panel.

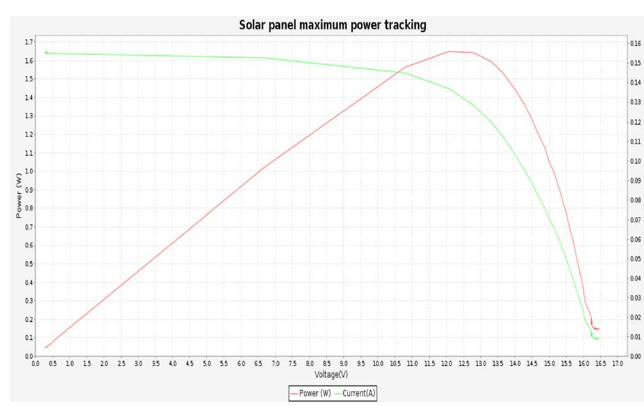



Fig. 20. Measured current and power as a function of voltage.

## V. CONCLUSION AND FUTURE DEVELOPMENTS

A wireless sensor network-based performance monitoring system has been developed for distributed solar panels. The developed system offers the following advantages.

- Can also be used as a standalone current and a voltage measuring transducer.

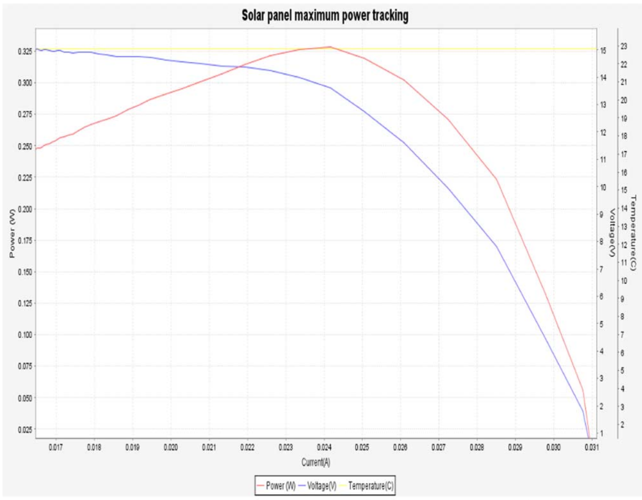



Fig. 21. Measured voltage and power as a function of current.

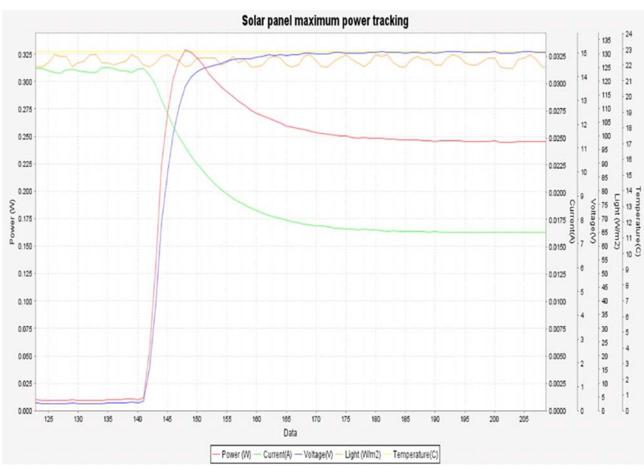



Fig. 22. Measured characteristics of voltage, power, temperature, and light irradiance with time.

- Integration of pyranometer also allowed both efficiency calculations and monitoring of atmospheric light changes during scan.
- Adjustable scan speeds eliminate 50 Hz AC interference from solar simulator.
- Use of filters to allow DC values from AC signals from MPP controllers.
- Small portable standalone microprocessor-based system.
- Isolated (i.e., isolation amps or digital isolation etc.).

The developed system will provide a low-cost solution for the regular maintenance information of the solar panel installed on the roof of the houses.

The developed system is flexible and can be used for any other performance monitoring system using wireless sensors and Zigbee communication.

The developed system has been demonstrated at the 2010 International Digital Signal Processing Creative Design Contest held in Tainan, Taiwan, on 19 November 2010, and a prize was awarded.

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