Development of Low-cost Remote Online Laboratory for Photovoltaic Cell and Module Characterization

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Abstract: Laboratory experiments are vital component of engineering education. In recent years, significant interest and shift of paradigm from in-class to online teaching is observed which although offers many benefits but poses a great challenge to integrate lab experiments into online courses and degree programs. Internet-based laboratories are a potential solution to address this challenge and to meet required course level outcomes for distant learning students. This paper discusses the design and development of a novel low-cost remote laboratory system and associated experiments designed for introductory level as well as advanced learners of photovoltaics and renewable energy courses. The hardware setup consists of an integrated source-measure unit, LED array illumination system, and interconnection electronics controlled by an embedded Python program running on a Raspberry Pi Zero W. Measurement multiplexing approach allows multiple users to access the system and perform real-time experiments at the same time. The system communicates to a remote computer through google APIs and therefore can work under any wifi environment or even cellular network connections without the hassle and complexity of hosting a local server. Users can remotely access the system, perform experiments and acquire experimental data through a graphical user interface developed using Visual C#. The user-end program is made freely available to students and is currently patent pending. The paper details the hardware setup, software interface, discusses the designed experiments and future prospects.

Introduction:

Solar power has become a major renewable energy source in the past decade due to technological advancements and volume production, leading to significant drop in the cost of solar modules and balance-of-system (BOS) components, thus making it cost-competitive with conventional fossil fuel based energy sources in many regions around the world. Over the next few decades, gigawatt scale installations are predicted each year leading to terra-watt scale solar power generation by 2050 [1-3]. As of 2017, more than 250,000 people are employed in the solar industry, which has grown more than 150% in the past decade [4-5]. Hence, there is a dire need to produce skilled engineers and professionals to support the demand of this growing job market. To become a successful PV engineer or researcher in the field of photovoltaics, it is important build solid understanding of the electrical characteristics of solar cells and modules. Hands-on experiments is an effective way of educating students at the university level, which reinforces theoretical knowledge and allows students to develop necessary skills and provide valuable training to the students for analyzing real-world experimental data [6]. However, developing and building a dedicated laboratory infrastructure with conventional benchtop measurement instruments and testbeds for a photovoltaics lab accommodating hundreds of students every year is expensive and is not feasible for every academic institution. In addition, number of online programs and courses are becoming increasingly popular for which on-campus labs are not a viable option. This paper discusses on the development of a low-cost, remote laboratory technology to facilitate various photovoltaics experiments that can address the challenges mentioned above and can greatly facilitate student learning through real-world experiments performed remotely. Although, the idea of this remote lab setup was initially conceived and developed to support a fully online graduate level photovoltaics course to provide a platform to perform real-life experiments by the distant
students, but the core technology can be easily adopted and tailored to develop and implement online labs for any undergraduate curriculum/course as needed.

The developed remote online photovoltaic lab has a wide-range of capabilities, including current-voltage (I-V) characterization of a solar cells under illumination and under dark conditions. Light intensity and temperature for measurements can be controlled to test cell behaviors under such environmental conditions. In addition, multiple cells can be interconnected as desired to create a string or sub-module. Remote lab setups are modular and multiple such modules can be stacked together, interconnected and used synchronously. This allows interconnection and testing modules (or sub-strings) under different light intensities to measure and learn electrical characteristics of the series-connected strings or modules under partial shading conditions. The fully equipped remote lab has about 1 cubic feet footprint, consumes less than 5W under standby, weighs less than 3 pounds and costs less than $200. Completing a typical remote experiment requires about 3 minutes. Several lab experiments have been designed to effectively use the remote lab facility and to aid advanced student learning. The following sections describe the fundamental theory behind electrical measurements of photovoltaics cells, introduce different experiments, design and components of the remote lab system highlighting its capabilities and discuss about the future improvement plans.

Background and Theory of Electrical Characterization of PV Cells:

Currently, the most dominant commercial photovoltaic technology uses single junction Si solar cells. These are essentially made of semiconductor p-n junctions, which produce electrical current under illumination. Various types of electrical characterizations can be performed on a photovoltaic device, such as current-voltage (I-V), capacitance-voltage (C-V), and electronic defect characterizations via open-circuit voltage decay (OCVD), short-circuit current decay (SCCD), impedance and transient spectroscopy etc. [2, 7-10]. While all these measurement techniques are useful to find various device level parameters, the current-voltage (I-V) measurement is the most important one, which provides all required PV performance parameters, such as open-circuit voltage ($V_{oc}$), short-circuit current ($I_{sc}$), fill factor ($FF$), voltage at maximum power ($V_m$), current at maximum power ($I_m$), maximum output power ($P_m$), and the power conversion efficiency ($\eta$). These PV parameters are essential and sufficient to model and design a PV system and therefore, I-V characterization is regularly performed in the industry. PV engineers are expected to be able to successfully analyze the I-V characteristics and calculate the PV performance parameters mentioned above. In addition to this, a power-voltage (P-V) curve can be derived from the I-V measurement data and appropriate knowledge of the P-V curve characteristics under various environmental conditions, such as partial shading can help an engineer to effectively apply the knowledge to successfully develop optimum solar energy harvesting circuits and systems by implementing maximum power point tracking (MPPT) algorithms.

Current-voltage characteristics of a PV cell is defined by the following equation based on the single diode model of a solar cell as shown in Fig 1(a).

$$I = I_L - I_S \left\{ \exp \left( \frac{V + IR_s}{nVT} \right) - 1 \right\} - \left( \frac{V + IR_s}{R_{sh}} \right) ... ... ... ... ... ... (1)$$
In Eq. 1, \( I \) is the solar cell current, \( V \) is the voltage, \( I_L \) is the current generated under illumination, \( I_s \) is the reverse saturation current of the p-n junction, \( q \) is the charge of an electron, \( n \) is the ideality factor of the p-n junction, \( V_T \) is the thermal voltage, where \( V_T = k_BT/q \); \( k_B \) being the Boltzmann constant and \( T \) is the temperature.

Efficiency of the solar cell can be estimated by analyzing the P-V curve using the relationship: 
\[
\eta = \frac{P_m}{P_{in}},
\]
where \( P_{in} \) is the optical power incident on the solar cell.

A typical I-V characteristic curve for a solar cell under illumination and under dark are shown in Fig. 1(b). The open-circuit voltage \( (V_{OC}) \), short-circuit current \( (I_{SC}) \), maximum power point \( (P_m) \), voltage at maximum power \( (V_m) \), and current at maximum power \( (I_m) \) are marked on the figure.

**Figure 1.** (a) Single diode equivalent circuit of a solar cell and (b) I-V characteristic curves under illumination and under dark conditions.

As the illumination intensity and temperature changes, the PV parameters change. Dependence of these PV parameters on illumination and temperature on photovoltaic cells have been reported in detail elsewhere [11]. Method of tracing the I-V curve under dark is similar to tracing the curve for a generic p-n junction diode. A programmable constant voltage source applies varying voltages across the cell under forward bias arrangement and the resulting current is recorded. There are various techniques to trace the illuminated I-V curve of a PV cell [12-13]. In this work, a programmable current sink (PCS) was used to measure the illuminated I-V characteristic. As the PCS is programmed to sink different currents, the voltage drop across the cell is measured and thus the illuminated I-V curve is produced.

**Design and Components of the Remote Lab System:**

Functional block diagram of the remote lab system is shown in Fig. 2. As shown in the figure below, users connect to the online remote lab hardware via internet interfaced through Google API (application program interface). This is a major difference from other remote lab attempts, since this technique does not require a local host server and therefore all hassles to set up the system and configuring the host server is completely mitigated [14-15]. Therefore, the designed hardware is functional under any type of internet connectivity including wired, wifi, and even cellular networks. In addition, the possibility of cyber-attack is significantly reduced. The current prototype allows up to 5 users to connect and perform experiments simultaneously in real-time. This is
achieved by multiplexing the measurements without requiring additional hardware. However, the lab module exhibits slightly slower speed of measurement as the number of parallel connected users increase.

Figure 2. Block diagram of the smart solar module characterization setup showing major components.

Schematic of the PV Lab’s host device hardware components are illustrated in Fig. 3. The entire system is controlled by a master Python program embedded on a Raspberry Pi (RPi) Zero W microcontroller. The program seeks available clients through Google API every 5 seconds and once connected, starts to execute the instructions received from the client. Polycrystalline Si solar cells are used for all measurements. The RPi controls the LED array illumination intensity by controlling a PWM signal fed to the LED driver circuit and uses similar approach to control the temperature of the flexible tape heaters attached at the back of two cells. A switching relay module is operated by the RPi to select a specific solar cell or to interconnect a set of cells in a series-parallel configuration to realize a string or sub-module for measurement.

Figure 3. Block diagram of the smart solar module characterization setup showing major components.

The programmable voltage source and current sink circuit is controlled by the RPi to perform the dark and illuminated I-V characterizations. This is achieved by feeding a precision voltage signal at the buffer amplifier of the source/sink circuit through a 16-bit, high-resolution digital-to-analog converter (DAC). Due to small size of the solar cells, the short-circuit currents are also small, at
the most around 450 mA. To accurately measure small currents, a current sense amplifier (MAX471) was used which includes a 35 mΩ internal current-sense resistor. A 16-bit analog-to-digital converter (ADC) then measures the sense amplifier’s output voltage which is read by the RPi and communicated to the Google API interface. The user performs the measurements and receives the data from the Google API through a graphical user interface (GUI).

Photograph of a single lab module is shown in Fig. 4. The module houses the solar cells, measurement and control electronics and the LED array with its power supply. Outer dimension of the module is 1x1x1 ft³. Note that the module is completely enclosed to avoid any stray light, particularly during dark I-V measurements. The front lead and side cover plates can be removed easily as they are magnetically attached. The developed hardware setup and the software technology is currently being assessed for a provisional patent application. The author(s) intend to demonstrate the functionality of a smaller prototype version of the online lab module at the ASEE meeting.

![Figure 4. Photographs of the fabricated remote lab module (v1.0) with the front lead open – (a) LEDs off, (b) LED array operating at 40% intensity, and (c) LED array operating at full intensity.](image)

Multiple of these modules can be used together to perform complex experiments, such as partial shading tests without requiring any physical interconnection. The software communicates to different modules to interconnect and set up to perform partial shading experiments. A linear mini actuator attached to the bottom of the solar cell mounting plate can tilt the cell holder up to 60°. A calibrated accelerometer (ADXL335) attached to the cell mounting plate is used for the tilt angle measurement. It is to note that this module can generate light intensities of up to 1.5 sun, i.e. 50% more than the standard AM1.5 radiation.

**Results and Discussion:**

A screenshot of the developed user-end GUI program (freely available to the students) along with a typical I-V characteristic obtained through the Remote Online Lab is shown in Fig. 5. The interface software was developed using the free community version of Visual Studio C#. As seen in Fig. 5, the user interface allows different cells or predefined modules to choose from. It plots the data and estimates the PV parameters after linear interpolation. This feature can be locked by the instructor for specific lab exercises, such as when students are first assigned the task of
calculating P-V parameters by analyzing the obtained data. On the left bottom corner, activities are logged and is automatically saved in an online repository for the instructor to review as necessary. After the measurement is completed, the data can be saved as an excel file by the student to his local computer through the ‘Save Data’ button.

Figure 5. Graphical user interface (GUI) of the user program (developed in Visual Studio C#) to measure I-V characteristics.

Student Feedback Considered During Design and Development:

During the development phase, anonymous feedbacks were collected from senior undergraduate students to learn the student view and expectations while using such Remote Online Lab facility. It was found that among the following figure of merits: (i) speed of measurement, (ii) user friendliness of the GUI, (iii) availability (24x7), (iv) features of the software (v) number of experiments, and (vi) compatibility (Windows & Mac), students considered availability, user-friendliness of the GUI and features of the software most important, while speed of measurement was not a major concern. Also, among various possible benefits of an online lab, students liked the flexibility (can perform lab at own convenience) and the factor that an experiment can be performed multiple times if needed. Notable, all students expressed strong/positive opinion that a Remote Lab opportunity can help learn better than having no lab opportunity.

Description of Lab Exercises:

Total six lab exercises have been developed to work with the remote lab. All labs are performed individually and have equal credits. Labs are assigned according to the lecture schedule and students have one week of time to perform the labs at their own pace. Details of the lab exercises including the target learning outcomes are presented in Table 1 below.

Table 1. Lab exercises and learning outcomes
<table>
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<tr>
<th>Lab #</th>
<th>Lab Title</th>
<th>Objectives and Learning Outcomes</th>
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| 1    | Dark I-V Characterization | • Perform dark current-voltage characterization of two different PV cells under forward and reverse biases.  
• Analyze the experimental data and estimate the diode ideality factor and the reverse saturation current.  
• Estimate the series and parallel resistances. |
| 2    | Illuminated I-V Characterization | • Perform illuminated current-voltage characterization of two different PV cells (cells selected in Lab 1) under 1 Sun.  
• Analyze the experimental data and calculate the PV performance parameters: $V_{OC}$, $I_{SC}$, $FF$, $V_m$, $I_m$, $P_m$, and $\eta$.  
• Estimate the series and parallel resistances from illuminated I-V data and compare with the results previously obtained through dark I-V in Lab 1. |
| 3    | Module Interconnections and Partial Shading | • Perform I-V characterization under partial shading conditions for two different modules.  
• Analyze the P-V characteristics. Calculate the global maximum power.  
• Compare and comment on the local and global maximum peaks found on the P-V curve corresponding to the irradiance differences of cells in the module. |
| 4    | Study the effect of Temperature | • Perform illuminated I-V measurements at 6 different temperatures, with 5°C increments from room temperature.  
• Estimate and plot $V_{OC}$ and $P_m$ vs temperature.  
• Calculate the temperature co-efficient of open-circuit voltage, temperature co-efficient of short-circuit current, and the temperature co-efficient of output power. |
| 5    | Effect of Light Spectrum | • Study the effect of light spectrum. Test a Si solar cell under Red, Green, Blue and White lights and compare the results.  
• Analyze the data and explain the differences. |
| 6    | Effect of Incident Light Angle | • Study the effect of angle of incidence by changing the tilt angle.  
• Identify optimal tilt angle by experiment for a given incidence and orientation. |

In the first exercise, students perform the I-V characterization under dark conditions and then analyze the data to extract important device parameters. By linearization of the forward I-V curve, the ideality factor, series resistance and the reverse saturation current values are extracted. By analyzing the reverse bias characteristics, the shunt resistance value can be extracted. Following the experimental data analysis, students are instructed to perform a fitting of the experimental data.
using MATLAB to study how closely the experimental data matches with the theoretical model (single diode model as shown in Fig. 1 (a)). In the second experiment, the illuminated I-V measurement is performed and the photovoltaic parameters are extracted from the plot. After the basic measurements performed in Lab 1 and Lab 2, students study a more complex scenario of partial shading in Lab 3. Students can select any random partial shading condition to study. This exercise also helps them to learn the usefulness of bypass diodes. In Lab 4, 5 and 6, they study the effect of temperature, light spectrum and effect of incident light angle. For temperature dependent measurement, maximum 75°C can be reached in less than 3 minutes. Temperature is controlled through a PID algorithm which can stabilize within about ±2°C, measured using a stick-on K-type thermocouple mounted on the tape heaters. To limit the cost, only two cells are equipped with heaters and thermocouples that allow temperature dependent measurements. For lab 6, the tilt angle can be varied between 0-60°. Each lab is graded based on a report that requires to include several components, such as drawing circuit diagram and explaining measurement procedure, data plotting, data analysis, simulation or data fitting (if applicable), error calculations (if applicable), and conclusions. Since the set of these specific lab experiments were developed first time for a new course, a comparison with and without labs cannot be made, however the authors plan to record student achievements for the next few semesters to better understand its impact which will be reported later.

Conclusions:

A low-cost online remote laboratory system was designed and developed. The remote lab can serve as an excellent tool to perform various complex experiments on photovoltaic modules remotely. The system is available 24x7 and can support multi-user real-time parallel experiments. The system makes effective use of Google API and does not require any complicated server setup. An easy to use software interface was developed to communicate to the online lab remotely, perform experiments, and acquire experimental data. A set of six comprehensive experiments have been designed for the remote lab. The developed technology provides a cost-effective way to perform PV experiments under various conditions and is a powerful teaching tool to aid student learning, specifically for distant students and can significantly impact fully online courses/programs. It is proposed that the technology can be easily tailored to develop such online lab platforms to implement in other fields of science and engineering education.

References:


