ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

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Paper ID #17458

Development of a Low-cost, Portable, and Programmable Solar Module to Facilitate Hands-on Experiments and Improve Student Learning

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Abstract

Solar energy has become one of the major renewable energy sources to meet a significant portion of the global energy demand in the near future. The photovoltaic (PV) industry is growing at a fast pace and is predicted to reach tera-watt scale power production capacity by 2050. Thus, creating highly qualified engineers by providing effective hands-on education is of primary importance. This paper discusses on the design, fabrication, and implementation of a low-cost, portable, and programmable solar module to improve the student learning outcomes of a solar power and renewable energy course by facilitating hands-on experiments. Solar cells within the smart module can be electronically interconnected in various configurations and I-V characteristics of the resulting module or any individual cell can be measured using integrated microcontroller and measurement circuits interfaced by a LabVIEW-based interactive data acquisition software. The developed plug-and-play smart solar module is an affordable and effective teaching tool that can be used for in-class demonstrations or to perform hands-on experiments. An experiment-based project was included into the course syllabus where students perform solar cell I-V characterization and extract the cell parameters by analyzing the experimental data. Student perception on the learning outcome and the impact of the project were measured based on student feedback. All of the students found that the experiment-based project helped them to reinforce the theoretical knowledge and a majority of the students believe that the learning outcomes of the course would be incomplete without it.

Introduction

Solar power is one of the most promising renewable energy resource and is predicted to be a major supplier of the future energy needs. Solar power has been the fastest-growing industry among all other renewable energies in the past decade. With an annual average increase of 6.8% in the installed capacity, it is predicted to reach tera-watt scale power generation capacity by 2050[1-5]. This rapid growth during the past decade has created a huge demand of skilled engineers and professionals globally. In the past six years, solar industry in the US has seen a staggering 123% growth in employment and is predicted to continue to increase by 15% in the coming years[1]. According to a recent report published by the Solar Foundation, in 2014 alone, nearly 31,000 new jobs in the solar industry have been created in the U.S. bringing the total to 173,807 – about 22% increase since 2013[1,2]. Thus, it is of utmost importance to produce skilled engineers for this rapidly growing industry by providing effective hands-on education at the university level. Hands-on laboratory exercises substantially help to reinforce the theoretical knowledge gained from the lecture – thus improving the student learning outcome. In addition, it also helps to develop the important experiment design, data acquisition, and data analysis skills desired by the industry and are highly beneficial for future graduate level research. This paper discusses on the development of a low-cost, portable and programmable smart solar module to facilitate hands-on experiments to the students in the classroom (or in the field) and improve the students' skills and learning outcomes of an electrical engineering course 'EE4490: Fundamentals of Solar Power and Renewable Energy'.

The developed smart module is capable of generating the I-V curve of a solar cell or a module of different configurations without requiring any other external equipment and costs less than $200 – thus making it an affordable system that can be used effectively for teaching. The entire setup weighs less than 2 pounds, does not require an external power adapter and can be operated using only 5V USB power from a laptop computer, which makes it an ultra-portable system for field experiments. The custom-built LabVIEW program enables plug-and-play experiments to be performed anytime, anywhere. Tracing each I-V curve requires less than two minutes to complete. An innovative experiment-based project was introduced to the course where the solar cell I-V characteristics are measured in the classroom by the students and the experimentally acquired data are then used for the completion of the project. Students plot current-voltage (I-V) and power-voltage (P-V) curves from the experimentally obtained data, and extract the solar cell parameters by analyzing the data. Finally, they use the extracted photovoltaic performance parameters to design a stand-alone PV array according to the specifications. The project requires implementation of the theory learned in the lectures and is expected to reinforce the concepts. The reconfigurable module design allows a wide range of experiments to be performed and helps the students learn how solar cell interconnections impact the module output voltage, current, and power. The developed system is an excellent teaching tool to aid student learning in a renewable energy or solar photovoltaics course without having a lab section. Students' perception on the learning outcome was measured based on a survey conducted at the end of the semester and the results are presented.

Background and Theory of Solar Cell I-V Measurement

The current-voltage (I-V) characteristic of a photovoltaic (PV) solar cell or a PV module under illumination provides important parameters, such as the open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF), voltage at maximum power point (V_{mp}), current at maximum power point (I_{mp}), maximum output power (P_{max}), and the photoconversion efficiency (η). A further analysis of the I-V characteristic allows to extract the electrical loss parameters, such as the series resistance (R_s) and the shunt resistance (R_{sh})[6,7]. These parameters are utilized to analyze and understand the behavior of a cell/module and evaluate the photovoltaic performance. Also, the design and modelling of a solar panel for on-site installation requires these experimentally measured data. The current-voltage characterization is performed for each cell/module produced in the industry for quality control and is the most important experiment that an engineer must fully understand. Thus, it is highly important for the students to develop and master the skills to characterize solar cells/modules, record the I-V curves, and be able to extract the cell/module PV performance parameters by analysis of the measured I-V data.

The equivalent circuit of a solar cell is shown in Fig. 1 (a) considering the single diode model. The current-voltage characteristic of the solar cell can be expressed by the following equation[5,6]:

$$I = I_{ph} - I_0 \left[\exp\left\{\frac{q(V + IR_s)}{nkT}\right\} - 1\right] - \left(\frac{V + IR_s}{R_{sh}}\right) \dots\dots\dots\dots.\dots\dots\dots\dots (1)$$

Where, I is the output current of the solar cell, V is the output voltage of the cell, I_{ph} is the photogenerated current, I_0 is the reverse saturation current, q is the electronic charge (1.602×10^{-19} C), n is the diode ideality factor, k is the Boltzmann constant (1.38×10^{-23} J. K^{-1}), and T is the temperature in Kelvin.

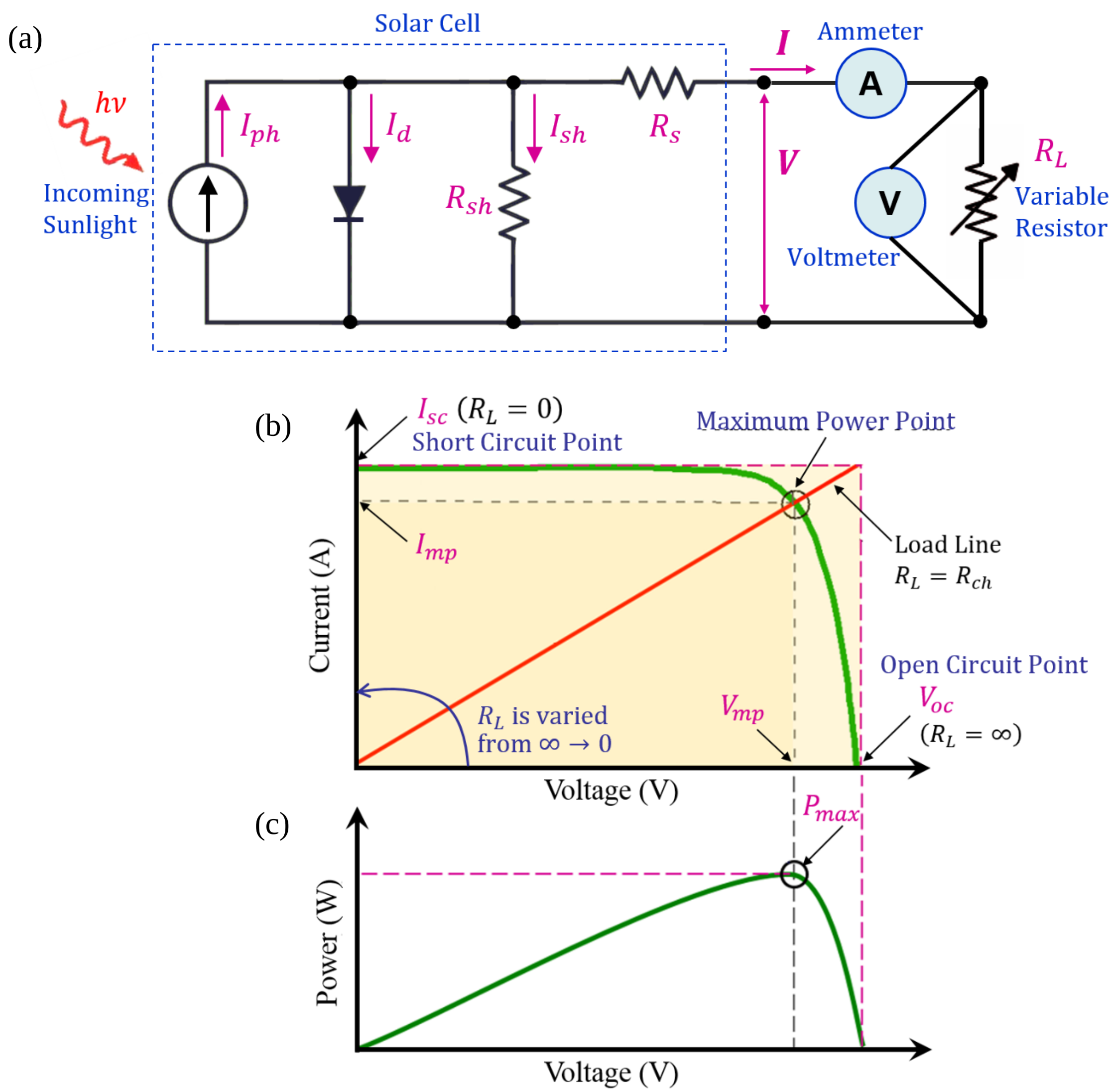

Figure 1. (a) Circuit diagram of the experimental setup for solar cell I-V measurement under illumination considering the single diode solar cell model, (b) typical I-V, and (c) P-V curve of a solar cell showing important data points on the curve.

Typical I-V and P-V curves of a solar cell/module are shown in Fig. 1(b) and 1(c), respectively. The open-circuit point, short-circuit point, and the maximum power point are marked on the I-V/P-V curves. From these three points, V_{oc}, I_{sc}, V_{mp}, I_{mp}, P_{max} can be obtained directly. Fill factor (FF) and efficiency (η) of the solar cell is then calculated using the following equations:

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\eta = \frac{P_{max}}{P_{in}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)$$

Where, P_{in} is the input optical power. When a module is formed by interconnecting multiple identical solar cells in series and parallel, the output current and voltage of the PV module can be related by the following equation:

$$I_T = M \times I_{ph} - M \times I_0 \left[\exp\left(\frac{q\frac{V_T}{N}}{nkT}\right) - 1\right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)$$

Where, I_T is the total output current of the PV module, V_T is the total output voltage of the module, N is number of cells connected in series, M is the number of cells connected in parallel, and I_{ph} is the photocurrent of each cell.

As shown in Fig. 1 (a), the I-V curve of a solar cell or a module can be generated by varying the resistance of the load resistor (R_L) connected at its output terminals and measuring the voltage and current corresponding to each resistance value. First, the resistance is set to a very high value or disconnected from the circuit ($R_L = \infty$) and the open-circuit point is obtained where $V = V_{oc}$ and $I = 0$. Then, the resistance is decreased and each point on the I-V curve is generated. Finally, the resistance value reaches to zero leading to the short-circuit point ($R_L = 0$) where $V = 0$ and $I = I_{sc}$. Thus, each point on the I-V curve corresponds to a certain load resistance. The load resistance at the maximum power point is known as the characteristic resistance, R_{ch}. At $R_L = R_{ch}$, the solar cell/module delivers maximum power to the load. In Fig. 1(b), the load line corresponding to the characteristic resistance is shown which intersects the I-V curve at (V_{mp}, I_{mp}). The characteristic resistance is the inverse of the load line slope and is given by:

$$R_{ch} = \frac{1}{\text{Slope}} = \frac{V_{mp}}{I_{mp}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5)$$

For a high-efficiency cell with a high fill factor, the characteristic load line passes through the corner of the outer rectangle intersecting the point (V_{oc}, I_{sc}) as shown in Fig. 1(b). Hence, R_{ch} can be approximated by $R_{ch} = V_{oc}/I_{sc}$. The power curve is derived from the I-V curve and as seen in Fig. 1(c), a maxima (P_{max}) is obtained corresponding to the characteristic load resistance.

Design and Fabrication of the Smart Solar Module

For research purpose and highly accurate measurements, commercially available instruments, such as source measure units (SMU) or PV curve tracers are regularly employed to generate the I-V curve[8]. However, these instruments are very expensive and lack portability for on-site experiments. Furthermore, the commercially available solar modules have permanent interconnections between the cells with a fixed configuration. In this work, a smart reconfigurable solar module was developed in which the electrical interconnections between the cells can be altered programmatically using a microcontroller – thus allowing the students to perform measurements of the module in various possible configurations for enhanced understanding of a solar module operation. The fabricated smart module included 12 solar cells, in which the cells can be interconnected in various configurations, such as 3×4 (three cells connected in series and then four of them are connected in parallel), 4×3 (four cells connected in series and then three of them are connected in parallel), 6×2 (six cells connected in series and then two of them are connected in parallel), 2×6 (two cells connected in series and then six of them are connected in parallel) and so on. Also, it allows formation of sub modules, such as 2×4 (two cells connected in series and then four of them are connected in parallel), 4×2 (four cells connected in series and then two of them are connected in parallel) and so on. In addition, each cell can be accessed individually allowing I-V measurement of any specific cell in the module. This provides a great flexibility to perform numerous sets of experiments with various cell configurations inside the module without the need of multiple solar modules. As a result, students get robust understanding of the module characteristics under various possible cell interconnections.

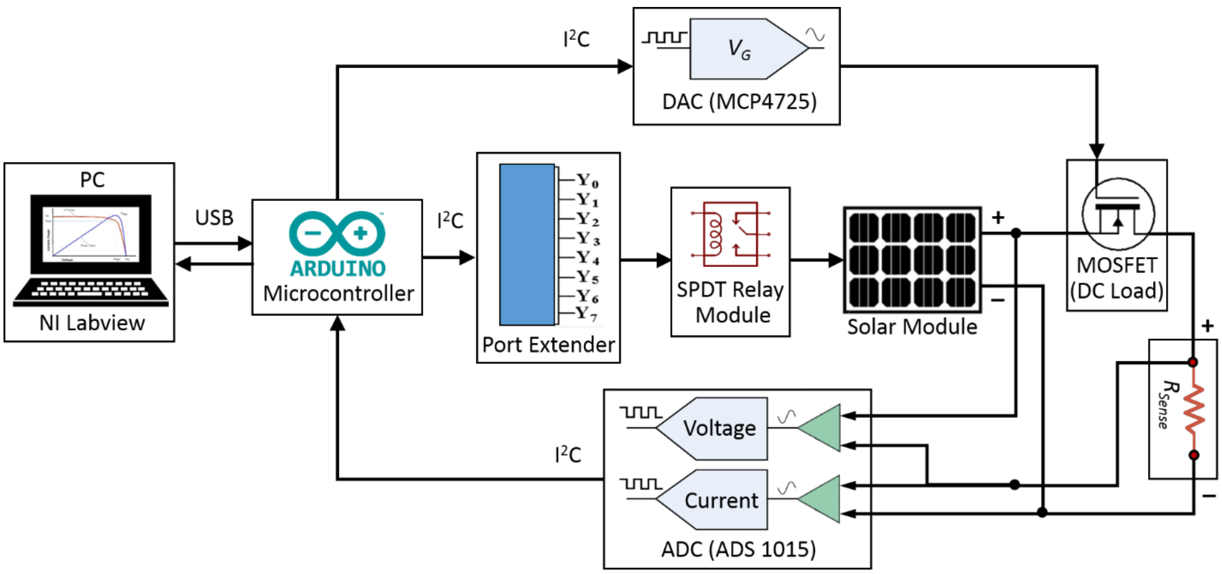

Figure 2. Block diagram of the smart solar module characterization setup showing major components.

Generating the I-V curve requires the measurement of current and voltage across a solar cell/module, while the load resistance (R_L) is varied from the open-circuit point ($R_L = \infty$) to the short-circuit point ($R_L = 0$). To achieve this, we have implemented an n-channel power MOSFET (Model: CSD18542KCS, Texas Instruments) connected across the solar module, where the channel resistance is varied by precisely controlling the MOSFET gate voltage. The applied gate voltage was precisely varied using a digital to analog converter (DAC) controlled by an Arduino microcontroller. The voltage and current measurements were performed using analog to digital converters (ADC) which return digital signals to the microcontroller corresponding to the analog voltage measured. Voltage measurement was carried out by directly connecting the ADC to the module output terminals. However, for current measurement, a small current sense resistor ($R_{sense} = 0.5\ \Omega$) was connected in series with the circuit and the voltage drop across R_{sense} was measured from which the current was calculated. The smart module configuration was achieved by interconnection of the cells via SPDT relays that were controlled by the Arduino. The graphical user interface (GUI), communications with the Arduino, and programming were implemented using NI LabVIEW. Schematic block diagram of the setup is shown in Fig. 2.

12 bit ADC (Model: ADS1015, Texas Instruments) and DAC (Model: MCP4725, Microchip) were used for voltage measurements and MOSFET gate voltage modulation, respectively. The SPDT relays act as electronically controllable switches which have been used for interconnecting solar cells to achieve various module configurations. A total of 23 relays were used for this 12 cell smart module design. Three sets of 8-channel SPDT relay modules were cascaded for this purpose. The relay contacts were rated up to 10A, 30V DC and are operated at 5V DC drive voltage drawing about 20 mA coil current. The relay modules were operated using two 16-channel I/O digital port extenders (Model: MCP23017, Microchip) since the microcontroller (Arduino micro) has a limited number of digital pins. Photograph of the built setup is shown in Fig. 3 and various major components are marked in the image. 52 mm × 38 mm polycrystalline Si solar cells were used for the solar module.

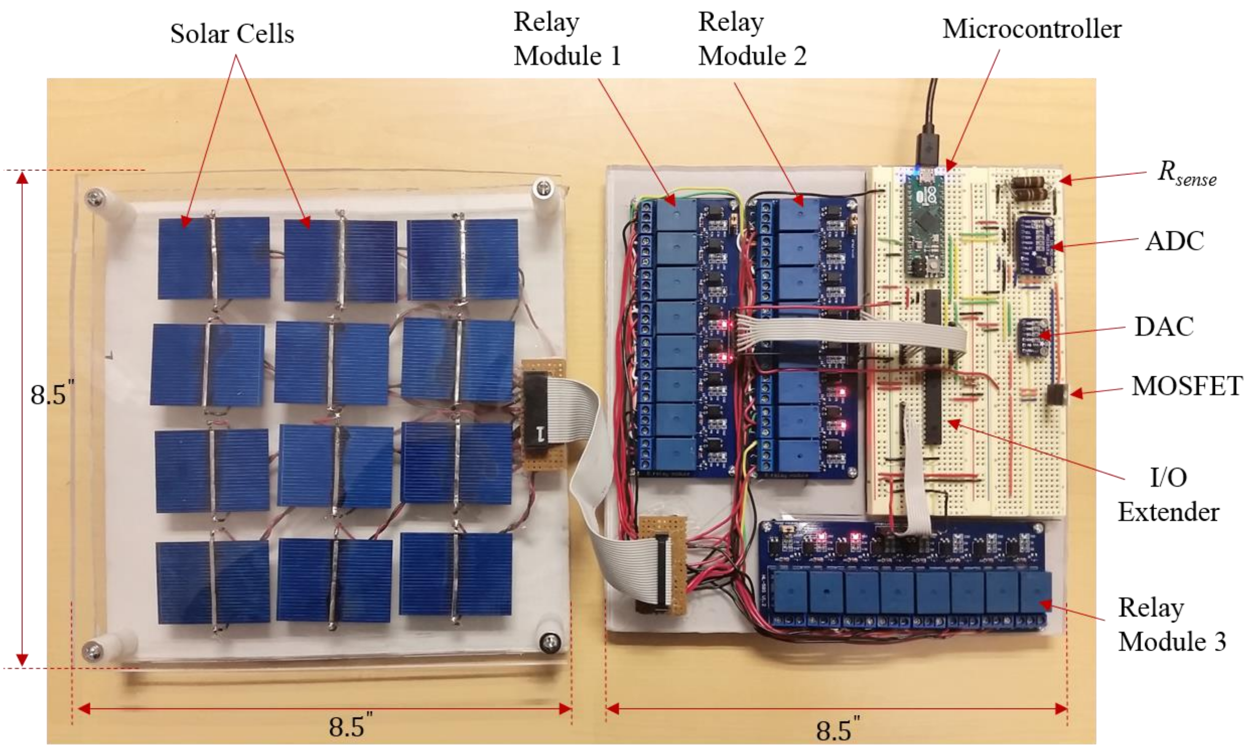

Figure 3. Prototype of the developed Smart Solar Module characterization setup.

LabVIEW is a graphical programming software that allows easy integration of instrument control and data acquisition via an interactive graphical user interface (GUI). A LabVIEW program was developed which performs two-way communication with the Arduino Micro – sends instructions to perform the measurements and reads the solar module voltage and currents. From the read voltage and current values, it plots the I-V curve in real-time. Communication with the Arduino is achieved via micro-USB which also powers the entire system. The Arduino communicates to all peripherals, such as the ADC, DAC, and I/O extenders via I^2C protocol. The LabVIEW GUI is shown in Fig. 4. On the left hand side, the 'Module Configuration' panel includes pre-designed cell configurations. In addition to various module configurations, each individual cell can also be selected for characterization. Below the 'Module Configuration' panel, the voltage and current waveforms are shown in real time. Corresponding to a selected module configuration, the relay settings (ON/OFF) are displayed at the bottom panel.

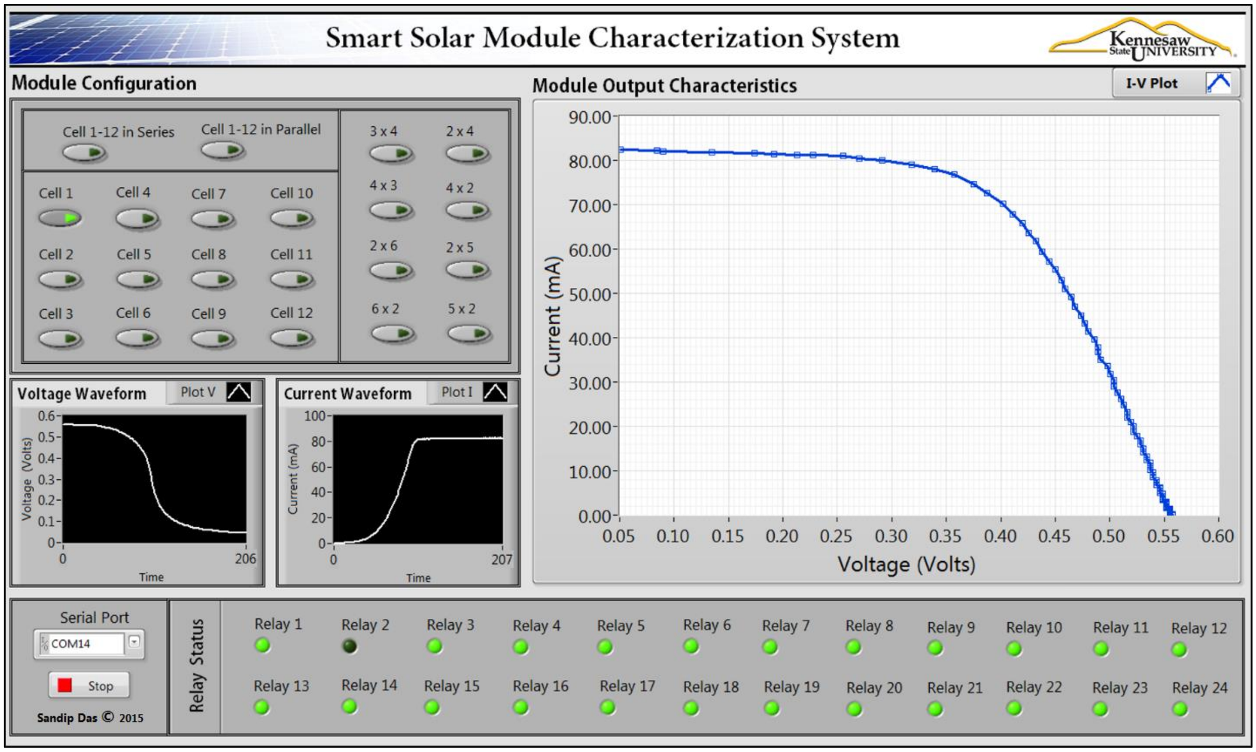

Figure 4. LabVIEW-based GUI for the smart solar module characterization and data acquisition.

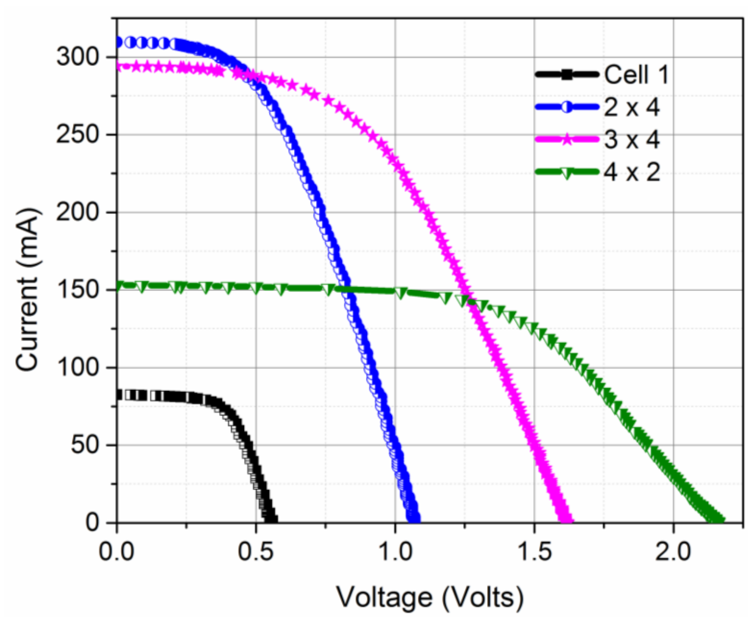

Figure 5. I-V characteristics of various cell/module/sub-module configurations recorded using the developed system.

On the right hand side, the I-V curve is generated in real time as the voltage and current values are acquired while increasing the MOSFET gate voltage. The acquired data can be saved for further analysis and completion of the course project. Any other custom module/sub-module configuration can be achieved by programming the correct relay connections in LabVIEW. I-V characteristics were obtained using the fabricated setup for various module configurations. In Fig. 5, four different I-V characteristics are shown for (i) a single solar cell, (ii) a 2×4 sub-module, (iii) a 3×4 module, and (iv) a 4×2 sub-module.

Student Perception on Impact and Learning Outcome

In order to understand the impact and the effect on the leaning outcome, an anonymous survey was conducted at the end of the semester which incorporated specifically designed questions to get feedback from the students. The survey questions used are presented in Table 1. For questions 1–3, the following five options were provided: (a) Strongly Agree, (b) Agree, (c) Disagree, (d) Strongly Disagree, and (e) No Response. For question 4, students were given few options to choose from, such as (a) Experiment Design, (b) Data Plotting, (c) Data Analysis, and a space to write their own. Student response for the first three questions are shown in Fig. 6.

Table 1. Survey Questionnaire

1	The course project helped me to reinforce the theoretical knowledge and improved the learning outcome.
2	This type of experiment-based project is helpful for courses that do not have a lab section.
3	Without the project, the learning outcome would have been incomplete.
4	The project has also helped me to improve the following skills.

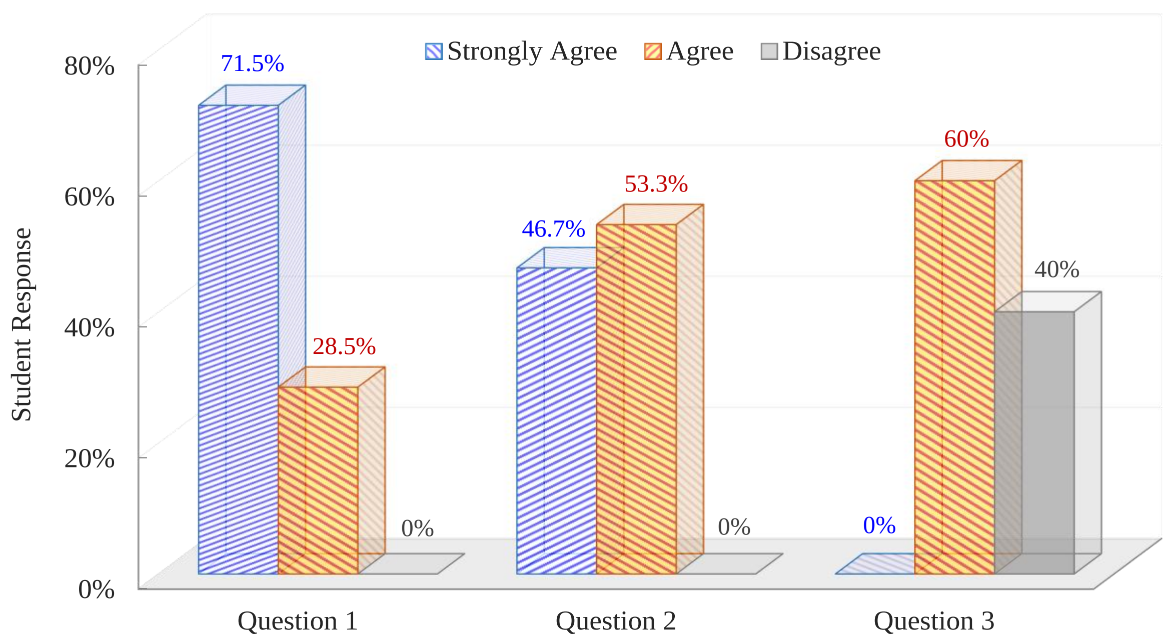

Figure 6. Student response to various survey questions to assess the impact and learning outcome.

It is found that all the students agree up to different extents (strongly/moderately) that the project helped them to reinforce the theoretical knowledge gained in the lectures and improved the learning outcome. Also, all students believe that this type of experiment-based project is helpful for the courses that do not have a lab section. In addition, the majority of the students feel that learning outcome would be incomplete without the project. Hence, it could be concluded based on the student response that the experiment based project introduced has high impact on learning. Every student selected one or more options for question 4 which showed that the project has substantially contributed to the improvement of various important skills including data analysis, experiment design etc.

Future Improvements

A number of improvements can be made to the current prototype resulting in better performance and reliability. Some of the improvements that are currently being implemented or planned for the future are summarized below:

(i) *Durability and reliability:* The current setup is built on a proto-board. By developing a custom printed circuit board (PCB) to house all electronic components and by stacking the electronics under the solar module will significantly reduce the footprint, improve durability, reliability, and portability.

(ii) *Measurement accuracy:* The prototype built in this work has used 12 bit ADC and DACs which restricts the resolution of voltage measurement at 3 mV. This resolution can be significantly improved by using 16 bit or higher resolution ADC/DAC. Also, due to the low 3 mV resolution, a 0.5Ω resistor (R_{sense}) was used for current sensing. This resistance is too high for current sensing and leads to the distortion of measured I-V curve at high current. Increasing the bit resolution will allow to use smaller R_{sense} and thus obtain more accurate measurement data.

(iii) *Measurement speed:* The current system requires about two minutes for each measurement. If multiple experiments are to be carried out, this leads to a long time duration. Under prolonged illumination the temperature of the cells increase leading to the change in cell parameters. Optimization of the algorithm is required for a faster measurement.

(iv) *Illumination intensity and temperature measurement:* For efficiency calculation, the incident light intensity data is required. A calibrated photodetector can be integrated into the system to measure the incident light intensity. Also, the measurement temperature is an important information which is useful for correcting I-V data or modelling of a solar cell. This can be achieved by integrating a digital temperature sensor into the circuit.

Conclusions

An electronically reconfigurable smart solar module was designed and developed to facilitate hands-on experiments to the students and improve the learning outcome of an undergraduate level Solar Power / Renewable Energy course in the Electrical Engineering discipline. The developed low-cost and portable module is an excellent tool to perform experiments by the students either in-class or in the field. An experiment-based project was introduced where students characterize solar cells in the classroom and collect the current-voltage data. The project is then completed by analysis of the experimentally obtained data followed by a stand-alone PV system design. Student perception on the impact and learning outcome were measured based on an anonymous student survey with the help of specific questions. Student feedback revealed that all the students believe the experiment-based project helped them to reinforce the theoretical knowledge and improved learning outcome while a majority of the students agreed that the learning outcomes would be incomplete without the project. Also, students believe such hands-on experiments to be helpful for any other course without a lab section. The developed smart solar module provides a cost-effective way to measure the I-V characteristics of solar cells and is a powerful teaching tool to facilitate hands-on experiments to the students, thus achieving improved student learning.

Acknowledgements

The author would like to acknowledge financial support under the 'Course Design Enhancement Fund (CDEF)', 2015 awarded by the 'Center for Excellence in Teaching and Learning (CETL)', Kennesaw State University for this work. Also, the author would like to thank senior Electrical Engineering undergraduate students, Alan Gregg Jr., Mathew Ginn, and Duane Wright for their help in building the prototype solar module.

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