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Board 80: Design and Development of a Rooftop Photovoltaics Laboratory for Advanced Engineering Education

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Design and Development of a Rooftop Photovoltaics Laboratory for Advanced Engineering Education

Abstract: Solar photovoltaics (PV) has emerged as a major renewable energy source. The tremendous growth of the solar PV industry has created a demand for skilled engineers to support the future green energy infrastructure. To prepare competent graduates, laboratory aided practical engineering education is of high importance. With this goal, a rooftop solar photovoltaics laboratory has been designed and developed for a solar power course. The laboratory facility is equipped with twelve 100 watts solar modules with a total installed capacity of 1.2 kilowatts. Tilt angles of the modules can be altered within a range of 30 degrees. Unlike conventional PV systems, the modules in this facility are not directly interconnected into a fixed array configuration. By programming through a graphical user interface (GUI), the array configuration can be changed as required for different experiments. The output cables from the modules are connected to a matrix of electromechanical relays that facilitate programmable rewiring of the modules. A GUI program has been developed which displays the system layout graphically with each component status represented in real-time. The GUI allows to visually interact with the PV arrays and perform various electrical measurements. After connecting the modules in a specific array configuration through the GUI, the output of the relay matrix is connected to a programmable electronic load. The lab computer communicates with a Raspberry Pi (RPi) which controls the relays and the electronic loads to perform current-voltage (I-V) and power-voltage (P-V) characterizations. In addition to flexible variable array configuration, another innovative and advanced feature of this lab facility is the capacity to implement maximum power point tracking (MPPT) algorithms. A set of six lab exercises were developed which include surveying and sketching the PV system layout, I-V and P-V characterization for series and parallel connected panels, analyzing daily power graphs for energy calculations, implementation of a hill-climbing MPPT algorithm, and studying the effect of different tilt angles on solar power production. This innovative, easy-to-use laboratory setup is expected to bolster the engineering concepts learned in the classroom, provide an enhanced learning experience to the students, and improve their competency level. Hardware and software design, details of the lab exercises, and future improvement plans are presented.

Introduction:

Transition to renewable energy has become more important over the last few decades due to the growing concern over climate change, depleting fossil fuel reserves, and the rising energy demand. Solar photovoltaics (PV) has emerged as one of the most promising and widely used renewable energy sources, and its share in the electrical energy production market is increasing at a rapid pace. Photovoltaics (PV) has experienced significant growth in the U.S. over the past decade. According to the Solar Energy Industries Association (SEIA), the cumulative solar PV installations in the United States increased from just 2.5 GW in 2010 to over 100 GW in 2020, representing an annual growth rate of over 40% [1]. Such massive growth has been driven by a combination of factors, such as declining module costs, supportive policies, and increasing awareness and demand for renewable energy. The sharp growth of the PV industry is expected to continue in the coming years, with the SEIA projecting that the U.S. will surpass more than 300 GW of installed solar capacity by 2030, which is three times more than the capacity in 2020 [2]. This growth will be driven by mass deployment of utility-scale and distributed solar installations, as well as due to the increasing adoption of energy storage technologies to help integrate intermittent solar power into the grid. Along with the rise in installed capacity, the photovoltaics industry has seen significant job growth in the United States over the past decade. According to the International Renewable Energy Agency (IRENA), the number of jobs in the global solar PV industry increased from around 1.2 million in 2015 to 3.8 million in 2019 [3]. As per the 12th Annual National Solar Jobs Census 2021 published by the Interstate Renewable Energy Council (IREC), the solar industry supported 255,037 jobs in the U.S. which represents an increase of 9.2% from the previous year [4]. This trend is expected to continue, as the demand for renewable energy continues to grow and governments around the world set ambitious targets for reducing greenhouse gas emissions. The IRENA predicts that the solar PV industry could employ up to 18 million people globally by 2050 if the world meets its renewable energy targets [5]. The Biden administration has set a goal of achieving 100% carbon-free clean electricity generation by 2035, which is expected to further boost the solar industry job growth [6]. Overall, the photovoltaics industry is expected to continue to be a major source of job growth in the U.S. as the country transitions to a cleaner and more sustainable energy economy.

Solar PV technology is complex, and thorough understanding of its principles, components, operations, and testing methods are essential for engineers working in this field. The traditional lecture-based approach is not sufficient to provide students with the practical skills and knowledge required to solve real-world engineering challenges [7-9]. The Solar Training Network reported that 79% of solar employers experienced difficulty finding qualified candidates for job openings in 2020 [10]. This data demonstrates that there is a critical shortage of skilled graduates in the solar PV workforce, which presents a significant barrier for the industry to meet the growing demand. Laboratory exercises can provide a more practical and interactive learning experience, where students can explore, experiment, and learn by doing [11, 12]. Thus, engineering education in the area of solar PV at the university level needs to adapt, evolve, and create appropriate learning facilities in response to the critical needs of the PV industry. Integration of hands-on laboratory exercises in a solar power course can provide an excellent opportunity for the learners to gain practical experience and achieve learning outcomes which would otherwise be impossible to attain without exposure to laboratory experimentation. This paper describes the design and development of a rooftop PV lab setup to facilitate various experiments to provide the students with systematic hands-on training and improve their engineering competency.

The PV Array and System Components:

The rooftop photovoltaic installation comprises of twelve 100 watts monocrystalline silicon-based solar modules (or panels), thus totaling an installed capacity of 1.20 kilowatts. Aluminum brackets were used to assemble the panels on heavy duty U-shaped signpost rails. Concrete blocks were then placed on top of the rails to secure the panels in place. The specifications and electrical parameters of the panels are given in Table 1.

The panels were mounted in horizontal configuration placed in two rows and fixed at a default inclination angle of 25° with respect to the roof surface. The tilt mount brackets allow to manually alter the inclination angle as needed within a range of 30 degrees. Ample spacing was maintained between the two rows of panels to ensure that no shadows are cast on the back row of panels by the front row of panels. A photograph of the installed solar PV array is shown in Fig. 1 below.

Table 1. Specifications of the Solar Modules used for the Laboratory Setup.

Module Parameter	Value
Maximum Power at STC	100 Watts
Open Circuit Voltage (V_{OC})	24.3 V
Short Circuit Current (I_{SC})	5.21 A
Optimum Operating Voltage (V_{mp})	20.4 V
Optimum Operating Current (I_{mp})	4.91 A
Module Efficiency (η)	17.8%

Figure 1. The rooftop PV array with an installed capacity of 1200 Watts.

Marine grade 12-gauge wires connected to individual modules are then laid through a one-inch diameter conduit and connected to PV combiner boxes. Circuit breakers are mounted inside the PV combiner boxes for protection. The outputs from the combiner boxes are then connected to a relay box containing a matrix of electromechanical relays. To accommodate a wide range of experiments, the individual modules are not interconnected into a fixed array configuration. Through the programmable relay matrix, the modules can be interconnected in different series-parallel configurations as needed for a specific experiment. This innovative component allows extreme flexibility to design various types of advanced lab training modules.

Measurement and Data Acquisition System:

Electrical measurements of a solar photovoltaic system involve tracing the current-voltage and power-voltage characteristic curves. Thereafter, all PV performance parameters, such as open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), maximum power (P_{max}), optimum operating voltage (V_{mp}), optimum operating current (I_{mp}), and fill factor (FF) can be calculated using the data obtained from these curves. In this work, we have used programmable DC electronic loads to trace the current-voltage (I-V) curves of PV panels. Two electronic loads together allow the system to trace I-V curves for up to six solar panels. It also allows to test two identical arrays under different conditions, each array having a maximum power limit of 300 watts. When necessary for some experiments, the electronic load can also be connected to the PV array through a commercial MPPT solar charge controller unit. Block diagram of the entire experimental setup is presented in Fig. 2 below.

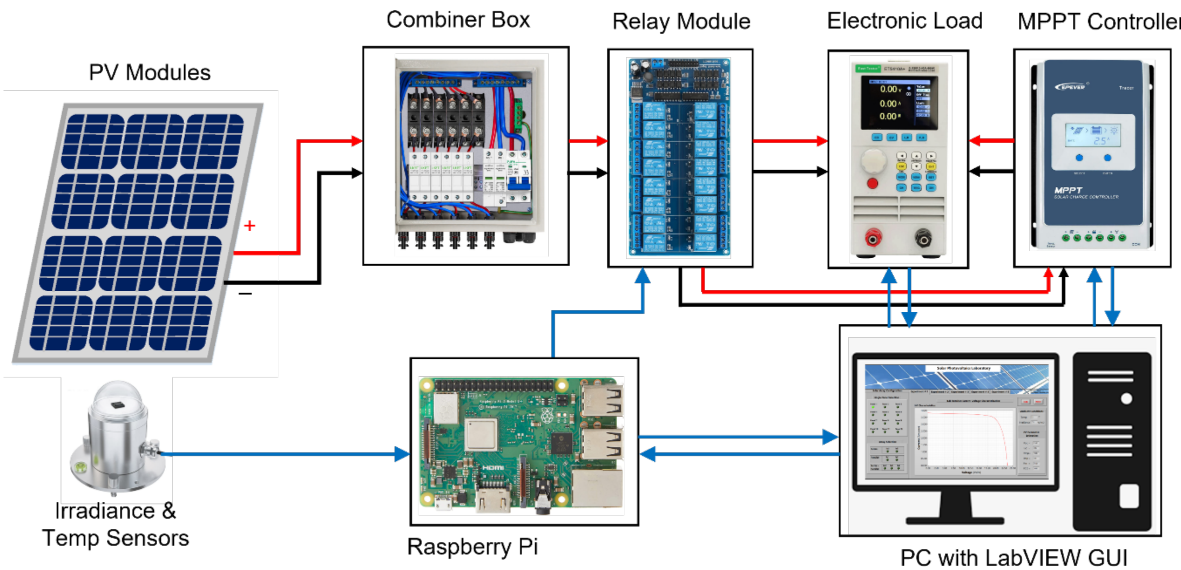

Figure 2. Schematic block diagram of the laboratory experimental setup showing all major components.

A calibrated photodiode-based light sensor and a digital temperature sensor are used to record the irradiance and ambient temperatures, respectively. The electronic loads were programmed using SCPI commands and operated in the constant current mode. By setting different constant current values and sweeping the current from short-circuit current to zero, the I-V curves are obtained. The electronic loads have built-in digital multimeter-like hardware that allow DC voltage, current, and power measurements. The measured voltage, current and power values are fetched directly to the computer during an experiment. Another advantage of using the programmable electronic loads is that maximum power point tracking (MPPT) algorithms can be implemented easily without requiring any additional hardware. The total estimated cost for all hardware used in the development of this lab facility was around $5,000. This cost includes materials and supplies, such as PV modules, aluminum mounting brackets, PV extension cables, marine grade wires, stainless steel U-channel posts, concrete blocks, electronic loads, fixed resistor banks, PV combiner boxes, electromechanical relays, MPPT charge controller units, Raspberry Pi, 1-inch-wide conduit pipes, junction boxes, nut-bolts, and electronic parts for the relay module breakout board.

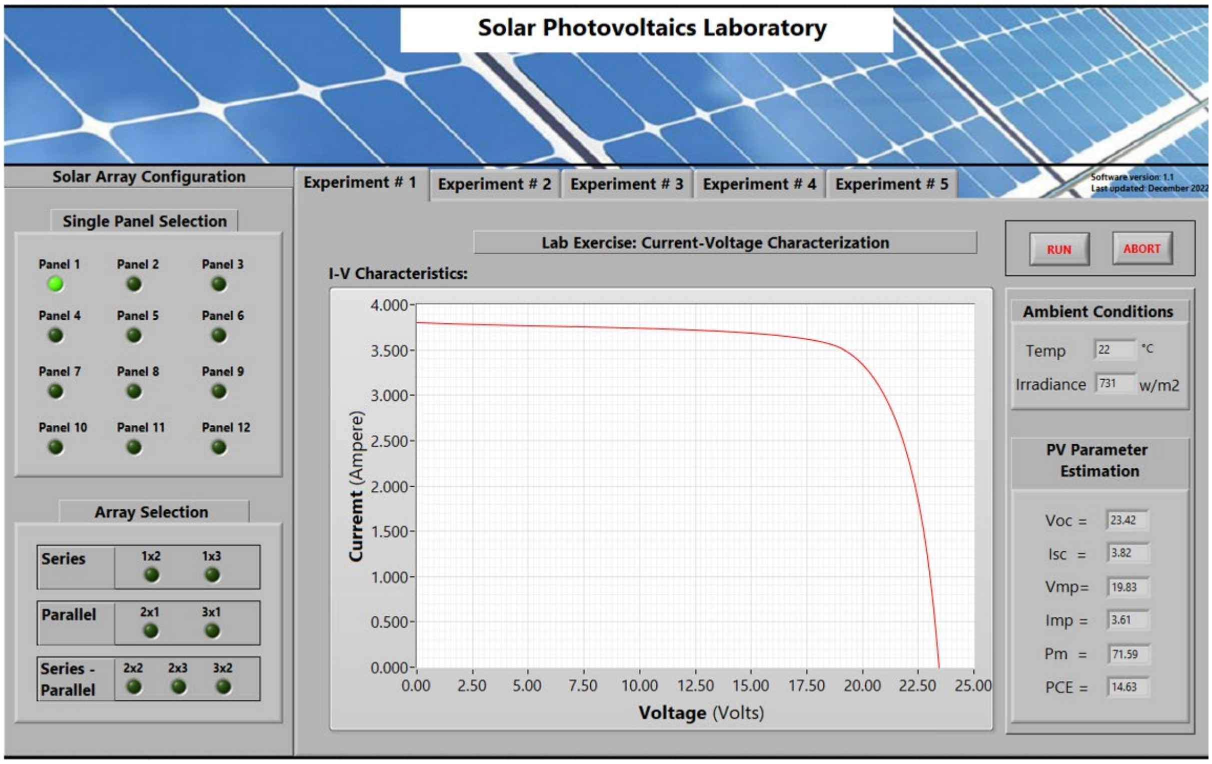

Figure 3. The LabVIEW-based graphical user interface (GUI) platform.

A graphical user interface (GUI) program was developed using LabVIEW which displays various PV array configurations graphically and allows the user to select a configuration for a specific experiment. A photograph of the developed GUI program is shown in Fig. 3. The GUI facilitates interaction with the PV system and provides the students with an easy-to-use platform to perform measurements. The LabVIEW program running on a windows 10-based computer communicates with a Raspberry Pi microcontroller unit which controls the electromechanical relays to connect a specific configuration of panels to the electronic loads for current-voltage (I-V) and power-voltage (P-V) characterizations. Once the I-V/P-V curves are acquired, students can save the data to an excel file. To perform different experiments, the learner can simply switch between the tabs on the LabVIEW interface.

Laboratory Exercises:

A set of six lab exercises have been developed, details of which are explained below:

Exercise # 1: — Surveying and Site Assessment: In this exercise, students are given an in-person (or virtual) tour of the PV system. A recording of the installation video is also shared with the students. This exercise introduces the basic components of a PV system, such as solar modules, charge controllers, PV combiner box, cables, connectors etc. Students will learn about the function of each component and how they are connected together. Specific tasks for this exercise include documenting the details of the PV system, such as orientation, tilt angle, and arrangement of the solar modules, the electrical specifications of the modules from the manufacturer's labels available on the back of the modules. Finally, students are required to – (i) sketch a layout of the PV system labeling each component, and (ii) create and simulate a model of a solar module in Simulink using the manufacturer's specifications as inputs, and submit a report.

Exercise # 2 — I-V and P-V Characterization: In this exercise (experiment # 1 using the lab setup), I-V and P-V characterizations are performed on two randomly chosen single panels, one series connected array, one parallel connected array, and one series-parallel array configuration, thus collecting total five sets of I-V data. Temperature and irradiance sensor values during the experiments are recorded. After the hands-on lab exercise, students are required to analyze the data and perform post-lab simulation tasks to complete the lab exercise. In the post-lab simulation tasks, the Simulink model of the PV module created as part of lab exercise # 1 is used to create arrays for lab exercise # 2 and generate simulated I-V and P-V curves at the temperature and irradiance during the experiments. All data are saved in excel file format. Following, both the experimental and simulated current-voltage and power-voltage curves are plotted using MATLAB. Finally, students are required to perform data analysis to extract important photovoltaic parameters including open-circuit voltage, short-circuit current, maximum power output, optimum operating voltage, optimum operating current, and the power conversion efficiency. The analysis tasks are accomplished by writing simple scripts in MATLAB to calculate the above-mentioned parameters. For example, the experimentally recorded voltage and current data the from the excel file are first loaded in MATLAB using the 'readmatrix' function and then the data is saved in two arrays to store the voltage and current values, respectively. Then, the power array can be calculated by taking matrix product of the voltage and the current arrays. Next, different parameter extraction techniques are applied. For example, a simple command line of 'Pmax = max(P)' in the MATLAB script returns the maximum power value (where 'P' is the power array). Similarly, simple command lines of '[Pmax, Index] = max(P)' followed by 'Vmp = V[index]' return the maximum power and the voltage at maximum power (V_{mp}), respectively (where 'V' is the voltage array). After estimating all PV parameters from the experimental and simulated curves, %errors are computed for each parameter to compare the experimentally obtained data with the simulated data.

Exercise # 3 — Datalogging and Energy Calculations: In addition to tracing I-V curves, the experimental system is capable of recording data for a prolonged period of time. In this exercise, the lab instrumentation is configured to record data on two different panels for multiple days and then the data is shared with students in an excel file format. The recorded data include irradiance, temperature, and power output. Students are then required to plot the daily power and irradiance graphs to calculate the energy produced each day by integration of the power curves. The irradiance and temperature data files are then loaded into a MATLAB program (created and provided by the instructor) which simulates the output power graphs and calculates the energy produced each day. Finally experimental vs simulated energy outputs are compared.

Exercise # 4: — Effect of Incidence Angle: In this exercise (experiment # 3 using the lab setup), the tilt angles of two panels are changed manually, one set to 15° positive and the other one set to 15° negative with respect to the default tilt angle of a reference panel. Then the I-V and P-V characteristics of three panels and analyze the data to investigate how power output and other PV parameters vary depending on the angle of incidence. Finally, they compare the experimental observations with the results obtained by simulation (using a pre-built Simulink model provided to the students by the instructor) and submit a report.

Exercise # 5: — Effect of Partial Shading: In this more advanced lab exercise, students are first required to configure three panels in a series configuration. Then different panels in that series-connected array are obscured using semitransparent plastic sheets to simulate partial shading conditions. Then I-V curves are obtained under three different partial shading scenarios and the data are analyzed to estimate the amount of power loss in each case. Following, the experimental data are compared with simulated I-V curves (obtained from Simulink models).

Exercise # 6: — Implementation of MPPT Algorithm: This is the last and most advanced lab exercise of all. As part of this lab, a pre-lab exercise is given which requires sketching an algorithm flowchart for a simple hill-climbing maximum power point tracking (MPPT) algorithm discussed in the class. Then during the hands-on lab, three panels are connected in series to form an array and two out of those three panels are obscured using a semitransparent plastic sheet to create a partial shading condition. Following, a pre-written hill-climbing algorithm is applied using the LabVIEW program interface. The program allows defining the starting point (the initial operating voltage point). Three pre-defined points are chosen as the initial operating points where the electronic load is programmed to initialize at the very beginning of the algorithm. Depending on the location of the initialization point, the algorithm may or may not be able to find the global maxima. The three initialization points are chosen such that only in one case, the algorithm will succeed in finding the global maxima and in the other two cases the algorithm will get stuck to a local maxima point, thus failing to find the true maximum power point. Students are required to plot the MPPT crawling points overlaid on the I-V curves as obtained from the experimental system, write a report documenting their observations, explain the advantages and limitations of the algorithm, and make concluding remarks.

Learning Outcomes & Course Alignment Map:

The target course is focused on solar photovoltaics and the course topics, course learning objectives are listed in Table 2 below.

Table 2. Course Topics and Course Learning Objectives.

Course Topics	Course Learning Objectives
• Fundamental concepts: Power and Energy • Solar Energy Resources and Solar Spectrum • Solar Irradiance and Sun Tracking • Introduction to Solar Photovoltaic Technologies • Review of Semiconductors and Photovoltaic Materials • Principles of p-n Junction Si Solar Cells • Simulation of Solar Cells and Modules using MATLAB Simulink	• Calculate Solar Irradiance, Power, and Energy. • Describe different PV technologies. • Explain the physics, structure and working principles of different types of solar cells. • Apply the basic governing equations to analyze the performance of a photovoltaic device/system.

<table>
<tr><td>Solar Cell Characterization, Performance Analysis, and Parameter Extraction
2nd and 3rd Generation Solar Cells
Multijunction Solar Cells
PV Modules, Arrays, and Balance of System (BOS)
Partial Shading and Current Mismatch
Maximum Power Point Tracking (MPPT)</td><td>Construct models and simulate solar cells/PV system using MATLAB/ Simulink.
Demonstrate knowledge of PV Arrays, BOS, and PV system.
Perform solar cell characterization and analysis.
Develop skills for writing scientific /technical reports.</td></tr>
</table>

Learning outcomes for each of the developed lab exercises have been identified and they are mapped with the course learning objectives (CLO). This is summarized in Table 3 below.

Table 3: Mapping of Lab Objectives with CLO.

<table>
<tr><th></th><th>Lab Objectives</th><th>Aligned Lecture Contents</th><th>Lab objectives mapped to Course Learning Outcomes (CLO)</th></tr>
<tr><td>Lab # 1</td><td>Identify components of a solar PV system.
Survey and Sketch PV system layout.
Create a model of PV module and simulate using Simulink.</td><td>PV Modules, Arrays and Balance of System (BOS).
Modeling and Simulation of Solar Cells and Modules.</td><td>Demonstrate knowledge of PV Arrays, BOS, and PV system.
Construct models and simulate solar cells/PV system using MATLAB/ Simulink.</td></tr>
<tr><td>Lab # 2</td><td>Demonstrate knowledge of current-voltage characteristics of PV modules and arrays.
Extract photovoltaic parameters by analyzing I-V and P-V curves.</td><td>Electrical Characteristics of Solar Cells and Modules.</td><td>Perform solar cell characterization and analysis.
Construct models and simulate solar cells/PV system using MATLAB/ Simulink.</td></tr>
<tr><td>Lab # 3</td><td>Compute energy from a given power curve.</td><td>Fundamental concepts: Power and Energy</td><td>Calculate Solar Irradiance, Power, and Energy.</td></tr>
<tr><td>Lab # 4</td><td>Determine the effect of incident angle on the power output of a solar PV system.</td><td>Sun Tracking: Methods and Impacts.</td><td>Demonstrate knowledge of PV Arrays, BOS, and PV system.
Perform solar cell characterization and analysis.</td></tr>
</table>

Lab # 5	• Analyze the effect of partial shading conditions on PV power generation. • Perform modeling and simulation of partially shared PV arrays.	Power Loss Mechanisms: Partial Shading and Current Mismatch	• Demonstrate knowledge of PV Arrays, BOS, and PV system. • Perform solar cell characterization and analysis. • Construct models and simulate solar cells/PV system using MATLAB/ Simulink.
Lab # 6	Apply a simple MPPT algorithm and assess its effectiveness and limitations.	Maximum Power Point Tracking: Fundamental Concept & Algorithms	• Demonstrate knowledge of PV Arrays, BOS, and PV system. • Perform solar cell characterization and analysis.

All labs require a report submission and therefore share a common course learning outcome of 'developing skills for writing scientific/technical reports'. The developed lab exercises align well with the course learning outcomes (CLOs) and promise to improve the learning experience and competency by providing students with hands-on photovoltaic testing and measurement experiences. The arrangement and flow of the labs follow the Bloom's taxonomy pyramid to help develop students' cognitive skills in a systematic way [13, 14]. Such flow is realized by first 'understanding' the concepts in the class and during pre-labs, then 'applying' the concepts in the lab while performing the experiments, followed by 'analyzing' the experimental data, and finally 'evaluating' the results to document meaningful conclusions. Sample lab manual instructions and datasheet for the analysis section of *Lab Exercise # 2* are presented below.

Exercise # 2 — I-V and P-V Characterization:
Task II: Analysis:
(a) Draw the equivalent circuit diagram for the I-V measurement under illumination and describe the complete measurement procedure. The circuit diagram must be hand sketched.
(b) Plot the I-V and P-V curves for the solar modules and arrays using MATLAB.
(c) Write a MATLAB script to compute/find the open-circuit voltage, short-circuit current, maximum power, voltage at maximum power, current at maximum power, fill factor, and efficiency.
(d) Complete Table 4.

Table 4. PV parameters extracted by analysis of the experimental data.

Module/Array	V_{oc} (V)	I_{sc} (A)	V_{mp} (V)	I_{mp} (A)	FF (%)	P_{max} (W)	η (%)
Module #							
Module #							

Series Array							
Parallel Array							
Series-Parallel Array							

Future Improvement Plans:

While the rooftop photovoltaics laboratory setup developed in this project offers many advantages and unique features to facilitate effective practical learning of students, there are scopes for further improvements. Currently, an extension of this lab setup is undergoing which comprises of two major innovative additions – (i) system integration with internet to allow remote access, (ii) develop two more advanced lab exercises. Enabling remote access through internet will allow the course to be offered in online or hybrid modality, thus making it more accessible to non-traditional students. The addition of two more advanced lab exercises will extend the range of this setup further to make it suitable for graduate level students and research scholars. The new labs would facilitate – (a) deploying student developed MPPT algorithms, (b) analyzing and comparing the efficiency of different MPPT algorithms, and (b) dynamic reconfiguration of solar modules and analyze how to mitigate the effects of partial shading through such mechanism. These are state-of-the-art concepts and are currently active areas of research in the photovoltaics field. Therefore, the addition of these features will extend the capacity of this lab facility and make it suitable for both undergraduate and best-in-class graduate level education and training. It will also open opportunities for graduate students and faculty researchers to conduct innovative research experiments.

Conclusions:

An innovative rooftop solar photovoltaics laboratory facility has been designed and installed. Six lab exercises have been developed which cover a broad range of topics and support learning introductory, as well as some advanced concepts through real-life experiments. Lab experiments target to bolster many crucial concepts and skills including I-V and P-V characterization, investigating the effect of incident angle, analyzing the effects of non-uniform irradiance conditions, understanding and evaluating the working of a maximum power point tracking algorithm etc. The innovative lab setup provides an easy-to-use graphical user interface program to facilitate various experiments and is expected to improve student engagement and learning outcomes in an undergraduate solar photovoltaics course. The developed lab exercises are aligned with the course learning objectives and are introduced in a sequence of increasing levels of complexity, starting from the most basic level to the highest level of evaluation. Labs include tasks that cover all levels of cognitive complexity according to Bloom's taxonomy, including 'knowledge', 'comprehension', 'application', 'analysis', 'synthesis', and 'evaluation'. Implementation of these lab exercises through the developed lab facility is expected to improve student learning outcomes and their competency level, thus producing more industry-ready competent graduates. With some additions and improvements, the developed lab setup can be used for teaching distant learners and graduate students, and support state-of-the-art research activities.

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