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RESEARCH ARTICLE

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Design and implementation of virtual laboratory for a microgrid with renewable energy sources

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Abstract

Growing demand for energy consumption worldwide has led to an increase in carbon emissions, which have significant effects on climate change. There is an urgent need for clean and renewable energy sources. However, most renewable energy sources, such as solar and wind, have very high initial costs, especially when used as a principal source. Distributed power generation using solar and wind power provides an effective solution to reduce the dependency on conventional power generation and to increase the reliability and quality of power systems. A mixture of distributed energy generation systems and loads can then be connected to form a microgrid. Virtual and remote laboratories are becoming widely accepted to conduct experiments in higher education. A virtual laboratory is especially suitable for the renewable energy-based microgrid to overcome cost, space, and time restrictions. In this paper, the design and implementation of a web-based virtual laboratory for a microgrid with renewable energy sources is presented. The virtual laboratory was developed using LabVIEW, Microsoft.Net Core, and Matlab/Simulink. Innovative courseware was developed around the virtual laboratory and used in several engineering technology courses to teach topics, including solar and wind power, dc-dc converters, battery management, and microgrid. The assessment shows that the virtual laboratory greatly increased students awareness, interest, and knowledge in renewable energy. It provided an interactive and convenient tool for students to experiment with renewable energy and microgrid.

KEYWORDS

distributed power generation, microgrid, power engineering education, renewable energy, virtual laboratory

1 | INTRODUCTION

Environmental concerns, ever-increasing needs for power generation, depletion of fossil fuel reserves, and steady progress in power deregulation have increased interest in renewable energy-based microgrids. Renewable energy sources, such as wind, solar, geothermal, wave and tide energy, and fuel cells can be used in standalone configuration or connected to the grid through a microgrid, which is a local energy grid with control capability.

Well-trained engineers and technicians are urgently needed to carry out the design, development, installation, operation, maintenance, and repair of renewable energy systems. According to the Institute of Electrical and Electronics Engineers (IEEE) U.S. Power and Energy Engineering Workforce Collaborative, the aging engineering workforce created a situation where there may not be enough engineering support to design, build, and maintain a reliable electric energy system and make it greener and smarter in the future [6].

Students need classic power system knowledge combined with communication, computing, and control to study modern microgrids. The power system curriculum typically emphasizes the fundamental and classic theories, which often lag behind the latest development from the industry. Although the current curriculum at Northern Illinois University (NIU) includes these components of microgrids, they are scattered in different courses. and students do not have an integrated platform to study microgrid as a system. This is the case for many other universities as well.

Laboratory experiments are critical to link theory with hands-on skills. For most students, laboratories are their first practical experience. Students will achieve optimum learning experiences and develop valuable skills for future employment from laboratory experiments. In addition, faculty can enhance the training of future engineers by promoting creativity and self-learning [8]. However, cost and space requirements, as well as daily and seasonal variation of solar and wind power, bring special challenges to establish a microgrid laboratory for many academic institutions [11,13].

Innovative educational methods and technologies have been introduced to promote the learning experience of renewable energy technologies. With internet and software technology, virtual laboratories and E-Learning were developed to enhance and extend the education system [17,25]. Flexible and cost-effective, virtual laboratories are software programs that provide a set of simulated experiments. E-Learning provides a structured platform, which helps to manage group projects and the delivery of students' work. Simulation software for renewable energy systems was developed using Java Applet [3]. Various components of renewable energy systems have been simulated. A photovoltaic (PV) panel emulator was developed based on a single diode model [9]. Power system simulation tool PowerFactory was used to develop case studies to improve understanding of power systems [10]. Educational 3-D video games were designed to teach digital circuits [15]. A virtual reality (VR)-based learning environment was developed to give training to engineering students about electronics laboratory [19]. Outcomes of the VR-based experiments indicated it had a positive impact on student knowledge, motivation, and cognition.

Remote laboratories are software programs that interface with and control real hardware and instruments at remote locations [12], which are capable to be used for teaching in a wide range of engineering fields. However, they have to handle real hardware at remote locations, thus are limited by the cost, time, and location for renewable energy applications.

Although significant effort has been spent to enhance the learning experience, professors from different universities usually designed the software for their specific institutions [5,18]. An examination of the literature shows there is very little detailed documentation of the design and implementation of web-based virtual laboratories for the entire microgrid system. Many virtual laboratories concentrated on specific areas of microgrid, such as solar power [9], wind power [7,20], electric machines [4], power electronics [3], and power engineering courses [23]. Most literature on virtual laboratories for microgrids was focused on the laboratory contents instead of implementation [14]. Often a brief description of the system architecture was presented. There is a lack of understanding of the tools and methods to build virtual laboratories. Table 1 shows a comparison of the design and implementation of previous developed renewable energy and microgrid virtual laboratories in literature.

A virtual laboratory for the microgrid is needed to integrate the topics of renewable energy, power electronics, power system, control, and communication in a central platform, which will frame innovative instructional modules around authentic problems. This will allow students to engage in problem-based learning and increase their motivation and self-efficacy. The virtual laboratory will also have the capability to continuously incorporate state-of-the-art technology to help bridge the gap between the curriculum and demand from the industry [21].

This paper presents a project funded by the United States National Science Foundation Improving Undergraduate STEM Education (IUSE) program from June 2017 to May 2021. The main objective of the project is to design and develop a virtual laboratory in microgrids with renewable energy sources for university students. The virtual laboratory is web-based. Its back end is supported by simulations developed using Matlab/Simulink and LabVIEW. The virtual experiments are available to students from anywhere and at any time at the website of https://renewablelab.niu.edu/.

The microgrid virtual laboratory was designed and built with the following objectives:

- *Scalability*: The software was designed to allow the addition of more experiments as they become available.

TABLE 1 Comparison of design and implementation of renewable energy and microgrid virtual laboratories in literature

Virtual laboratory	Design and Implementation
Ref. [13]	Hardware implementation of a laboratory-scale wind-PV-battery microgrid. No virtual lab
Ref. [1]	Hardware implementation of an education laboratory-scale microgrid. No virtual lab
Ref. [3]	LabVIEW implementation of the simulation. No networking functions
Ref. [10]	PowerFactory implementation of the simulation. No networking functions
Ref. [7]	Discussion on implementation is very brief. Lab content is limited to wind energy
Ref. [14]	Discussion on implementation is very brief. Only a basic system architecture was provided
Ref. [22]	Designed a smart house virtual laboratory. Focused on communication infrastructure
Ref. [24]	Multilocation virtual smart grid laboratory with a testbed for the analysis of secure communication and remote cosimulation

- *Interaction*: The web interface was designed with intuitive icons and virtual reality. We tried to make the virtual experiments as close to real-life experiments as possible. Various open-source tools, such as CanvasJS, Inkscape, Jquery, and Fritzing-parts-master were used to enrich the user interface of the experiments.
- *Maintainability*: The software was designed to be modular; therefore, it is easy to modify and maintain.
- *Response time:* Fast response was achieved by using techniques, such as customized TCP/IP socket communication packages, and integration of programming language with platforms, including Matlab/Simulink, LabVIEW, and,.Net Core Application.

This paper provides a comprehensive presentation in system design and implementation, including tools used to build the system. It combines modeling, simulation, programming, communication, and website design. The virtual laboratory used multiple open-source software to enrich functionalities, improve performance, and virtual reality, as well as reduce cost. The virtual laboratory was designed to be modular and scalable so that it is easy to maintain, modify, and expand. Several novel features were designed to improve interaction and support the learning experience. The virtual laboratory used a customized communication package to reduce the complex interfaces between various systems. It embedded a laboratory report generation subsystem to eliminate manual typing or drawing the experiment results so that students can concentrate on mastering concepts and knowledge. Another new feature is to set up visual connections between pictorial and schematic diagrams. The virtual laboratory uses various electrical components. There are misconnections between real-world components and their corresponding symbols in schematic diagrams for engineering students. To deepen the understanding and connection, a schematic diagram is drawn simultaneously when students build the virtual experiments using components.

The paper is organized as follows. Section 2 describes the design of the microgrid virtual laboratory. Section 3 describes the design of the virtual experiments. Evaluation and results are presented in Section 4. Finally, the conclusion is provided in the last section.

2 | DESIGN OF THE MICROGRID VIRTUAL LABORATORY

The architecture of the virtual laboratory is shown in Figure 1. The main components include a web server (Microsoft Internet Information Services-MS IIS), application servers, database (MS SQL Server 2019), backup database, Matlab/Simulink, and LabVIEW simulations for the microgrid. The web server manages all direct interactions with users, submits simulation tasks to the application servers, and conveys simulation results back to users. The application servers on Windows 10 Operating System host all the applications and performs simulations. The web server communicates with application servers using TCP/IP sockets, in a client-server manner. A predefined data structure of the communication pack is used for data exchange between the web server and application servers. A decoder and an encoder are enrolled on the communication pair to facilitate the message exchange. The communication program package on the web server was developed using ASP.NET, and data exchanged between the systems is in JavaScript Object Notation (JSON) format. The communication program package on the application servers was developed with the corresponding programing language. This simplified the website

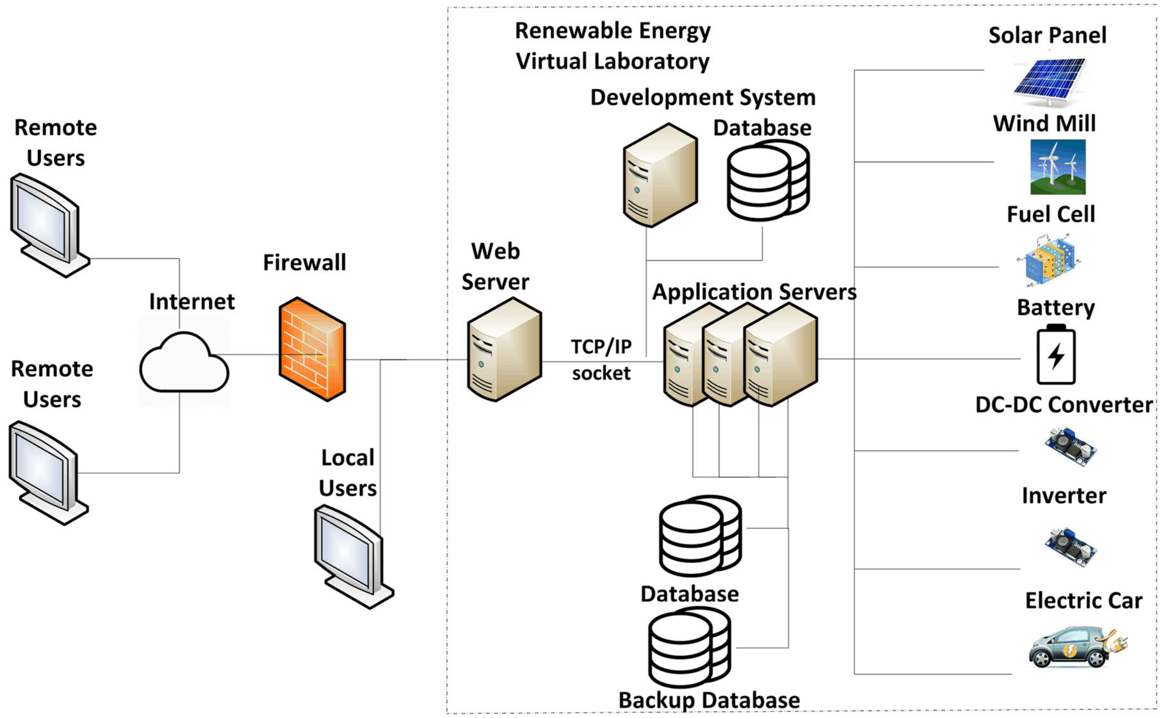


FIGURE 1 Network diagram of the virtual laboratory for microgrid

design and reduced the load on the web server. At the same time, it provided fast and efficient data exchange between the web and the applications on the application server since only useful data are exchanged between the servers.

Applications and simulations for the microgrid were developed using both Matlab/Simulink and LabVIEW. For Matlab/Simulink-based applications, a Daemon process is created and runs in an infinite loop. The daemon process keeps listening on the specified port for any request from the web server. When there is a request, the received data package is decoded and the corresponding simulation program will be called. The output will be encoded and sent back to the web server. The web server decodes the result data and then sends them back to the user. For LabVIEW-based applications, a similar TCP/IP socket-based communication method is adopted. When the web server sends data to the TCP listening port on the LabVIEW server, a connection is set up, and then data is decoded and processed with a LabVIEW experiment. Similarly, data received from experiments is encoded and sent back through the same connection.

The TCP/IP socket programs made it flexible to configure the servers and perform load balance. In addition, the web server and application servers can be hosted on the same computer or distributed to multiple computers. The web server keeps a list of the application servers' IP addresses and listening port numbers.

2.1 | Design method

The virtual laboratory was designed with the objectives of scalability, interaction, maintainability, and fast response time. Various design methods were utilized to facilitate the development process and improve workflow. On the top level, we modulated the applications so that experiments are independent of each other. Experiments are further modulated to share common modules among applications. The reuse and sharing of common modules or functions not only shortened the development and testing time but also improved its robustness and maintainability. For instance, common communication packages were developed to manage the conversations and data exchange among the web server and application servers. The packages provided services to applications to encapsulate complex issues. Data validation and database operation were developed in the common utilities, which were shared by experiments. Data and diagram exporting functions were designed and developed in the report utilities. In addition, multiple powerful open-source packages were employed to enrich the web interface and fulfill design objectives.

Development was divided into multiple stages. Functionalities were defined at the start of the project. Once one or more functionalities were ready, they were released and deployed. The newly released functionalities were used by students and feedback was collected to have incremental improvements. The reiterative releases improved efficiency by allowing the programmer to fix defects at the earliest stage.

2.2 | Development of the virtual laboratory

The web server was developed using the Microsoft (MS) Visual Studio 2017, which has a rich set of powerful and convenient tools for website development and easy deployment. The web application was built with Microsoft ASP.NET Core framework. The Razor Pages technique (Razor version 2.1) was used to make coding page-focused scenarios more productive than using controllers and views. Also, an open-source framework for building modern, cloud-enabled, Internet-connected apps was adopted to increase the speed of the development process and meet the design objectives.

2.2.1 | User interface

User interfaces were designed and developed to provide an optimal user experience. To help students understand the concepts and guide them smoothly through each experiment, intuitive and vivid graphic interfaces were created. Various commercial and open-source software packages were utilized in the development and design process. For example, animations of a wind turbine and a solar tracking system were developed using SolidWorks and embedded in the front page of the virtual laboratory to inspire students' interest.

In the experiments on circuits, the virtual circuit diagrams were created using Inkscape (open source: https://inkscape.org/), which procures vector graphic content instead of a pixel image. A vector graphic image is scalable without distortion so that it can be fitted to different sizes of screens, such as a computer monitor or a cell phone screen. To help students understand and conduct the experiments more effectively, all electrical components on a circuit diagram were represented by their standard image icons. When there was no standard icon, an intuitive icon was created using Fritzing (open source: https://fritzing.org/parts/).

2.2.2 | Visualization of experiment results

Virtual experiments results were displayed as graphs or tabulated as numerical data. Charts and waveforms were drawn using the open-source package CanvasJS (https://canvasjs.com/), which provides easy interfaces to display data in various graphic formats. Interactive user interfaces were designed to make experiments more interesting and appealing. Conducting a virtual experiment mimics the experience of playing a video game, which increased students' motivation and interest. The functions of dragging and placing were implemented by using the open-source package Jquery (https://jquery.com/). Students get feedback in real time on whether the placement is correct. If the placement is incorrect, the system will explain the reason. Once all the input is collected, the system will submit a request to the application server to conduct the simulation. After completing the simulation, the result data will be displayed in an appropriate format.

Data points of simulation results have a large variation, ranging from 100,000 to a million. For a larger dataset, waveforms were created using CanvasJS to display the results. This allowed us to show the results effectively, as well as zoom in for clear visualization and close observation. The waveform and data can be downloaded for further analysis.

2.2.3 | Modeling and simulation

On the application servers, LabVIEW and Matlab/Simulink were used to design and develop all simulations for the experiments. LabVIEW is a system-design platform and development environment for a visual programming language, which contains virtual instruments. LabVIEW is suitable to develop measurement experiments. Matlab is ideal for intensive numerical calculations, algorithm development, data visualization, and analysis. Simulink contains an extensive set of toolboxes for power electronics, electric machines, renewable energy sources, energy storage, and control. In this project, signal acquisition and Graphical User Interface was designed with LabVIEW, modeling and simulation of microgrid were developed in Matlab/Simulink.

2.3 | Data flow and data structures

Web-based applications typically transmit a large amount of data. However, most of the data are redundant or unnecessary to be transferred to the application servers. In this project, only the core data were exchanged between the web server and application servers. This is achieved by using the TCP/IP socket-based communication program packages, which employ the JavaScript Object Notation (JSON) data object. Figure 2 shows the data flow between the web server and the application servers.

A customized data structure is used to have a minimum amount of data transferred between servers.

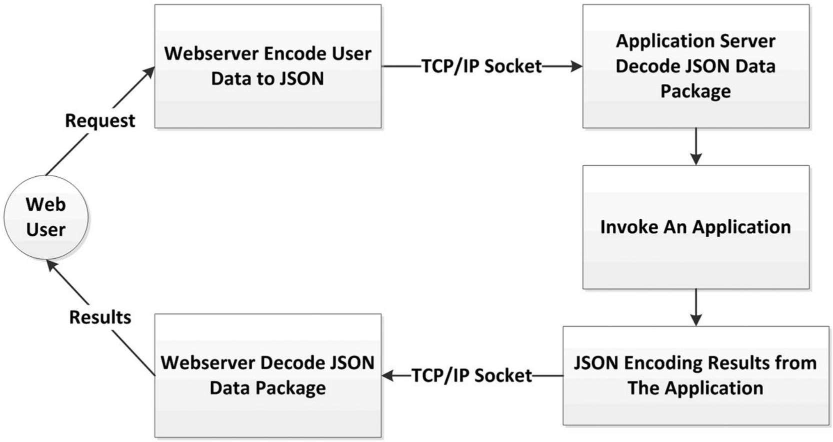


FIGURE 2 Data flow of virtual experiments

Once an experiment is initiated, the socket program on the web server sends a request JSON data object (JSON_REQ) to the application server. Upon request, the application servers decode the JSON data object and dispatch the request to the proper application. After the simulation or calculation is completed, the application server creates a result JSON data object (JSON_RESULT) and sends the data object to the web server to display on the screen. The data structure of JSON_REQ is composed of the unique experiment or simulation identification (UID) and corresponding input parameter value pairs. The UID will be decoded on the application server first, and the decoding of the remaining data is determined by the UID. The data structure of JSON_RESULT is made of output parameter value pairs.

3 | DESIGN OF EXPERIMENTS FOR THE VIRTUAL LABORATORY

Current research on cyber-learning [2] and best practices in instructional design was used to design, program, and implement the virtual laboratory. To facilitate critical thinking, all the experiments were designed to allow students to execute tasks independently in a supervised environment. The virtual laboratory followed the learning objectives to provide students with a sound understanding of microgrids and its components. The experiments started with simple components of the microgrid, and then progress to a more complicated system and its control. This scaffolding of knowledge is built through problem-based learning, an approach that engages students in solving problems that are authentic and complex.

The microgrid system is a simulated power system that includes solar power, wind power, energy storage system, and the grid. Following are the topics of the experiments.

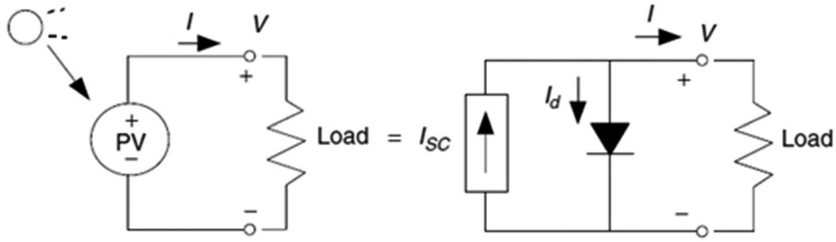
1. Voltage and current of solar cells.
2. Series and parallel connection of solar cells.
3. Data acquisition for renewable energy systems.
4. Maximum power point tracking (MPPT) for photovoltaic systems.
5. Buck converter.
6. Closed-loop control of buck converters.
7. Boost converter.
8. Closed-loop control of boost converters.
9. Battery charging and discharging.
10. Microgrid systems.

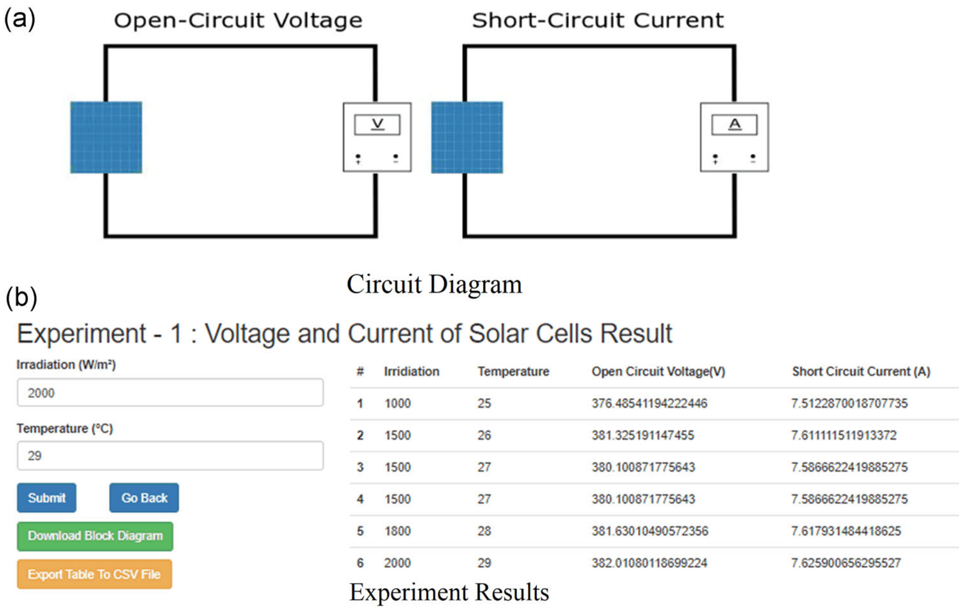
Four experiments presented in this paper are: (1) voltage and current of solar cells; (2) MPPT for photovoltaic systems; (3) buck converter; (4) microgrid systems.

3.1 | Voltage and current of solar cells

The first experiment is the basic experiment to measure open circuit voltage and short circuit current for solar cells. The experiment helps students learn about the model and characteristics of solar cells, and get familiar with basic experiments in the virtual laboratory. We first introduced different types of solar cells, an equivalent circuit of a PV model shown in Figure 3, and standard testing conditions. Next, students used the available components on the selection list to build the measurement circuit in Figure 4a. The system gives feedback if the circuit was built correctly. Then students can fill out the parameter of irradiation level and temperature. Next, the simulations with parameters are submitted to the web server, and then relay to the application server. Finally, the simulation of solar cells is run using Matlab/Simulink on the application server. The results are returned and listed in the user interface as shown in Figure 4b.

FIGURE 3 Equivalent circuit of a PV model





#	Irridiation	Temperature	Open Circuit Voltage(V)	Short Circuit Current (A)
1	1000	25	376.48541194222446	7.512287001870735
2	1500	26	381.325191147455	7.611111511913372
3	1500	27	380.100871775643	7.586662241988527 5
4	1500	27	380.100871775643	7.5866622419885275
5	1800	28	381.63010490572356	7.617931484418625
6	2000	29	382.01080118699224	7.62590065629552 7

FIGURE 4 Voltage and current of solar cells experiment: (a) circuit diagrams; (b) experiment results

3.2 | MPPT for photovoltaic systems

The second experiment is MPPT for photovoltaic (PV) systems. The main objective of this experiment is to study the (1) concept of maximum power point for PV; (2) feedback control for MPPT; (3) different MPPT methods; and (4) operation of MPPT control. Students first studied the topics in (1), (2), and (3) by building block diagrams and filling out flowcharts. Next, they conducted virtual experiments on MPPT control.

The I-V and P-V characteristics are shown in Figure 5a. The I-V characteristics of PV modules will vary with different irradiance and temperature, which makes the maximum power point vary in real time. Figure 5b shows the general MPPT control block diagram. The MPPT controller takes feedback from PV voltage V_{PV}, PV current I_{PV}, output voltage V_O, and current I_O from the DC–DC converter then uses different control algorithms to calculate the duty cycle for the DC–DC converter. The control algorithm will automatically adjust the duty cycle to move the PV voltage and current to make it operate at the maximum power point (MPP), extracting the maximum power available [16]. Figure 5c shows a Perturb and Observe (P&O) control algorithm. The P&O method measures the PV module's output voltage and current and then perturbs the operating point to determine the change direction. If there is an increase in power, the subsequent perturbation should be in the same direction to reach the MPP. If there is a decrease in power, the perturbation should reverse direction to reach the MPPT. The experiments can be carried out with specified irradiation. Detailed waveforms, including voltage, current, power, and power–voltage curve, shown in Figure 6 along with the data are sent back to the client web browser.

3.3 | Buck converter

DC–DC converters are power electronics circuits that convert a DC input voltage to a different DC output voltage level. They are being used widely in renewable energy systems and microgrids. The objective of this experiment is to study (1) characteristics of buck converters; (2) capacitor and inductor selection; (3) output

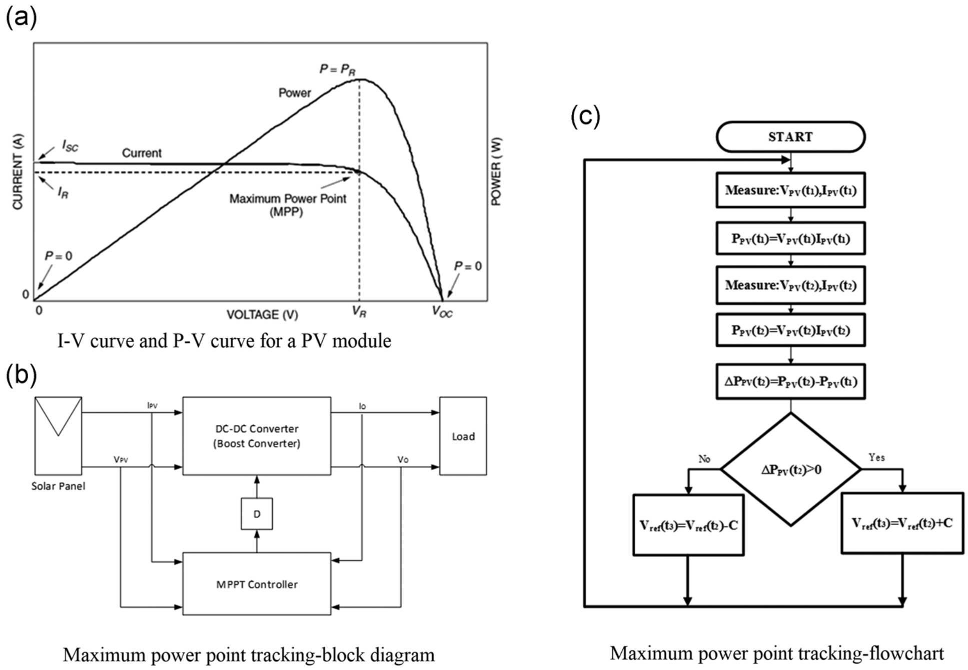


FIGURE 5 MPPT for photovoltaic system experiment (a) I-V curve and P-V curve for a PV module; (b) MPPT block diagram; (c) MPPT control flowchart

voltage and current; and (4) continuous and discontinuous mode.

The experiment interface is shown in Figure 7a. Students took components in the available list and built a buck converter circuit. Whenever a component is placed on the circuit board, a corresponding schematic circuit diagram is drawn simultaneously beneath the component list. This helped students understand the connections between the actual circuit and its schematics diagram. A buck converter's output voltage is always lower than the input voltage. Figure 7b shows the schematics of a buck converter. It has a DC input voltage, a transistor working as a switch, an inductor and a capacitor forming a low pass filter to smooth out the output voltage, and a load resistor. The diode provides a path for the inductor current when the switch is opened as shown in Figure 7c and is reverse biased when the switch is closed as shown in Figure 7d. The simulations are submitted to the application server once all the components are placed at the correct locations, and all the required parameters are provided. The experimental results of voltage and current waveforms are displayed using CanvasJS.

3.4 | Microgrid

A microgrid is self-sustaining and can be operated in grid mode, or island mode where the system is disconnected from the main grid. The learning objectives of this experiment is to: (1) understand the power sources and loads in a microgrid; (2) observe the input and output power.

Figure 8 shows the structure of a DC microgrid. There are several power sources, including wind turbines, solar panels, and fuel cells. Wind turbines are connected to the DC grid through an AC–DC converter. Solar panels and fuel cells are connected to the DC grid through DC–DC converters. The bidirectional converter is an interface between the rechargeable battery and the grid. When extra energy is available from the battery, the battery is discharged to send the energy to the grid. When extra energy is available from the grid, it is used to charge the battery. Students can experiment with power management algorithms and observe experimental results.

4 | EVALUATION

The virtual laboratory was used in three courses at the Engineering Technology Department at Northern Illinois University (NIU). The courses are TECH 175 Electricity and Electronics Fundamentals, TECH 423 Automated Manufacturing Systems, and TECH 426 Electric System Applications for Alternative Energy. A quasi-experimental design compared students' reactions and learning after using the virtual laboratory in a

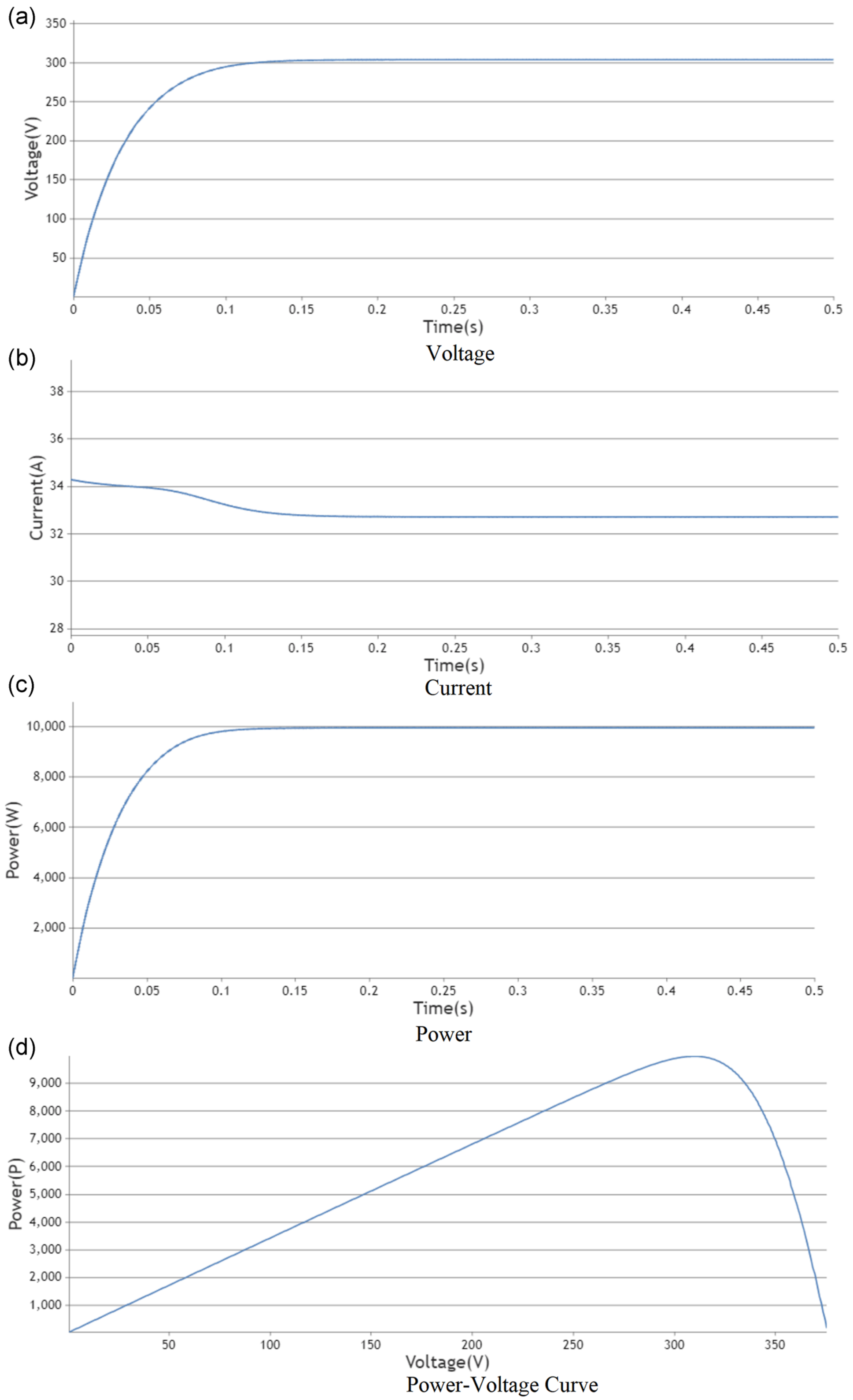


FIGURE 6 Experiment waveforms of MPPT for photovoltaic systems: (a) voltage; (b) current; (c) power; (d) power–voltage curve

course compared to students exposed to the same course but without the virtual laboratory component. A survey was developed by the evaluator using standard criteria for scale development that assessed the following dimensions: (a) quality of instructional features; (b) student interest and attention to the topic; and (c) likelihood of continuing education in the topic. The survey addressed two research questions:

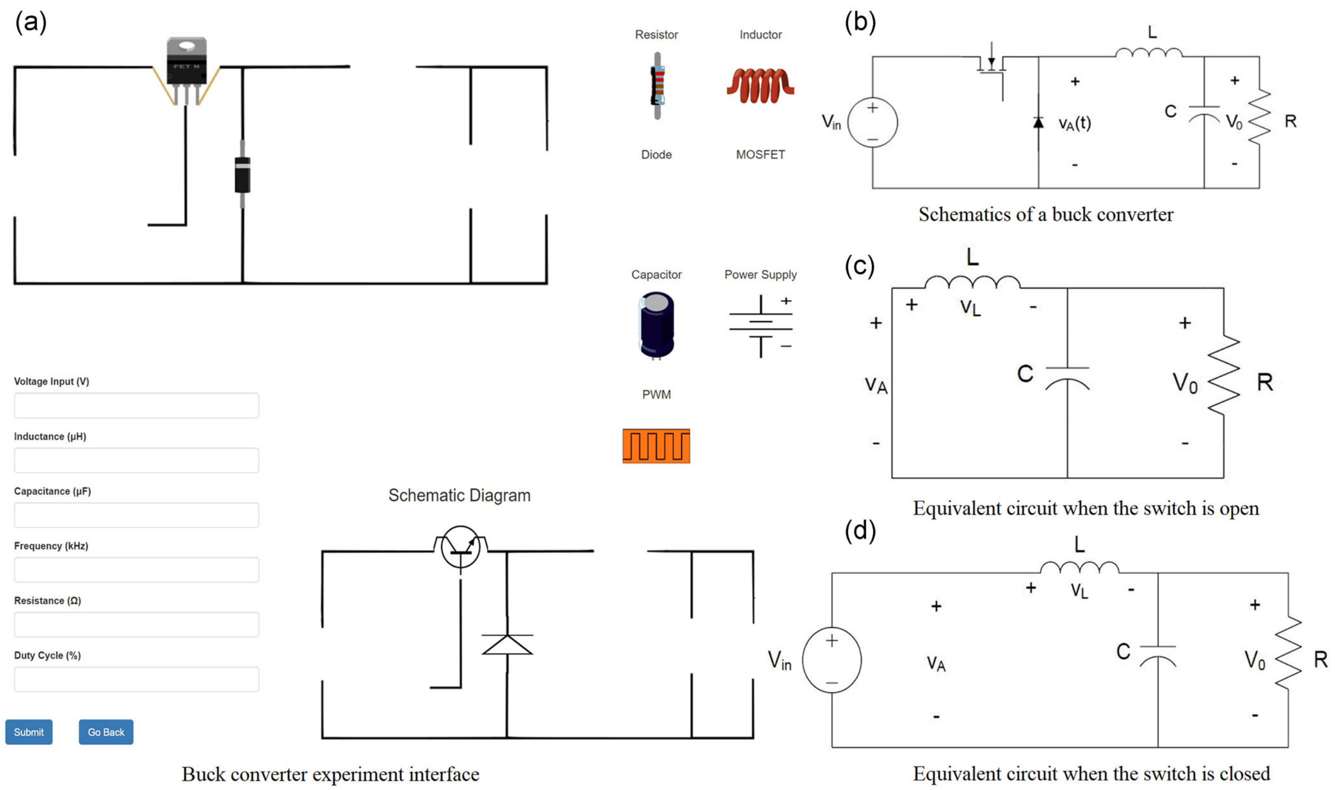


FIGURE 7 Buck converter experiment: (a) buck converter experiment; (b) schematics of a buck converter; (c) equivalent circuit when the switch is open; (d) equivalent circuit when the switch is closed

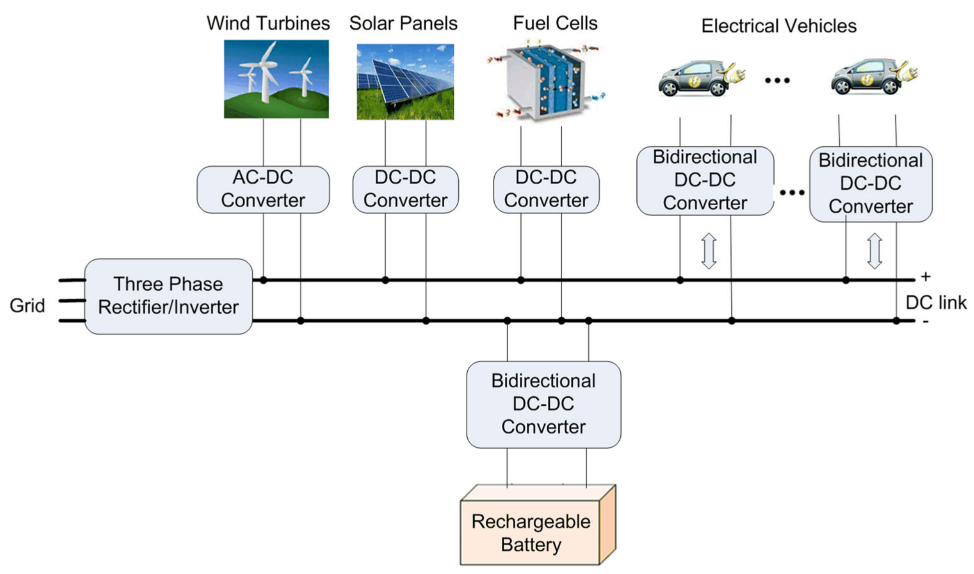


FIGURE 8 DC microgrid experiment

(1) Did the virtual laboratory about renewable energy enhance college students' knowledge and awareness?

(2) Did college students perceive changes in their interest in renewable energy because of the virtual laboratory?

The surveys were administered during the 1st week and the last week of each course in which new materials are used as well as control courses. The group sizes for analysis are based on the number of students who completed both the pretest and posttest for each measure. For the formal comparison analyses, the control group included 55 students and the intervention group included 41 students.

Mixed analysis of variance (ANOVA) was used to analyze the survey. ANOVA is a collection of statistical models and their associated estimation procedures were used to analyze the difference among means. A mixed ANOVA comparing pretest to posttest scores on the knowledge test revealed a significant increase in knowledge test scores ($F(1, 94) = 141.15$, $p < .001$). There was also a significant difference in average knowledge scores for students in the intervention group as compared to the control group ($F(1, 94) = 110.69$, $p < .001$). Moreover, there was a significant interaction ($F(1, 94) = 101.64$, $p < .001$), suggesting that the increase in knowledge scores from pretest to posttest was larger for students in the intervention group as compared to the control group.

A mixed ANOVA comparing pretest to posttest scores on the interest showed no significant increase in interest scores across groups ($F(1, 94) = 0.61$, $p = .44$) and no difference in average interest score for students in the intervention group as compared to the control group ($F(1, 94) = 1.85$, $p = .18$). However, there was a significant interaction ($F(1, 94) = 5.00$, $p = .03$), suggesting that the increase in interest from pretest to posttest was larger for students in the intervention group as compared to the control group.

A mixed ANOVA comparing pretest to posttest scores on awareness of the field revealed a significant increase in topic awareness ($F(1, 94) = 38.07$, $p < .001$). There also was a significant difference in average awareness scores for students in the intervention group as compared to the control group ($F(1, 94) = 11.68$, $p = .001$). Moreover, there was a significant interaction ($F(1, 94) = 19.40$, $p < .001$), suggesting that the increase in awareness scores from pretest to posttest was larger for students in the intervention group as compared to the control group.

Finally, we conducted a similar analysis to examine differences in interest with an alternative measure (unipolar response scale). The analysis revealed a significant increase in interest scores across groups from pretest to posttest ($F(1, 94) = 7.02$, $p = .01$). Although there was no significant difference in average interest score for students in the intervention group as compared to the control group ($F(1, 94) = 0.50$, $p = .48$), there was a significant interaction ($F(1, 94) = 23.03$, $p < .001$), suggesting that the increase in interest from pretest to posttest was larger for students in the intervention group as compared to the control group.

5 | CONCLUSION

This paper presented the design, development, and evaluation of a web-based virtual laboratory on microgrids with renewable energy sources. Information and networking technology was used to create the virtual laboratory. The virtual laboratory was designed with the objectives of scalability, interaction, maintainability, and fast response time.

This paper described the architecture of the virtual laboratory, its design method, development tools, data flow, and data structures. Ten experiments around the topics of renewable energy and microgrid were developed, including voltage and current of solar cells, series and parallel connections of solar cells, data acquisition, maximum power point tracking, dc-dc converters and control, battery charging and discharging, and finally microgrid system. The virtual experiments were used in three courses at the Engineering Technology Department at NIU.

A quasi-experimental design compared students' reactions and learning after using the virtual laboratory in a course compared to students exposed to the same course but without the virtual laboratory component. Evaluation results show that there was a significant increase in knowledge and awareness for students in the intervention group using the virtual laboratory as compared to the control group using traditional instruction, and the increase in interest from pretest to posttest was larger for students in the intervention group as compared to the control group.

The interactive nature of the virtual laboratory helped students construct their own knowledge through the use of iterative strategies within the virtual environment. The virtual laboratory not only increased students' interest but also deepened their understanding of knowledge and concepts. The advantages of the virtual laboratory provided excellent learning opportunities for students to reach their learning objectives in renewable energy and microgrid.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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