Education in the Sustainable Energy Based on Simulation and Laboratory Innovation: A Case Study

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***Abstract*—This paper presents a case study about the practice of using professional simulation and experimental tests in the undergraduate and graduate students' education and training. A real renewable energy system including PV modules, boost converter using maximum power tracking (MPPT) method and batteries as energy storages was built up. Simulation tools including Matlab and PSIM are used for PV modelling, MPPT strategies evaluation. The use of simulation in lecture, tutorial and laboratory exercises will help students understand fully the operating principle of the electrical circuits. This real prototype will help students appreciate the benefits of various MPPT methods in a short period time. Results from the students' performance in simulation and laboratory are presented to verify the effectiveness of the proposed method.**

***Index Terms*—Education, power electronics, industry-standard tools, simulation**

I. Introduction

The field of power electronics and renewable energy is experiencing rapid development, which requires the improvement in the education quality [1]. According to the international e-survey in 2012 concerning the most urgent education needs and subjects nowadays [2], where solar energy, Wind Energy, Electric Vehicles, and Energy Saving are selected as five most interesting thematic areas by 138 participants from industry and educational institutions. Both researches in Europe and China shows the importance of power electronics education [2], [3]. Traditional laboratory education could not bridge the gap of theoretical concepts learning by attending lectures and hands-on skills in designed circuits. This paper will take power electronics education as example to present the effectiveness of virtual laboratory in engineering courses education.

Although Web based education and virtual laboratory are useful tools to cover a wider audience in engineering education since students can perform the laboratory exercises online. However, how to evaluate the students' learning performance is challenging. Thus, a practical way is to closely link the course learning and industry demands and make the education innovation. For instance, using simulation tools, dynamic behavior of devices under failure modes and destructive test can be analyzed. Furthermore, a complete renewable energy system including PV modules, wind turbine and batteries will be adopted in simulation. Unique experiments are designed to meet various-levels teaching requirements and help students gain practical design experiences since the problem-solving skills or experiences in the field of power electronics and renewable energy are emphasized by companies.

Taking a photovoltaic power system as example, this paper presents a power electronics education method that is suitable for both undergraduate and graduate student's education and training by using simulation and experimental tests. With widely utilization of information technologies, numerous programs are available especially for the simulation of power electronics circuits. This education innovation can help students gain necessary experiences and skills in solving practical engineering problem. Results from the students' performance in simulation and laboratory are presented and discussed in this paper.

This paper is organized as follows. In Section II and III, we describe the characteristics of PV modules with respect to temperature and irradiance through simulation. In Section IV, the basic operation of boost converter is presented with main components design in prototype. The comparison of various MPPT strategies is provided in Section V. The prototype and experimental results are provided in Section VI. Then, we give a discussion on the education performance through students' feedback analysis.

II. Typical PV System

Photovoltaic (PV) energy is one of the most important sustainable energy sources, which has experienced dramatic growth all over the world. It's reported that the world's cumulative PV system capacity has grown from 300 MW in 1996 to 102.16 GW in 2012 [4]. In China, Photovoltaic (PV) energy system has become one of the most important sectors in the total sustainable energy category. In 2011, nine Chinese companies were ranked in the top fifteen manufacturers in the world and took a share of 30% in the world [5]. For the PV system, one technical problem is how to extract the maximum power under various weather conditions, which is named as MPPT.

As one of the key technologies for future energy development, power electronics education has been widely emphasized by most countries. For instance, the ratio of mandatory sustainable energy in Australia is targeted to be increased to 20% within the next five years [6]. In Korea, there is a growing demand on power electronics engineers and the corresponding educations are provided in most of Korean Universities [7]. Thus, the electrical engineering curriculum is expected to be optimized and provide the corresponding state-of-the-art training for electrical engineerings to relevant industry application field.

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Fig. 1 illustrates a typical PV system with MPPT function, where PV modules directly convert sunlight into electricity and power interface is connected between the PV module and the load. MPPT block will regulate the duty cycle of the DC/DC converter by measuring the terminal voltage and current. The research on PV power system is mostly focused on the PV modeling [8], converter topology [9], MPPT control [10], and others [11], [12]. The PV modelling, boost converter and MPPT control are discussed here to show the effectiveness of simulation and laboratories in the sustainable energy education.

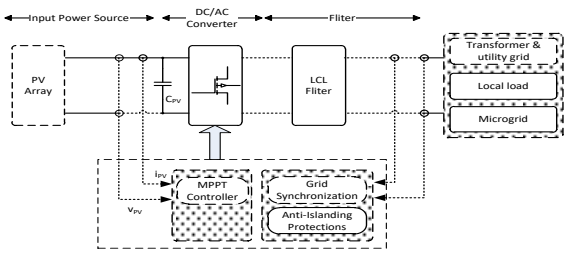
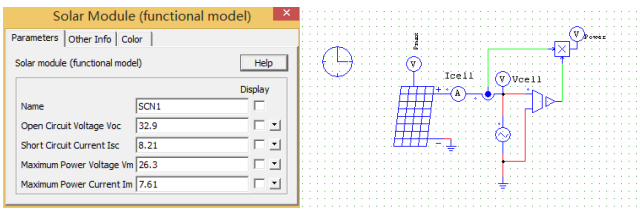


Fig. 1. The typical PV system with MPPT function.

One traditional way in sustainable energy education is "E-Learning", which the main content of a course will be presented via the internet. This teaching method can be used for the working engineers and not suitable for university students [13]. Interactive method using virtual experiments can be used for lifelong education and self-education [14]. For instance, by implementation in Labview, a useful tool will be developed for researching and teaching activities in power electronics area. [15] reported that different dedicated modules can be provided to interactive conceptual training for analysis, design, and control of DC/DC converters.

III. PV Modelling

Here the industry-standard tools such as PSIM will be used to build a simulation model of PV array. Comparing with single diode model, this model is simple and easy-to-implement since only four parameters are required, as shown in Fig. 2(a). Then, a simple circuit using this function model can be constructed, as illustrated in Fig. 2(b). In order to compare the accuracy of PV models, a poly-crystalline KC200GT solar PV module is used and the manufacturer specification is provided in Table I.



(a) (b)

Fig. 2. PV Model in PSIM (a) Main parameters; (b) test circuit.

Fig. 3 shows the results comparison of single-diode model, two lines in each diagram compare model results and experiment results. Fig. 4 presents the absolute error for two modeling approaches with respect to the experimental data of KC200GT PV module.

Through PV modelling, students can learn the characteristics of PV modules with respect to temperature and irradiance through simulation. Students can learn the method to extract the simulation parameters through product datasheet. Besides, students learn to compare the accuracy with different methods through comparison with experimental results.

TABLE I: Module Specification

Parameter	*KC200GT*
I_{sc}	8.21 A
V_{oc}	32.9 V
I_m	7.61 A
V_m	26.3 V
α	3.18×10^{-3} A/°C
β	-1.23×10^{-1} V/°C
N_s	54

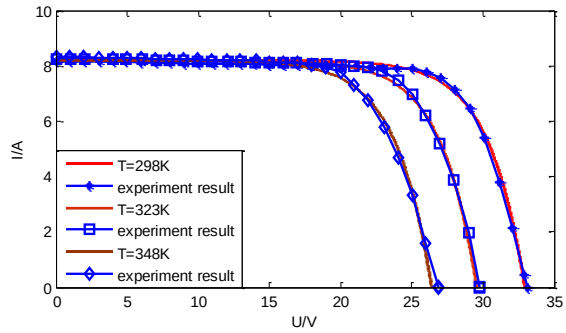


Fig. 3. I-V cures comparison.

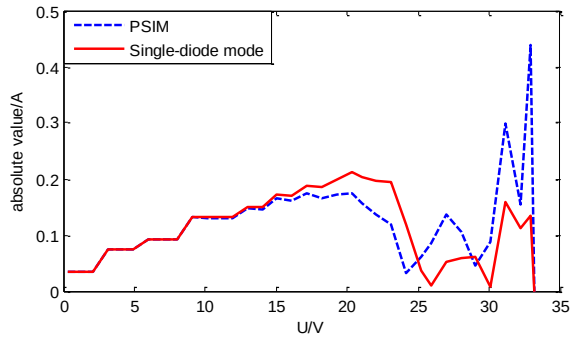
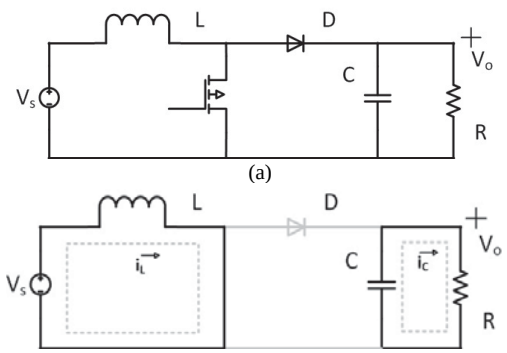


Fig. 4. Absolute error of two modeling approaches.

IV. Power Interface Analysis

Power interface such as the DC/DC converter is widely used and students should know the equivalent circuits for different intervals. Take the boost converter as example, which transforms a high input DC voltage to a low output DC voltage. The circuit diagram is illustrated in Fig. 5(a), which includes an inductor *L*, diode *D*, capacitor *C*, resistance *R* and a MOSFET device.



(a)

(b)

(c)

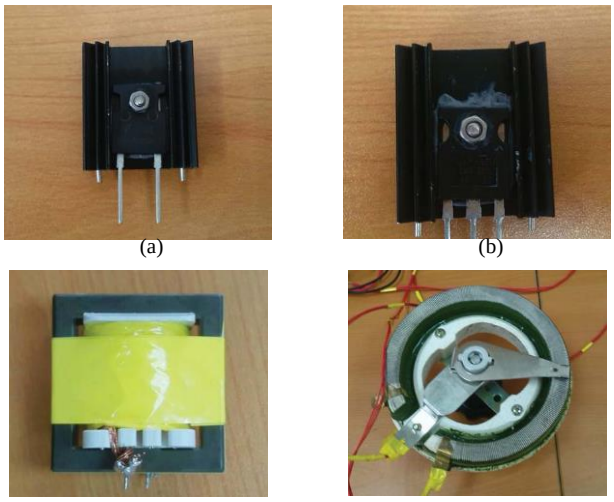
Fig. 5. Boost converter and the equivalent circuits

Student should learn the equivalent circuit for different intervals, such as when MOSFET is on, the diode is reverse biased and the load is supplied by the capacitor, as shown in the Fig. 5(b). When MOSFET is off, the input voltage supplies the inductor and the capacitor parallel connection to the load through the diode, as shown in the Fig. 5(c). When the boost work is in the continuous conducting mode, we have.

$$\frac{V_o}{V_s} = \frac{1}{1-D} \tag{1}$$

where V_s is the supply voltage, V_o represents the output voltage and D is the duty cycle of the switch.

Fig. 6 shows the main components for the boost converter. Students can learn to build a real power converter and improve the hands on skills.



(a) (b) (c) (d)

Fig. 6. Main components for boost circuit: (a) Diode, (b) IGBT, (c) Inductor, and (d) Load resistor.

Through this simulation and boost converter design, students can learn the operation characteristics of boost converter. Besides, students will learn the magnetic inductor design method. Students will design the IGBT gate drive circuit, the voltage and current sampling circuit correctly. A 200W boost converter was built up in the lab successfully. The debugging for typical soldering and connection errors are also required in this process.

V. MPPT Control

MPPT is one essential design challenge in order to enhance the yield power from the installed PV systems. The challenge has been addressed by various maximum power point tracking (MPPT) solutions, such as the Hill-Climbing, Perturb and Observe and Incremental Conductance algorithm. Students are required to know the features of these methods, for instance the complexity, convergence speed, and implementation hardware, [16]. The implementation flowchart is also required. Fig. 7 shows the flowchart of the incremental conductance (INC) method used for PV power system [17].

A diagram of the MPPT for the incremental conductance algorithm in Matlab is shown in Fig. 8, two zero-order holds were used for the voltage and current transducer.

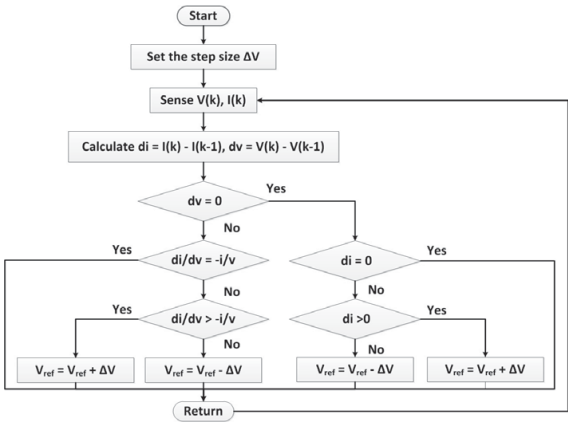


Fig. 7. The flowchart of incremental conductance algorithm.

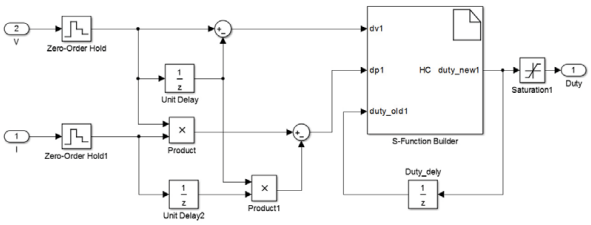
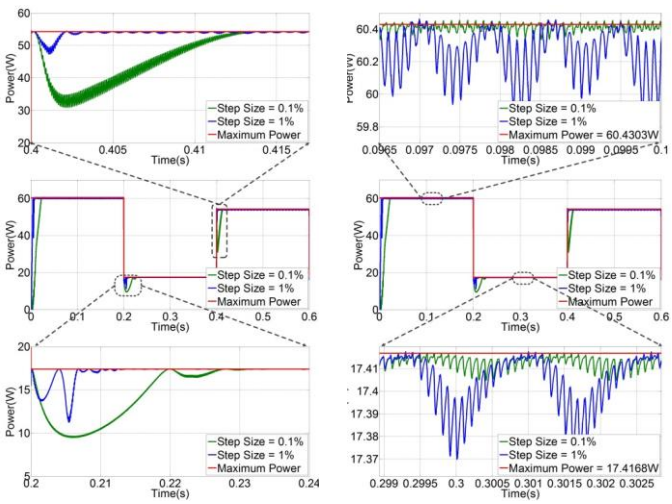


Fig. 8. The diagram of MPPT for hill climbing method in Matlab.

As illustrated in Fig. 9(a), the hill climbing method with the large step size (1%) produced a superior performance to the small size (0.1%) due to a reduction of the time for transients. In contrast, the small step size produced a more effective performance than the large step option due to its smaller power ripple during the steady-state stage, as shown in Fig. 9(b). Thus, students must make a tradeoff between the static errors and dynamic response.



(a) (b)

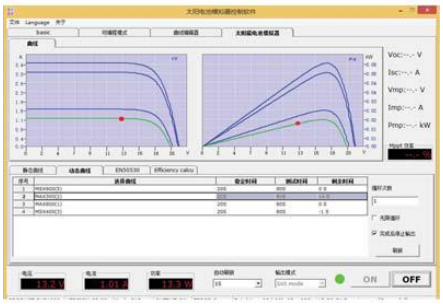
Fig. 9. Simulation and zoomed results with the hill climbing method.

Through the simulation analysis of MPPT strategies, students can learn how to build the PV system simulation model. The ability to implement the MPPT strategy according to the flowchart and the analysis in comparing different MPPT strategies with main indexes such as the static error and dynamic speed are the main teaching objectives.

VI. Experiments

The PV emulator is a programmable DC supply, which can output I-V curves of a PV module or a PV array. Therefore, in the experiment, a solar array emulator PVS1000 Series was introduced as the PV module. The PV emulator is connected to a computer via the RS232, as shown in Fig. 10(a), where users can employ a computer to set the configuration of the PV emulator. After this, Fig. 10(b) shows the user interface of the PVS1000 Series. Here, users can use the curve editor and import the I-V curve data which includes 128 couples of current and voltage points. Then, the I-V curve data can be downloaded into the PV emulator for the next MPPT test.

(a)



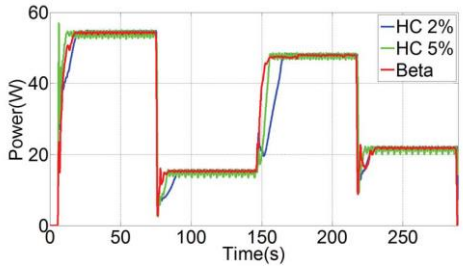
(b)

Fig. 10. The solar array emulator PVS1000 Series (a) and the user interface of the PVS1000 Series (b).

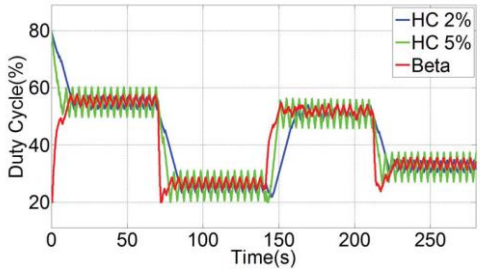
The dSPACE DS1104 is a useful control platform and students can use MATLAB/SIMULINK algorithm to generate codes and directly control the hardware [18]. The software of the dSPACE consists of the Real Time Interface (RTI) and Control Desk Next Generation (CDNG). The CDNG can plot the data which is measured in the scope, in the Matlab/Simulink, such as the power scope and duty cycle scope as shown in Fig. 11. Furthermore, the measured data can be recorded in the CDNG, and it can be exported and plotted with a high image resolution in Matlab.

The parameter setting of the PV emulator follows the sequence of 900W/m^2–300W/m^2–800W/m^2–400W/m^2 with the operation time of 70 seconds. Since the first few seconds of the operation time is the transient time, the PPV (t) was the choice of the power data from the time 30s-60s, 100s-130s, 170s-200s and 240s-270s for the irradiation 900W/m^2, 300W/m^2, 800W/m^2 and 400W/m^2 respectively.

Fig. 11. The user interface of the host computer control desk next generation (CDNG).



(a)



(b)

Fig. 12. Experimental results for the HC methods and another advanced Beta-parameter based method. (a) Output power and (b) Duty cycle.

TABLE II: Teaching Methods Comparison for the Module "Photovoltaic Energy Technology"

Knowledge Points	Conventional Methods	Proposed Method
Be knowledgeable about solar cells	Only basic description	Fully understand the features through simulation
Analyze solar radiation in energy terms.	Basic Level	Fully understand the features through simulation
Design and operation of a photovoltaic system	Knowledge level	Design level through simulation and experiments
Identify and size a photovoltaic system for a given application	Knowledge level	Design level
Tackle some problems of energy conversion using batteries and solar cells.	Knowledge level	Design level with lots of field experience
Describe the fundamentals of photovoltaic energy conversion	Basic Level	Advanced level, clearly know a complicated system

Through the experimental test, students can learn how to generate the I-V and P-V curves for a specific condition with PV emulator. Students can know the skills in implementation the MPPT strategy in DSPACE. Besides, the skills in

analyzing the performance with various MPPT strategies are also required in the teaching module. Students' hands-on experiences or skills to solve practical problems are improved, which is beneficial for the development of renewable energy.

VII. Discussion

A comprehensive comparison of the key knowledge required in the module of "photovoltaic energy technology" and actual teaching methods is listed in Table II, which shows that by widely use of industry-standard tools including Matlab, PSPICE, and dSPACE and innovative experiments arrangement, it can meet various-levels teaching requirements and improve students' hands-on experiences or skills to solve practical problems.

VIII. Conclusion

This paper presents a case study about the practice of using professional simulation and experimental tests in the undergraduate and graduate students' education and training. Firstly the characteristics of PV modules with respect to temperature and irradiance through simulation are described. The basic operation of boost converter is presented with main components design in prototype. Then the comparison of various MPPT strategies is provided. The prototype and experimental results are also provided. This paper shows that the effectiveness of simulation in lecture, tutorial and laboratory exercises will help students understand fully the operating principle of the electrical circuits. Students' hands-on experiences or skills to solve practical problems are improved, which is beneficial for the development of renewable energy.

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