Laboratory Development for a CCLI Course on PV Engineering

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Dr. Hirak Patangia is a professor of Electronics and Computer in the College of Engineering and Information Technology with teaching responsibilities in both Engineering Technology and Systems Engineering. He has served the university in various administrative positions including interim dean, associate dean, and department chair before returning to full time teaching and research. He has involved undergraduates in his research extensively and many of his publications include undergraduates as coauthors. He was the first recipient of an NSF research initiation grant (now CAREER Award) at UALR. He has a strong grant funding record and in 2011, he received funding from NSF for curriculum development in the area of Photo-voltaic (PV) Solar Energy. The project involves developing exemplary course modules and innovative laboratory modules for adaptation at other schools for undergraduate/graduate teaching and research. Recently, he completed three projects for Arkansas Highway and Transportation department related to highway lighting using solar energy. He established a commercial PV system with solar panels on the rooftop of ETAS building for teaching and research with funding from Arkansas Energy Office. With NSF funding (2001), he developed a project based freshman engineering course for engineering and other university students who want to explore engineering as a career path or for personal enrichment. He has written a textbook and a laboratory manual for the course 'Introduction to Electronics and Electrical Systems: A PBL Approach'. He is the first author of more than 100 refereed research publications in international journals, symposia, and conferences and has chaired several international conferences. He holds two patents. He has received numerous awards for teaching excellence at UALR including Donaghey Outstanding Teacher award. He has also received recognition for research excellence from the chancellor and college. His research interest is in the general area of signal processing (analog/digital) and he is working on new approaches in inverter design and solar controller to improve efficiency of solar energy conversion. He received the bachelor's degree with honors from Indian Institute of Technology, Kharagpur and Ph.D. degree from McGill University, Canada, all degrees in Electrical Engineering. He is a registered PE in the State of Arkansas, a life member of IEEE, branch counselor for IEEE UALR chapter, current chair of student activities for Arkansas section, and served the section as president for two years.

Development of a CCLI Course on PV Engineering

Abstract

A Course Curriculum Laboratory Improvement (CCLI) Type I NSF proposal under the title "Development of Novel Learning Materials for Green Energy Education Centered around a PV Test Station" was awarded in August, 2010 to develop exemplary learning materials and laboratory modules for PV engineering at the undergraduate/graduate levels. The paper discusses a preliminary version of course modules developed as of now, the laboratory facilities and experimental projects, and assessment of its impact on students.

Keywords: Photovoltaic, Renewable Energy, Curriculum

1. INTRODUCTION

With energy cost rising and the dangers of climate change due to energy-related greenhouse effect, there has been a great national interest in renewable energy. Energy security has been a public concern. Among the clean and green power sources, the photovoltaic solar power has the potential to supply a significant fraction of electrical energy need. With the sky rocketing gas price of past years, people are paying serious attention to alternate energy and this enthusiasm must be carried on to undergraduate engineering education. As a cornerstone of his energy, environment, and economic plans, President Barack Obama urges the country to transform its energy system to make it greener and smarter. This project seeks to address such a challenge with contemporary courses on alternate energy harnessing and electric smart grid (ESG).

Many universities across the nation have been engaged in solar energy research. Their primary focus is to improve physical properties of silicon cells to improve panel efficiency and reduce cost. However, undergraduate courses that focus on the practical design and implementation of solar system starting with the panel to end user are virtually absent in the literature. A few EE courses devote about fifty percent of the course to semiconductors and the remaining to system hardware. The fundamentals of the system components are covered in other courses in EE curriculum and no focus on integration to solar conversion is presented. However this approach needs serious revision in view of the importance and national focus on harnessing alternate energy, and the need for graduates trained in this field. In the design of the proposed course materials, emphasis is placed on the hardware side starting from the solar panel output to end user and grid connectivity. Integration of our research finding from previous and current work will be a major factor in the course design**.** The paper presents a summary of the present state of the course development.

2. PROJECT GOAL

The overall goal of the project is to develop course materials on photovoltaic engineering to be supplemented by hands-on laboratory work. The course topics are centered on the blocks illustrated by the following diagram:

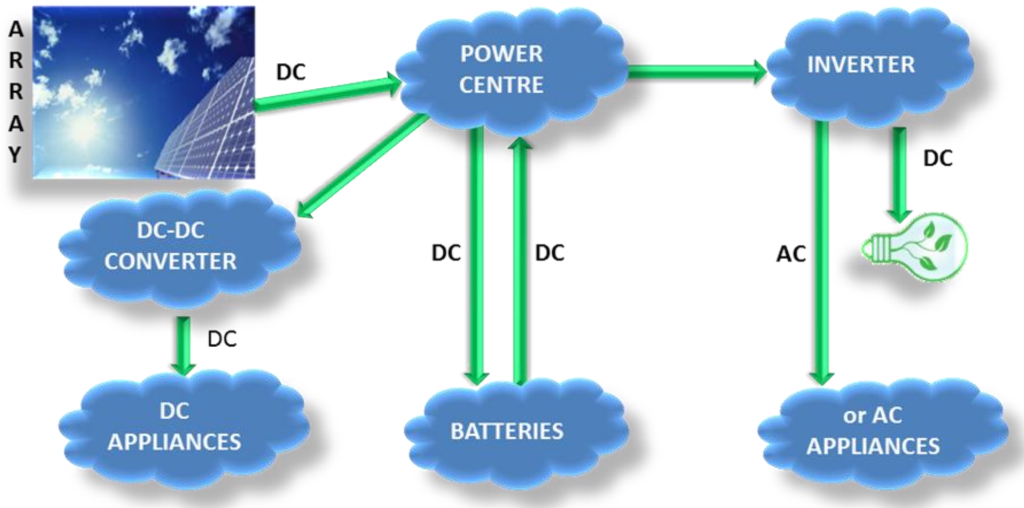

Fig.1 Block diagram showing various components of a solar photovoltaic system

The laboratory activities are to correspond to each or a combination of the topics and to be culminated by the design and testing of a stand-alone/grid connected PV system. Laboratory activities will include simulation, modeling, and experimentation using commercial size panels. The PV voltage of the panels mounted on building rooftop has been fed directly to the laboratory. This will provide a realistic learning experience and facilitate experimentation under varying insolation and weather conditions.

3. Course Module Development Activities

A comprehensive research on the published books and materials was undertaken to examine the current state of available literature in this field. There is no single book or textbook that includes all the topics planned for our development. A tentative course syllabus was developed and power point slides for each of the topics has been compiled based on the research of existing books and journal/conference publications. The PI has practical experience on PV systems through three projects he completed for Arkansas Highway and Transportation Department (AHTD) and DOE, and that experience has been embedded while designing the power point presentation. The course topics and a summary of the power point slides for each module are presented in the following:

3.1 Course Module Topics

- Solar Resource and Renewable Energy
- Introduction to Photovoltaic Systems
- Photovoltaic Materials & Semiconductor Physics
- Single Photovoltaic (PV) cell and its Model
- Electrical Characteristics of the PV cell
- Solar Cell Arrays, PV Modules and PV Generators
- Power Electronics and Interfacing PV modules to Load
- Power Conditioning and Inverter Design
- Maximum Power Point Trackers and DC to DC Converter
- Battery Characteristics and Energy Storage (Super Capacitors)
- A Standalone PV System
- A Complete Residential PV Systems and Demonstration
- PV System Sizing and Trade Off
- Grid-connected PV Systems

3.2 Power Point Presentation Slides

3.2.1 Solar Resource and Renewable Energy (1), (4)
An introduction to solar resource, and important concepts like solar irradiance, solar insolation, Air Mass ratio, solar window etc. A discussion on the impact of these concepts on available solar power at various times of the day and year, and other panel characteristics such as efficiency. Brief discussion about other types of renewable energy- definition and basic characteristics.

3.2.2 Introduction to Photovoltaic Systems, Materials and Semiconductor Physics (Band Gap Energy) (2), (4)
The presentation covers in depth about the photovoltaic systems and technology till date, about the types of materials used in photovoltaic manufacturing industry, and the differences between them. As the students might not have complete awareness about band gap theory, discussions on all the relevant topics about semiconductor physics and the impact of band gap for a material to be useful in solar cell manufacturing industry have been included.

3.2.3 Single Photovoltaic (PV) cell, its Model and electrical characteristics (3), (4), (6)
As a continuation to the previous presentation, this is more towards the electrical side rather than physics. The main focus is on the internal parts of a solar cell, it's equivalent electrical model and the basic electrical characteristics like Maximum Power Point, Fill Factor, I-V and P-V curves, impact of internal resistance of a solar cell with emphasis on series and parallel leakage resistance, voltage and current equations etc.

3.2.4 Solar Cell Arrays, PV Modules and PV Generators (3), (4). (5)
This presentation covers the transformation of solar cell to module to array- effect of number of cells in a solar module, a comparison of I-V curves of modules containing different number of cells; parallel, series and hybrid combination of solar cells and the variation in I-V and Power curves. An in depth discussion about temperature and insolation impact on I-V curves, shading effects, methods to minimize shading effects-use of bypass diodes and blocking diodes were a major part of the module.

3.2.5 Power Electronics and Interfacing PV modules to Load **(**4), (6)
A basic introduction to power electronics and interfacing of various loads with the PV modules are discussed. An in depth presentation on operating point of various loads, its definition and variance in position under different insolation is part of the module. The presentation includes the I-V curves and power curves showing operating points under different solar insolation for simple resistive load, dc- motor, and battery.

3.2.6 Maximum Power Point Trackers and DC-DC converter (7), (8), (9), (10), (11), (12), (22)
This section of the modules emphasizes on maximum power point trackers (MPPT), the research that's going on in this topic as well as its design and construction. Various methods that include dc-dc buck, boost, and buck-boost converter-their voltage, current and power equations, practical design, effect of temperature on duty cycle parameter, hourly I-V curves are included. Hill climbing MPPT method which is often used in commercial system is emphasized.

3.2.7 Power Conditioning and Inverter Design (17), (18), (19), (20)
This module includes dc-ac inverters-definition and technology as it is one of the main components of a photovoltaic system for grid connectivity. An introduction to Total Harmonic distortion, inverter efficiency, various types of inverters-their advantages and disadvantages, pulse width modulation techniques and its practical implementation is a major part of the unit. The PI also discusses importance of micro-inverter design and the on-going research on the topic

as well as the work he is doing related to this technology. A closer look at IEEE publications on inverter design and technology is provided.

3.2.8 Battery Characteristics and Energy Storage (Super Capacitors) (1), (14), (15), (16)
The first section of this presentation discusses batteries-classification and important differences between various batteries. Important concepts like battery charging and discharging characteristics, temperature effects, different battery combinations, storage capacity, energy losses, battery sizing, and role of charge controllers are included. The second section includes other emerging efficient energy storage elements like super capacitors- their advantages over batteries, electric al characteristics, methods to measure the capacitance, basic construction and characteristics like ESR, life expectancy, and applications to batteryless PV systems.

3.2.9 Grid-Connected PV Systems and Standalone PV Systems (1), (4), (5), (21)
An in depth discussion about classification of PV systems, types of grid connected systems-single stage and multistage grid systems, various design topologies like CACERES and BARBI, SCHEKULIN, KASA, XUE, Huang et al., etc is a major part of the module. This module also covers a broad discussion on standalone PV system design: examples like solar powered traffic light system, solar powered water pumping and heating system- their design conditions and construction including wire sizing. Role of MMPT and charge controllers, inverter and the situational use of different inverters are explained through exemplary models.

3.2.10 PV System Sizing and Trade Off, Complete Residential PV Systems and Demonstration (1)
The final topic of the course is a real life design that could be implemented for residential purpose. This covers a micro-inverter based design example with all the calculations of PV area, MMPT, inverter design, and the system is based on a 200W micro inverter. The presentation ends with an in depth discussion about BOS selection and design completion-Rooftop junction box, source circuit combiner box and surge arresters, wire and circuit breaker sizing: dc side & ac side, wiring and standby loads, equipment grounding conductor & grounding electrode conductor sizing.

4. LABORATORY ACTIVITIES

The College of Engineering has assigned a modern laboratory space for the project implementation. The space has been renovated, electrical connections dropped, and six modern lab tables with storage facility have been installed. Each station is equipped with test equipment from Tektronix and they include: Tektronix AFG 3022 B Dual Channel Arbitrary/Function Generator, Tektronix MSO 3014 Mixed Signal Oscilloscope, Tektronix DMM 4010 5-1/2 Digital Multimeter, and Instek SPD-3606 Dual Range DC Power Supply. Each station is also equipped with a desktop computer and the computers are interfaced to the equipment through Ethernet cable. Each computer is equipped with latest windows operating system, high speed processor, and major electronic and math software like MatLab, LabView, ArbExpress (interfacing software to Tektronix AFG 3022 B). The software provides the capacity to download simulation or implementation data to the test equipment. The funding for the test equipment has been provided by the College. The NSF funding component for equipment has allowed us to install six 235W panels on the building rooftop and the panel outputs are fed directly to the lab benches. A data acquisition system to monitor temperature and humidity of the panels will also be installed. National Instruments or Keithley Instruments real time PV measurements system is under consideration for module characterization.

Few experiments related to Power, Voltage, and current characteristics, PV's Thevenin's and Norton's model, and MPPT controllers have been completed as of now. The laboratory activities will be expanded in the following order:

Lab-1: Hands on tutorial on nano-solar fabrication through University's Nano-Technology Center.

Lab-2: PV Characteristics: VI, IP, VP and Maximum Power Point Tracking.

Lab-3: Buck-Boost Converter Design

Lab-4: MPPT Controller design using Hill-Climbing Method.

Lab-5: Design of a Low Power PV system including battery voltage management for a parking lot lighting system. Employ commercial MPPT controller or Fairchild IC.

Term Project:
Power efficient and Low THD Micro-inverter Design. In this lab the student will investigate various PWM signals through MatLab simulation and determine THD. Use the data points to generate a PWM signal using arbitrary generator. Use the PWM signal to drive an H-Bridge with transformer interface for grid connectivity.

The lab activities will continue to focus on the topics shown below:

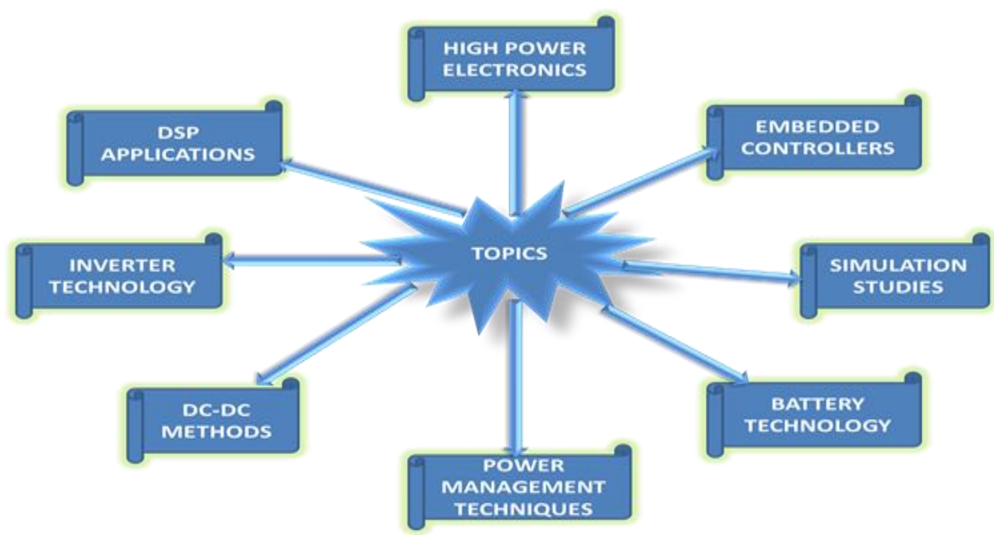

Fig.2 Planned laboratory topics

The following pictures illustrate the PV system installed and the equipment in the new lab.

Fig.3 PV System: Panels on roof top and 4KW inverter with battery back-up

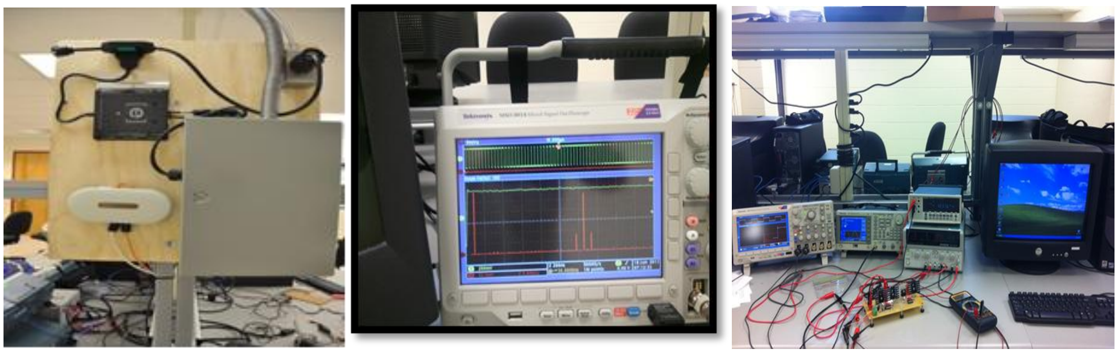

Fig.4 Micro-inverter and lab equipment

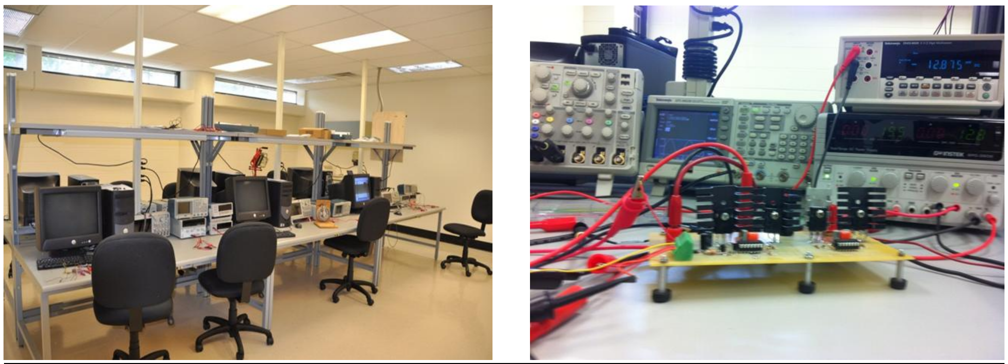

Fig.5 PV lab stations and H-Bridge testing

Field Testing of Course Modules

Two field-tests have been completed: one in the summer of 2011 and the second one just completed on August 8, 2012. With the input we received through the course evaluation of 2011, the modules were modified in the order of presentation and the power point slides were updated with new materials. Students' course evaluations were carefully studied and their comments were taken into account when delivering the course second time in August, 2012. The evaluations we received in this cycle will be studied by the project director and the assessment coordinator and adjustments will be made to reduce the feedback error for the next offering in spring 2013. As in the past, the course was made open to students from Systems Engineering, Engineering Technology, and Science. Nine undergraduates (juniors and seniors) and one observer attended the course compared to four undergraduates we had past summer. This is more than a two-fold increase, although we haven't officially publicized the course. It's the word of mouth that has attracted the students and we have noticed a great enthusiasm for alternate energy in the students. The spring 2013 enrollment has jumped to 12 students which is our lab capacity. Students' informal feedback was collected as the course progressed and the data from the formal evaluation have been compiled. There were twelve questions for students to comment about various aspects of the course and one ranking question about the topics of the course. The following data have been included to highlight some of the students' comments and their rating of the course topics:

- Please rate the course topics based on your understanding, instructor's teaching effort, topic's content, and your interest in the topic. Scale: **5 - Very Good**, **4 - Good**, **3 - Average**, **2 – Below Average, 1 – Poor**

	Responses: 9	Very Good (5)	Good (4)	Average (3)	Below Avg. (2)	Poor (1)
a.	Solar resources	6	2	1	0	0
b.	Physics of PV cell and electrical characteristics	6	3	0	0	0
c.	PV modules and PV arrays	6	3	0	0	0
d.	Effect of shading and minimizing its effect on power generation	6	3	0	0	0
e.	Maximum Power Point and MMPT controller	6	2	1	0	0
f.	Basics of DC-DC Converter & application to MPPT controller design	5	4	0	0	0
g.	Survey of MPPT controller in current literature	4	3	1	1	0
h.	Basics of Inverter and importance of THD	5	1	2	1	0
i.	PV storage and battery characteristics	6	3	0	0	0
j.	Battery sizing and PV array sizing	7	2	0	0	0
k.	Super-capacitors for storage	5	4	0	0	0
l.	Design of stand-alone PV systems	4	4	1	0	0
m.	Grid connected PV systems	4	4	1	0	0

1. Do you feel the course has been meaningful for your career interest? If yes, in what way?

Very interesting course on a relatively young industry. Possibly a good career path.
I love the "Green Energy" field. I believe that using combination of solar, wind, and other renewable resources, we can solve our power needs.
Solar energy technology is becoming more and more popular today. I believe this course will help me know how to use the technology.
Yes. This field interests me to begin with. It has inspired me to learn more.
Possibly career interest. Definitely personal interest. Alternative (Free) energy has always held my attention.
Yes. It was practical material that gave me a basic foundation in PV. I may not be ready to assemble a PV system, but I now know what I'd need to study & consider & I bet I could do it with a bit of time & serious effort.

2. Because of the focus and need for renewable energy, would you recommend the course to other students?

Yes
Yes, although challenging, it was interesting.
Most definitely.
Yes, I would recommend that every ECET and SYEN student take this course.

Yes.
Yes. This market is going up steadily and this course introduces us to the industry.
Yes. I feel strongly about this.

3. Do you think we should offer a beginning course on renewable energy to freshman students? The course will be a basic one without the need for specific prerequisites.

Yes, it is a valuable and important concept.
Not a bad idea, this would allow freshman to taste an industry that pre-college education focuses on. The youth is the "environment conscious" youth.
More is always better.
I don't think a beginning course is necessary.
Yes.
Maybe a course to cover more forms of alternative power.
Yes. Include smart grid fundamentals. This is extremely relevant to electrical considering going into Power.

4. List the reason(s) why you are taking the course and if the course met your expectation.

I took it because it sounded interesting and it is. I did not expect so much work though. Some of the material taught was very complex.
This is my second time to take it. I continued to learn new and interesting material. The course exceeded my expectations.
I am taking this course because solar energy technology is improving and I find this topic very interesting and useful for the future.
Technical elective for a mechanical technology degree. I think it has met my expectations and more.
Personal interest. I didn't really have any expectation, but it has been more than I "would have" expected.
I took it because I was interested in the material and because Dr. P was teaching it.

5. Any other comments that you think would help us to develop a solid course in this field.

More practical labs and more in depth training on how to apply this material to current world conditions. Example: How to create, design and install a small PV system in your own home.
I have really enjoyed the class and as stated before, look forward to continue learning in this area.

There is lots of material here and it could easily fill a regular semester. Summer IV may be too short.
More examples polish the handouts.

Students had no negative comments about the selection of course topics and the delivery method. They would like to see more solved problems and design examples. This will be improved upon in the next phase of module development. The power point slides were distributed to the students for every lecture through university's 'online course management system' and the majority of the class would like to see a formal textbook developed for the course. The students completed three lab exercises and they recommend more labs in the MPPT controller and converter area. The PI is also considering a standalone PV system as the course platform.

Outreach Activities

Three groups of students, each with 25 students, from various high schools within Arkansas and outside the State attended Engineering Scholars Program from June 17 – 23, June 24 – 30, and July 15 – 21, 2012. The purpose of the program is summer enrichment in engineering and exposure to different programs within the College of Engineering. The students spend 1- ½ day learning about each of the programs. As in the past year, the PI organized a half day program on renewable energy that included a guest speaker, overview of solar/wind energy, and hands-on laboratory activities on PV engineering. The speaker is a PV energy enthusiast who gave a power-point presentation on harnessing of solar energy including cost analysis. The PI discussed the NSF project and presented the fundamentals of solar generator along with its advantages and current drawbacks. The PI also went over some fundamentals of electrical quantities to ready them for the hands-on activities to be carried out that afternoon.

The students were provided with a 3W PV panel and a DMM to go outside (group of two) to carry out voltage current measurements under sun at various tilt angles of the panel and also under shade. They compiled the results in the lab to examine the power curve. Second half of the lab activities included an RC car race powered by the panels. The students mounted two panels on the car's roof top and they were connected in parallel to provide the high starting current the motor needs. The cars were tested under halogen lamp in the lab and once functioning, they were tested outside in the parking lot. The students competed with each other and it was fun for the students as attested by their evaluation at the end of the program.

The same activities were repeated for each group on three Fridays and the PI was assisted by both graduate and undergraduate students. The EIT College carried out its evaluation of all programs offered for summer enrichment and the three groups of participants in the PV program ranked our activities with the following overall rating: **3.78/4 (1st rank/10), 3.43/4 (6th/10), and 3.69/4 (1st/10).** Each group had 25-27 students. The PI also carried out its own evaluation of each group with questions pertinent to our grant activities. The student comments are very supportive of our PV activities.

Fig.6 Outreach Activity speakers

Fig.7 Students outdoor with Graduate Asssistants

Fig.8 Students with solar powered RC cars

Fig.9 Outdoor and indoor testing & student groups

5. CONCLUSIONS

The students' high level of enthusiasm in the course indicates that the course has the potential of motivating and attracting students to the field of alternate energy. The course is still in the developmental stage and current focus is to improve on the laboratory activities. The feedbacks from students indicate that the development of the course appears to be in the right direction. The comments from the high school students indicate that the outreach activities have a major impact in their interest in alternate energy. This is a good sign for the nation as a whole. These activities will be continued to further the enthusiasm in alternate energy.

Acknowledgements

The paper is based upon the project funded by the National Science Foundation under Grant No. DUE-0942327.

References

(1) Roger A. Messenger, *Photovoltaic Systems Engineering.* 3rd edition, CRC Press, 2010.

(2) Chetan Singh Solanki, *Solar Photovoltaics: Fundamentals, Technologies, and Applications*. PHI, 2009

(3) Tomas, Markvart, *Solar Electricity*. 2nd edition, Eiley, 2000.

(4) Gilbert M. Masters, *Renewable and Efficient Electric Power Systems*. Wiley, 2004.

(5) Photovoltaics Design and Installation Manual, NSP, 2007.

(6) Luis Castaner and Santiago Silvestre, Modeling of Photovoltaic Systems using PSPICE. Wiley, 2002.

(7) Trishan Esram, Patrick L. Chapman, "Comparision of Photovoltaic Array Maximum Power Point Tracking Techniques," IEEE Trans. Energy Conv., vol. 22, pp. 439-449, June, 2007.

(8) E. Koutroulis, K. Kalaitzakis, and N.C. Voulgaris, "Development of a microcontroller-based, photovoltaic maximum power point tracking control system," IEEE Trans.Power Electron., vol. 16, pp. 46-54, Jan.2001.

(9) N. Femia, G. Petrone, G.Spagnuolo, and M. Vitelli, "Optimization of Peturb and Observe Maximum Power Point Tracking Method," IEEE Trans. Power Electron., vol. 20, pp. 963-973, July 2005.

(10) J. Enslin, M. Wolf, D. Snyman, and W. Swiegers, "Integrated Photo-voltaic Maximum Power Point Tracking Converter," IEEE Trans. Ind. Electron.,vol.44, pp.769-773, Dec. 1997.

(11) Cuauhtemoc Rodriguez, Gehan A. J. Amaratunga, "Analytic Solution to the Photovoltaic Maximum Power Point Problem," IEEE Trans. Circuits and System, vol. 54, pp. 2054-2060, Sep. 2007.

(12) Cesare Alippi, and Cristian Galperti, "An Adaptive Syatem for Optimal Solar Energy Harvesting in Wireless Sensor Network Nodes," IEEE Trans. Circuits and Systems, vol. 55, pp. 1742- 1750, July 2008.

(13) Davide Brunelli, Clemens Moser, Lothar Thiele, and Luca Benini, "Design of a Solar-Harvesting Circuit for Batteryless Embedded Syatems," IEEE Trans. Circuits and Systems, vol. 56, pp.2519-2528, Nov 2009.

(14) Hirak Patangia, "Assisted Night Vision for Motorists in Highway Construction Zones: Phase II," www. Mackblackwell/MBTC2064, 2007

(15) K. Shukla, S. Sampath and K. Vijayamohanan, "Electrochemical supercapacitors: Energy storage beyond batteries", Current Science, vol. 79, no. 12, December 2000

(16) Marin S. Halper, James C. Ellenbogen, "Supercapacitors: A Brief Overview", MITRE McLean, Virginia, March 2006.

(17) H. Patangia, "Amplitude Division Multiplexing Scheme in Analog Signal Processing", in Proc. IEEE Int. Midwest Symp. Circuits & Systems, August 2005, Cincinnati, Ohio

(18) H. Patangia and D. Gregory, "Sectionalized PWM(S-PWM): A New Multilevel Modulation Strategy," in Proc. IEEE Int. Symp. Circuits & Systems, May 2008, Seattle, WA.

(19) H. Patangia and D. Gregory, "A Class of Optimal Multilevel Inverters Based on Sectionalized PWM (S-PWM) Modulation Strategy" in Proc. IEEE MWSCAS 2009, August, 2009, Cancun, Mexico

(20) Daniel W. Hart, *Power Electronics*. McGrraw Hill, 2010.

(21) H. Patangia, Final Report: Solar Powered Lighting for Overhead Highway Signs – MBTC 2096, January 2009. www.mackblackwell.org

(22) Hirak Patangia, Srinikhil Gupta Gourisetti, Afzal Siddiqui, and Sachin Sharma, "A Simplified PV Model for Low Power MPPT Controller Design" in Proc. IEEE APCCAS 2010, December, 2010, Kuala Lumpur, Malaysia