AC 2011-256: COMMISSIONING A 5 KW PV ARRAY FOR ELECTRICAL ENGINEERING UNIVERSITY CURRICULUM.

Jaime Ramos, University of Texas, Pan American

Dr Ramos has been at The University of Texas Pan American since 2005, in the Department of Electrical Engineering. His research activities are directed towards the integration of renewable energy sources to the electric grid. Dr Ramos is a Registered Professional Engineer in the state of Texas, and the Chair of the Rio Grande Valley Chapter of IEEE Power & Energy Society. Before coming to Texas, he accumulated significant experience in manufacturing, consulting, and teaching Electrical Engineering. He obtained a PhD in Electrical Engineering in 1976 from Stanford University.

Leonel Aguilera, UTPA

Leonel Aguilera earned his his B.S degree in Electrical Engineering from The Technology Institute of Saltillo, Coahuila, Mexico in 2006. He expects to earn his MSE degree in Electrical Engineering at the University of Texas-Pan American in Edinburg, Tx on Dec 2011. His research interests are: Networking and Renewable Energy.

Elizardo Garcia, Universidad TecMilenio
Sanjeev Kumar, Electrical and Computer Engineering, The University of Texas - Pan American

Dr. Sanjeev Kumar is active in research & teaching in the area of Computer Security, Smart Grid Security, High-Speed Internet Switching/Routing, Wireless Ad Hoc Networks, Computer Architecture, and Digital Logic Systems. Before joining UTPA, Dr. Kumar worked with the leading networking companies in the US. In the networking industry, Dr. Kumar played a leading role in planning, research & development of new communications equipment and networks.

Dr. Kumar has authored over 50 technical papers. Dr. Kumar's research findings have been cited by other researchers in the field. Dr. Kumar has served as Associate Editor for networking Journals, and as a member of technical program committee for international conferences. He has been awarded US and International patents for his inventions in the area of broadband networks. Dr. Kumar received the Ph.D. degree in Computer Engineering from North Carolina State University, Raleigh, North Carolina. He is the founder of NSF funded Network Research Lab (NRL) in Electrical Engineering Dept. at UTPA, and an elected Senior member of IEEE..

Roman Garcia, IEEE

Roman Garcia earned his degree as an Electronic Technician in 2007. He is coursing his B.S degree in Electrical Engineering at The University of Texas Pan-American. He is looking for a cleaner way to provide energy and illumination at lowest prices. His goals and vision on renewable energy and LED lightning had brought him to work as a research assistance on the project described in the paper.

Jose Sanchez, The University of Texas Pan American

Jose Sanchez, The University of Texas Pan American Jose Sanchez received his BSEE degree from The University of Texas Pan American in May 2008. He expects to earn his MSE degree in Electrical Engineering at the University of Texas Pan American in May 2011. His primary interests lie in the development of Energy Efficiency and Renewable Energy Systems and Technologies, Power Electronics, and Smart grid design.

Commissioning a 5 kW PV array for Electrical Engineering University curriculum

Universities around the world [1,2,3] are developing new curricula on renewable energy, to prevent the shortage of qualified electrical engineers in power systems. This paper describes the commissioning of a 5kW DC photovoltaic generation system (PVS), which is being used at The University of Texas Pan-American (UTPA) as an educational tool, to let students learn the fundamental principles and to get hands-on experience with power and renewable energy systems. The system topology is shown in Figure 1.

The PVS is called a hybrid system because it has been designed to supply energy in three different configurations: (a) for stand-alone and battery applications, (b) for grid-tied applications, and (c) as a back-up (emergency) system that supplies power to smart-grid laboratory at UTPA.

During the first stage of the commissioning process, our efforts have been focused on understanding the behavior of the system and on operating it in a reliable way, in the stand-alone configuration. So far, (i) an energy balance of the PVS has been made, (ii) the correlation factor between its energy input and output has been computed, (iii) the efficiency has been calculated, (iv) the actual operating point has been analyzed, and (v) the maximum power and total energy production is being reported daily.

Results show that the system is working with an efficiency close to 90%, with respect to the photovoltaic generated power, but that it operates far away from its maximum power point. This is due, largely, to a second harmonic current introduced by the charge controller. The next step, in the commissioning process, will be to filter out a second harmonic current generated by the charge controller (a Sunny Island unit) and to drive the PVS to its maximum power point.

1- Introduction

As State legislatures approve guidelines for the composition of renewable energy in the total generation portfolios of electric utilities, several actors in the private as well as the public sectors have increased year by year the amount of electric energy generated by wind, solar and other green technologies.
In the past two years the federal government, through its Department of Energy has increased the amount of capital to stimulate the development of solar technologies, as well as the formation of well trained human resources to support this national effort.

Solar photo voltaic technologies have been increasing its participation because they rely on the mature and powerful semiconductor industry, and also because they offer unique operational characteristics which the residential and commercial sectors can use for distributed generation.This environment has created within Universities a strong interest from students for the acquisition of knowledge on Renewable Energy. Correspondingly, Faculty has made significant number of proposals to develop on-site low power photovoltaic generation resources, as a response to the student´s interest.

This paper describes the work done during 2010 at the Electrical Engineering Department of The University of Texas Pan American- UTPA- to install photovoltaic systems to develop and construct learning materials. Basic experiments are described in detail. Topics include commissioning a 5.18 kW_{DC} fixed PV array; monitoring the energy and power produced by a 5.52 kW_{DC} two-axis sun tracking PV array; and obtaining current voltage characteristics of single modules, by manual and automatic methods.

The experiments are being evaluated with the assistance of undergraduate students who have enrolled in one of the courses offered the Energy and Power systems course concentration.

2- Resources and Facilities

The learning materials have been designed to use software and hardware available at UTPA. The ENGR fixed array uses software developed by Sunny Portal[4] www.sunnyportal.com; students operating this array will use LabVIEW programs to monitor electric variables. The TXU Sun Tracking Arrays use software developed by Insight View/Fat Spaniel[5] to monitor its performance. These computational resources monitor the operation and state of the electronic inverters. Additionally, students use software developed by the authors to calculate the sun trajectory and incidence angles on the fixed modules.

The hardware based experiments will be determined by the photovoltaic systems already available at the University. Two systems are shown in Figures 1 and 2. Each experiment includes a collection of modules, inverters, meters, and loads. A list of the PV systems is shown in Table 1. Table 2 includes a list of basic, intermediate and advanced experiments.

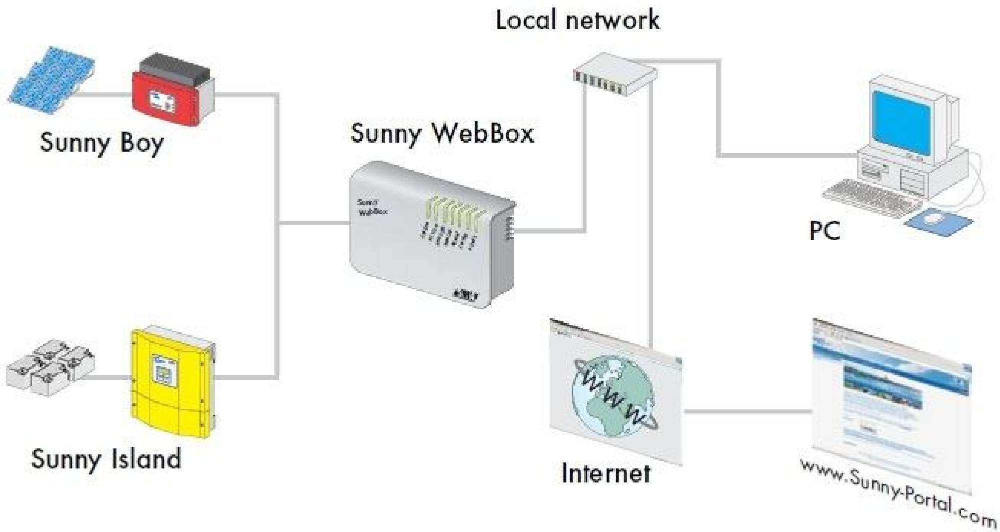

Figure 1 - Schematic view of ENGR PV Solar Power System

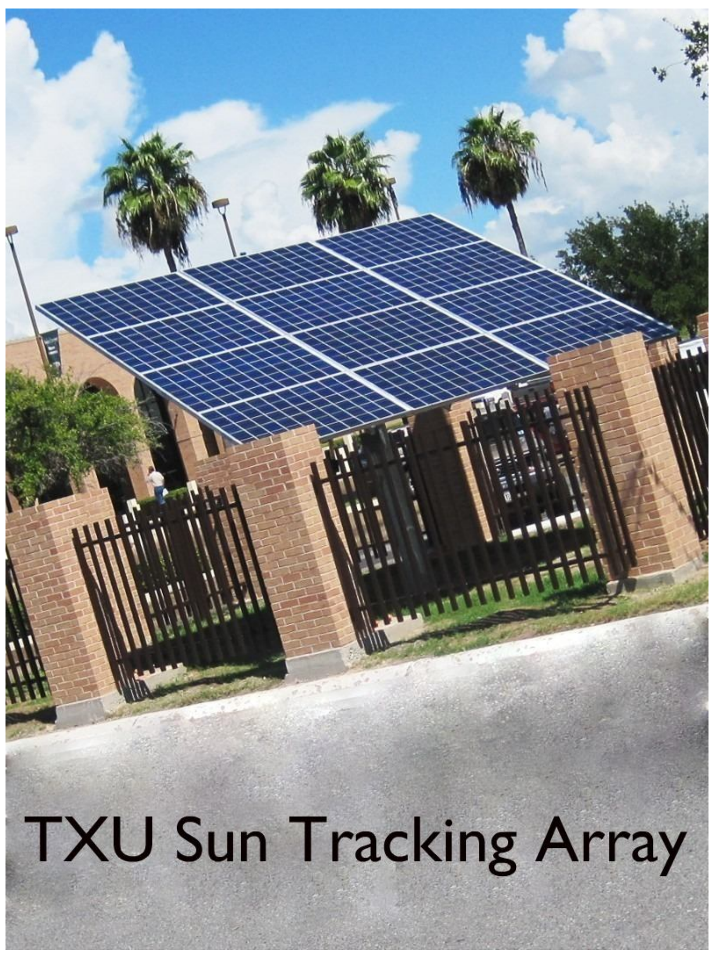

Figure 2 - North Half of the TXU Sun Tracking Arrays

Table 1- Main photovoltaic components

System	Ratings	Use	Initial cost
1- ENGR PV fixed array	5.18 kW_{DC} V_{OC} =438 V, I_{SC} = 8.1 A	DC grid battery storage. AC grid tied	$ 57,000
2- TXU Sun Tracking Arrays	5.52 kW_{DC} V_{OC} =443 V, I_{SC} = 8.3 A	AC grid tied	$ 70,000
3- Single module	155 Watts, V_{OC} =43 V, I_{SC} = 4.8 A	$I – V$ characteristic	$ 1,000
4- Sun Radiation Power Meter	Watts / m²	Hand held, inexpensive	$ 150

Table 2- List of basic, Intermediate and Advanced Experiments

Topic	Activity	Systems
1- Length of day	Calculation & Monitoring	1- ENGR PV fixed array
2A- I V characteristic	Manual measurements	3- Single module
2B- I V characteristic	Oscillographic measurements. Maximum Power Point	3- Single module
3- Battery Storage	Ampere-Hours calculations	1- ENGR PV fixed array
4- Battery Storage	System kWh energy balance	1- ENGR PV fixed array
5- Capacity Factor	Compare PV systems	1,2
6- Commissioning of the ENGR PV Array	Upgrade instrumentation. Networking	1- ENGR PV fixed array

3- Overview of available Renewable Energy Technologies

During the planning phase of this work we addressed the question: Which renewable energy source would be best suited to the general physical conditions of the UTPA campus? Our natural interest within a Department of Electrical Engineering would be to operate a distributed generation resource able to evolve naturally as a micro/smart grid[6,7] with a certain degree of flexibility to cover different utilization or integration schemes (DC /AC grids).

We then examined the possibility of using wind turbines located on campus, with a limited budget. From the wind speed data at Edinburg, TX provided by the Texas Environmental Quality Commission[8] we constructed yearly histograms. Our calculation showed the average wind speed to be less than 9 mph, making the UTPA campus a wind power class 1 site. Furthermore, we studied the market of small (micro) wind turbines, searching for one which mounted on a not too high tower could be operated reliably many days of the year. When we focused on their cut in windspeed characteristics we did not find a proper solution.

After reaching this conclusion our attention turned to solar photovoltaic systems. A nearby city (Brownsville) was listed in Tables of Solar Insolation by City[9] with a yearly average of 5.0 kWh/m²/day. This flux would guarantee the daily operation of the PV system, with the advantage of ease of installation on the rooftop of the Engineering building, with a small maintenance burden.

As we know solar PV technologies have evolved from silicon to flexible thin film, and to multiple band gap semiconductor third generation cells. Facing the need to choose from these technologies, we valued most to find a local provider which could deliver a turn-in-key system. Our choice was to start with a simple PV system, the ENGR fixed PV array.

4- Experiments / Learning Materials

4.1- Day length calculation and monitoring

Standard texts on Solar Energy[10] include a Chapter on how much sunshine is available. In this exercise the students will learn how to calculate the solar position at any time of day, and consequently sunrise and sunset times.

The ENGR PV array main inverter (Sunny Boy 5000) outputs a daily file thru the Internet- www.sunnyportal.com condensing the activity of the device starting with the morning call and ending with the good night call. For every day of the academic semester students will log in their calculation and the Sunny Boy reports in Figure 3.

4.2- Current Voltage Characteristic curve of low power modules

This experiment is performed using System 3 of Table 1. Rooftop placed modules can be wired to a two-pole disconnect in the Energy & Power System Lab, with a 120-ft feeder made of 2-6, 1-10 AWG copper conductors in conduit tube. The curve can be obtained with two different methods:

A) Manual- Using two 150 Watts rheostats, 0-10 Ω and 0-100 Ω, as well as voltmeter and ammeter. Several points of the characteristic are plotted, including the open circuit voltage and short circuit current. Since this procedure takes several minutes, no attempt is made to correlate the plot with the insolation.

B) Automatic curve tracing. At least two students participate in this experiment, using their cell phones. Student A on the rooftop is measuring normal solar radiation to the module, with instrument 4 of Table 1. Student B at the workbench of the E&PS Lab is running the

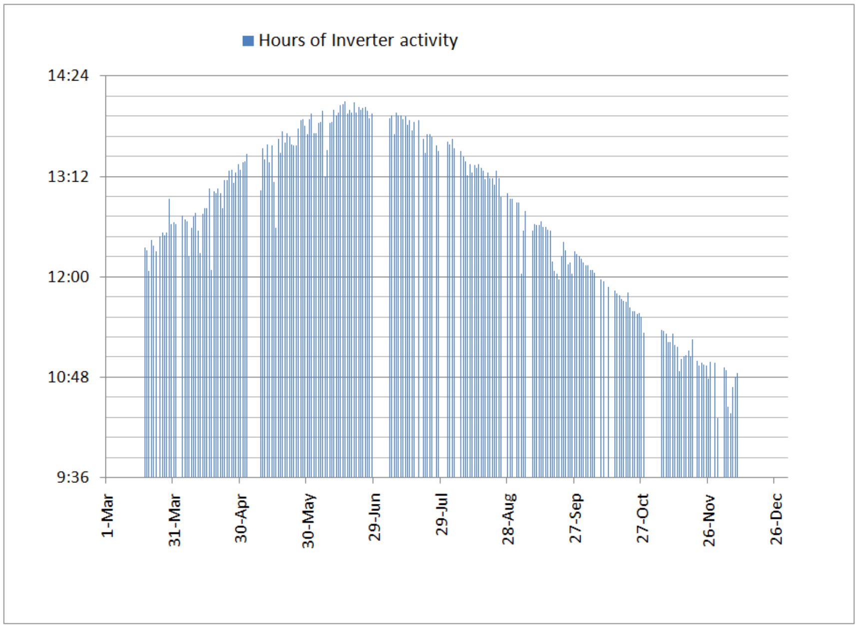

Figure 3- Day Length according to the SMA inverter report

oscilloscope and recording *I V* signals in channels 2 and 1, Figure 4. The module positive terminal is connected to the collector of a 115 W npn bipolar transistor. From the emitter, a small resistor- 0.25 Ω- is used as a current voltage converter. The base of this transistor is driven by in a Darlington configuration by a ramp voltage, driving the solar module from open circuit to near short circuit. Digital oscilloscope can plot the characteristic curve, and also produce CSV files, which on further analysis, will yield Excel graphs, such as the one shown in Figure 5**.**

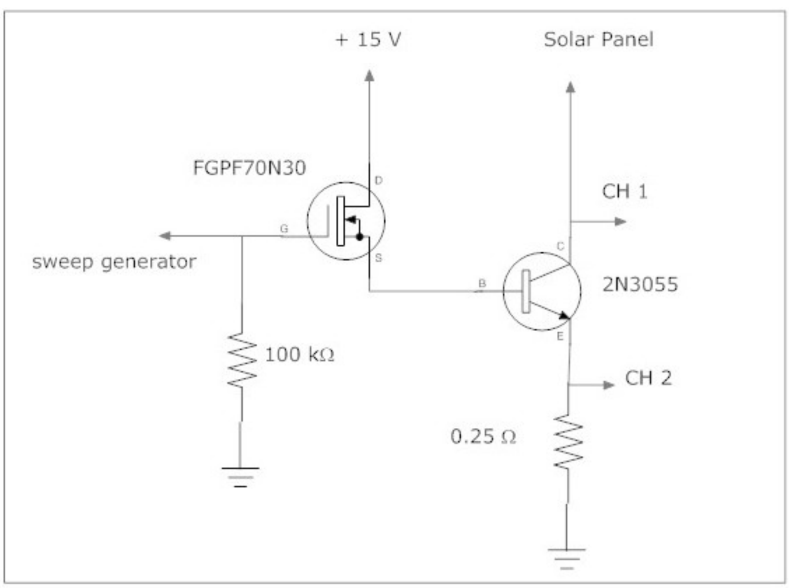

Figure 4- Schematic of transistor circuit to scan the solar module characteristic

This experiment has several important outcomes:

A) correlate the *I V* graph with insolation

B) correlate the curve with the solar trajectory and the module orientation.

C) Obtain maximum power point; introduce the concept of MPP tracker

D) Obtain an estimate of the module´s efficiency.

E) Discuss alternative method to measure short circuit current.

F) Train students on the installation and operation of series/parallel combination of modules.

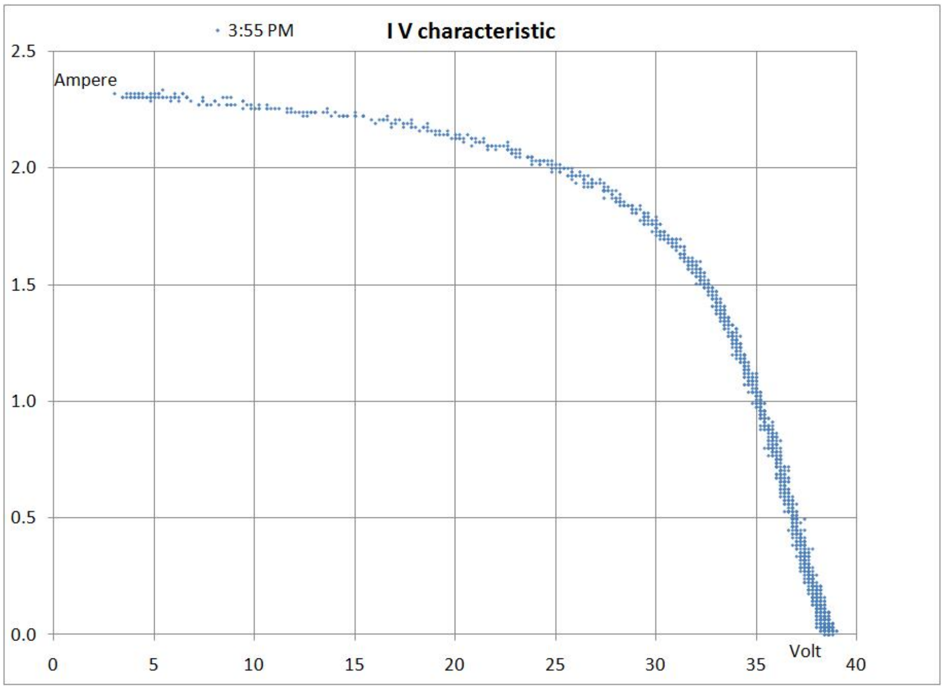

Figure 5- Single Panel Characteristic graph obtained with electronic sweep

4.3- Battery Storage Amp-hours calculations

This experiment and the next one are performed on the fixed ENGR PV array. A schematic of the components which integrate this system is shown in Figure 5. This system is endowed with 3 sets of current and voltage sensors, located in three buses: # 1, at the array, # 2, at the battery, and # 3, at the load. A data acquisition was put into use, with 6 analog to digital differential channels to monitor and store these electrical variables. Usually, samples are taken every second, and their averages are stored every 5 minutes (300 seconds).

Further calculation of power, energy and charge can be done and displayed using usual software. Figure below shows the charge and discharge cycles for several days. Additional outcomes of the experimetn are:

A) observe the various types of charging modes.

B) Discuss instrumentation or measuring problems.

C) Observe charge controller set points

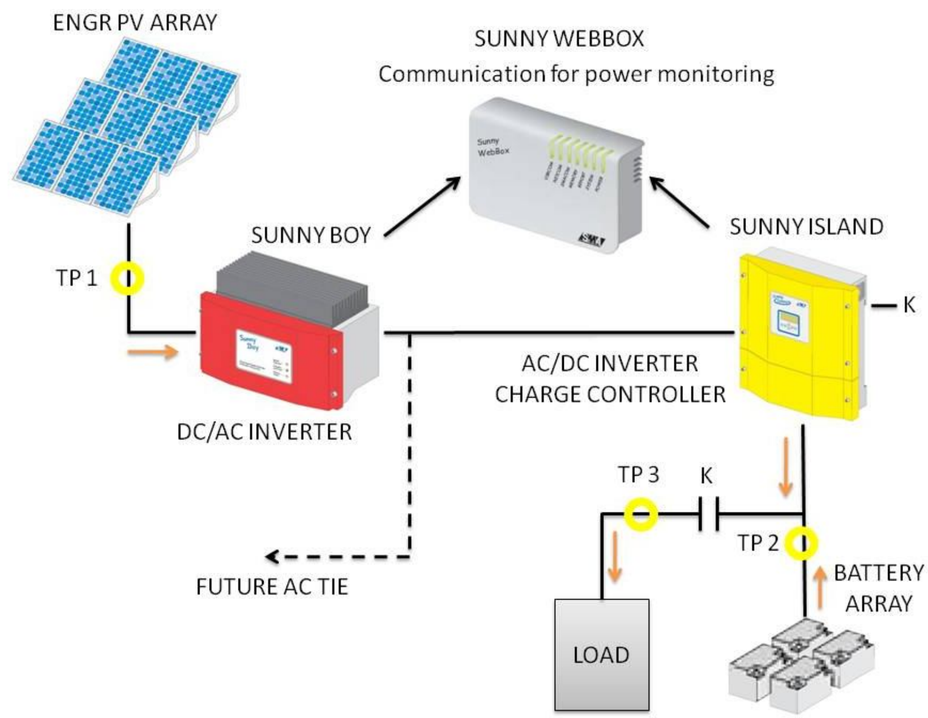

Figure 6- ENGR fixed PV Array schematic showing major subsystems

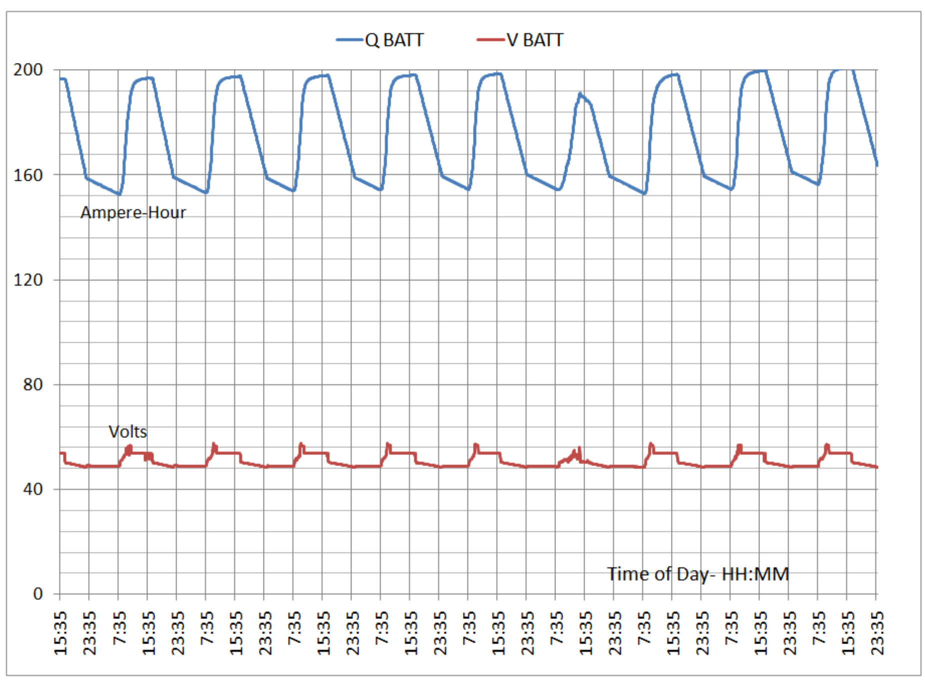

Figure 7- Battery nine-day charge and discharge cycle (December 2010)

4.4- Battery Energy Balance kWh Calculation

The basic equation is the time derivative of the energy dw/dt = p(t), which can be integrated to $\int P_{PV}\,dt + \int P_{BATT}dt = \int P_{LOAD}dt$

p(t) being the electric power = v(t) i(t). These integrals can be numerically performed using time intervals of 5 min. In such manner the graphs of Figure 8 can be produced. They show the amount of PV energy generated, and energy consumed at the battery and load. The student will be able to estimate the efficiency of the electronic inverters.

4.5- Capacity Factors

The presence on campus of two PV arrays of similar power, but different tracking characteristics is a good opportunity for the student grasp the concept of capacity factor, C. A usual definition for C = kWh produced / (kW Nominal * Hours). The relevant data can be obtained from the web services embedded on the fixed array [3] and tracking [4] inverters.

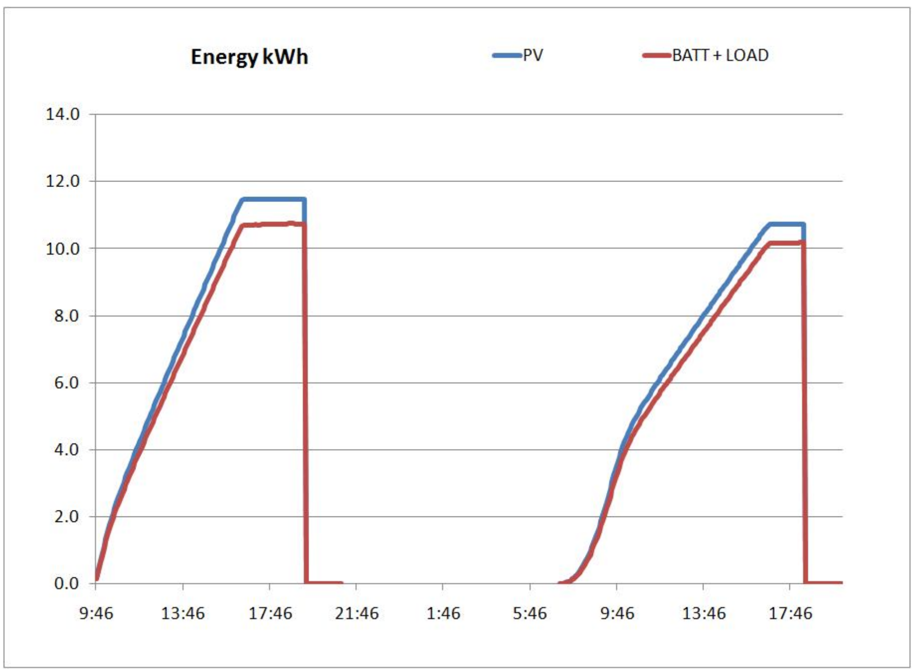

Figure 8 - Energy balance in the ENGR fixed PV array

Table 3- Capacity factor for two arrays, during November 30th, 2010

Array	Production kWh	Max Power kW	Capacity Factor
1- ENGR PV fixed array	10.24	2.73	8.23 %
2- TXU Sun tracking array	30.54	4.53	23.0 %

4.6- Commissioning the ENGR fixed PV array

A data acquisition system was put into use, with 6 analog to digital differential channels to monitor the voltage and current of those points 1 (array), 2 (battery) and 3 (load), according to Figure (1). Currents were measured with Hall effect sensors, and voltages with simple resistive divider circuits.

As we developed trust in our instrumentation a good test is to verify the compliance with Kirchhoff current law.

$$I_{\text{charge controller}} + I_{\text{batt}} = I_{\text{load}} \quad . \qquad (1)$$

Equation (1) was tested in two cases: $I_{load} = 0$ and $I_{load} > 0$. The oscillograms in Figures 9 and 10 are evidence that our methods are devoid of fundamental errors.

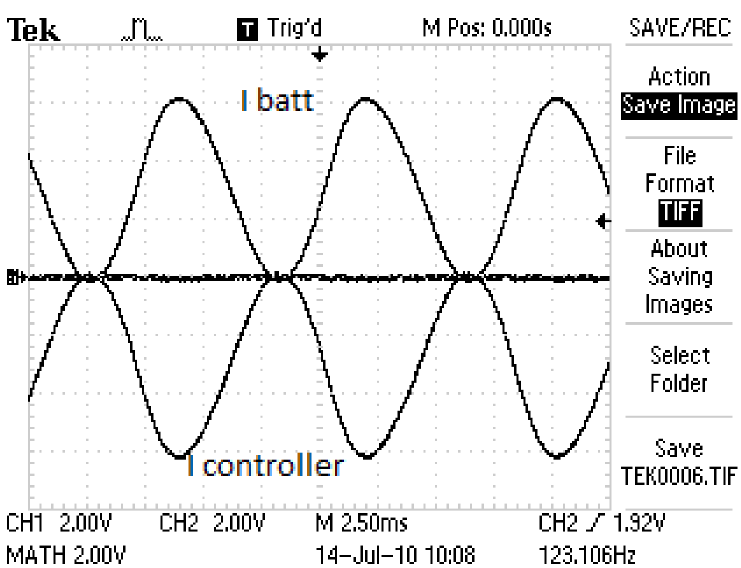

Figure 9. Battery and controller's currents showing 180 phase difference when $I_{load} = 0$.

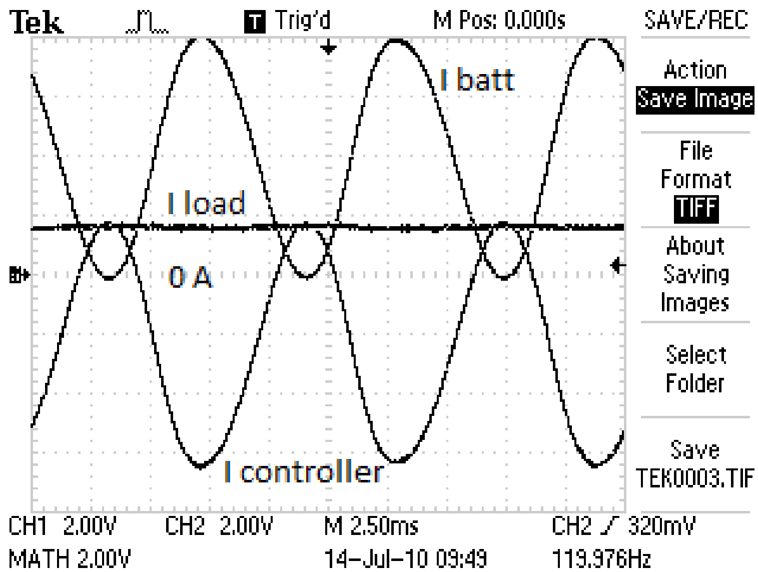

Figure 10. Battery and controller currents make up to I_{load} =19 A.

As I_{load} is fairly constant, or slowly varying, the variation of battery current will be determined by the variation of the controller current. Figures 9 and 10 show a strong second harmonic component. Presently there is no element in the system to eliminate that harmonic content, therefore to monitor the current during daily periods 5-minutes averaging methods were adopted, in particular mean and rms values.

Other main measurements at the selected points in Figure 6 are their voltages. We have used simple resistive dividers, designed with outputs in the range of 5 Volts, which are suitably handled by the data acquisition system.

Students will design voltage divider circuits and make experiments for their calibration, as well as Hall effect current sensors.

5- Integration to curriculum

The Energy studies option at the EE Dept in UTPA is formed with the following set of courses:

a. ELEE 4333 Renewable Energy
b. ELEE 4372 Electric Machinery & Power Systems Fundamentals.
c. ELEE 3371 Electric Power Systems Design & Applications (Buildings)
d. ELEE 3370 Power Electronics

The equipment and systems developed in this project will enable UTPA to support this string of courses, and make a better course curriculum for ELEE 3370 Power Electronics. The DC power source from the ENGR PV array will enable a variety of lab tests and experiments for the students.

All experiments described in Section 4 require a basic knowledge of electric power topics. Students will benefit from previous work with basic instruments for voltage, current, power and diagrams. Experiment 2B about *I V* characteristics requires knowledge of electronics circuits, and it would be possible to introduce the concept of transistor as switch to compensate for a lack of study. UTPA is now offering ELEE 4333 Renewable Energy as an elective course for juniors and seniors. All the learning tools described in this work will be useful, in particular for power generation and system integration of solar technologies.

6- Collaborative Research, Technology Transfer and Student Evaluation

The equipment and systems developed in this project is enabling joint collaborative research activities in the area of smart grid and security, involving researchers from the data networking field. Research proposals for joint collaborative research, in the area of smart grid, have been submitted to funding agencies at the state and national level, such as National Science Foundation.

There are two campuses of The University of Texas in the Lower Rio Grande Valley: at Brownsville and at Edinburg, with similar sunshine characteristics. These two campuses of UT are active in writing joint educational proposals[11] with the objective of developing and sharing learning tools in the Renewable Energy field.

The general educational outcomes of the EE program in UTPA are, concisely written: 1- use math, 2- make experiments, 3- design equipments, 4- do team work, 5- communicate ideas, 6- be responsible, 7- lifelong learning, and 8- computer literacy. Student's working on these experiments can develop further these abilities. Assessment of these outcomes will be done by the inclusion of pertinent questions in Lab handouts.

7- Conclusion

Given the current interest in the integration of solar technologies to the electric utilities, and the lack of teaching materials in this area, UTPA has developed six laboratory experiments on PV solar technology topics. The experiments use software and hardware tools available by two PV arrays constructed on campus. The experiments are designed to be conducted by triplets of students in two hour laboratory sessions.

8- Acknowledgements

This work has been possible in part by the generous gift of TXU Energy, Dallas Texas, who have funded the TXU Sun Tracking Arrays.

This material is based upon work supported by the Department of Energy under award number DE-EE0004007.

References

1- R. W. Wies, R. A. Johnson, John Aspnes, "Design of an Energy-Efficient Standalone Distributed Generation System Employing Renewable Energy Sources and Smart Grid Technology as a Student Design Project." POWER ENERGY SYSTEMS GENERAL MEETING 2010- GM 1450

2- Gregory F. Reed, William E. Stanchina, "Smart Grid Education Models for Modern Electric Power System Engineering Curriculum." POWER ENERGY SYSTEMS GENERAL MEETING 2010- GM 0775

3- Marija Il'ic. "Teaching Smart Grids: Yet Another Challenge and Opportunity for Transforming Power Systems Curriculum." POWER ENERGY SYSTEMS GENERAL MEETING 2010- GM 1376

4- Sunny WebBox Web Enabled Data logger & Controller for Alternative Energy Systems. 2005 SMA America Inc. http://129.113.130.242 (not public).

5- http://siteapp.fatspaniel.net/siteapp/simpleView.jsf?eid=553237.

6- B Prokoski, et al. "Making microgrids work" IEEE power & energy magazine, May/June 2008, p41

7- J. Driesenm F. Katiraci. "Design for Distributed Energy Resources". IEEE power & energy magazine, May/June 2008, p30.

8- http://www.tceq.state.tx.us

9- Gilbert M. Masters- Renewable and Efficient Electric Power Systems. Wiley Interscience, 2004.

10- M Iqbal. An Introduction to Solar Radiation. Academic Press 1983.

11- University of Texas at Brownsville and University of Texas Pan American. South Texas Initiative. Energy & Environment Subcommittee. Report, June, 2010