Photovoltaic Power Systems
An Undergraduate Electrical Engineering Senior Elective Course

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ABSTRACT

A 3-credit, undergraduate elective course in photovoltaic power systems was developed and taught during the spring, 1995, semester. A revised version was then offered during summer, 1996, and the third offering was during spring, 1997. The objective was to create a course which would stimulate the interest of electrical engineering students in photovoltaic power production, while concurrently challenging them to explore alternate solutions to an assortment of design problems with an emphasis on computer use. Since organizations such as the Florida Solar Energy Center[1] offer courses in PV system design at the turnkey/technician level, and since it is possible to purchase a variety of turnkey systems, the challenge was to put enough “meat” into the course to be able to justify it as a senior electrical engineering elective course. The key was to create a course in which students would learn enough engineering principles to enable them to apply discretion in system design.

COURSE PROGRESSION

A modified top-down approach was used in the progression of the course. Sun parameters were discussed for the first two weeks, followed by three weeks of performance characteristics of PV system components. In order to lay the final groundwork for system design, life cycle costing was discussed next. With the design tools in place, six weeks were spent on design of a wide variety of systems. The remainder of the course covered environmental effects of electrical generation technologies and the physics of various PV technologies, with an emphasis on PV cell design considerations for maximization of PV cell performance.

Markvart[2] presents a good discussion of sun parameters. After the first lecture, which presents a summary of present global energy use, sources and challenges, such as reducing CO_2 production, attention is turned to quantifying the observation that the sun rises in the east and sets in the west at different times on different days at different latitudes. Black body radiation is discussed and why a 6800 K blackbody should make 1367 watts/m^2 available at a distance of 93 million miles is assigned as a computational problem. Air mass absorption and dispersion effects are discussed as formulas for direct, diffuse and reflected components of sunlight are presented. At the end of this section, students have an appreciation that someone has spent a lot of time developing a set of involved formulas based on solid geometry and a significant amount of empirical data, and have a more quantitative feeling for the amount and composition of sunlight available at various locations during various times of the year.

PV system components are discussed next from an applications perspective. Cell I-V characteristics are presented along with their dependence upon irradiance and temperature. Fill factor and cell power production efficiency are then discussed. Cells are then connected to form modules and modules are connected to form arrays. Arrays are then connected to controllers, inverters and other power conditioning equipment, and battery characteristics are discussed. Finally, one period is spent on the time value of money, with emphasis placed on the fact that predicting the future is an interesting and important guessing game when system alternatives are explored.

Then comes the system design part of the course. The Sandia Manual[3] presents a collection of design examples ranging from a direct coupled d-c fan to a hybrid residential system. In this part of the course, as the design examples are presented, emphasis is placed on alternate designs. In all of the designs, the problem is to collect enough watt-hours from the sun to meet the watt-hour requirements of the system loads plus system losses in the most cost effective manner. The discretionary part of the process includes determination of the specific PV modules to use; the battery type, size and voltage; the number of storage days; the type of controller; the most cost effective loads; whether to use dc, ac or a combination; whether to use generator or grid back-up; choosing a suitable system voltage and sizing the system wiring to minimize wiring losses.

A nice feature of the Sandia Manual[3] is that it contains worksheets for calculation of the load, the array size and tilt angle, the battery needs, protection components, wire sizing, seasonal derating, pump sizing, hybrid determination, hybrid component selection, economic analysis, controller specification, power conditioning equipment specification, water pumping load calculation and equipment sizing and worksheets to determine proper equipment choice for cathodic protection systems. The worksheets are generally in the form of spreadsheets, so many students choose to incorporate the worksheet format into their own computer spreadsheets to make it easier for them to change design parameters and immediately observe the outcomes of their design choices. While working through the design examples, special attention is paid to the reasoning behind the worksheet entries, so students will understand the origins of default values. They are then able to decide whether default values are appropriate for specific designs.

At the conclusion of the design portion of the course, students should be able to design a variety of systems and should be able to make design choices to achieve the best system life cycle costs.

The design portion of the course establishes the importance of obtaining highly reliable components at the least possible cost. At this point, sufficient interest in the systems should have been developed to make the discussion of PV physics more palatable, perhaps even interesting. The equation for diode current is presented and then the parameters which determine the photo current and reverse saturation current are discussed in the context of maximizing the ratio of photo current to reverse saturation current to maximize the cell open circuit voltage, and, hence, the cell power production. Design of the cell to minimize resistive losses and the trade-offs between resistive losses and power generation are discussed.

Following the general discussion of cell optical and electrical behavior, specific cell technologies are discussed, including single crystal silicon, poly silicon, thin film silicon and other thin film devices, with an emphasis on electrical and optical properties of the materials as well as a look at factors which affect the expected lifetimes of the various cell technologies. Markvart[2] presents some material on cell physics, but other solid state electronics texts[4,5] have been used as supplements to the material in Markvart.

HOMEWORK

Taking the existence of good homework problems for granted is easy when one teaches out of textbooks such as Nilsson and Riedel[6] or Sedra and Smith[7] . Although Markvart has good study questions, the book does not contain the typical analysis or design problems to which the engineering educator has become accustomed. It was thus necessary to develop a set of homework problems which followed the course progression and which challenged the students to meet the learning goals of the course.

The first set of problems focused on those properties of sunlight which were considered to be of greatest relevance in the understanding of PV system performance. A particularly interesting problem is to use the Planck blackbody radiation formula to determine the solar constant (1367 W/m^2). The formula is sufficiently nasty to justify numerical integration over all wavelengths and sufficiently subtle to challenge the student to realize that zero to infinity really means a range of a few micrometers. It also presents a nice analog to the electric field problem associated with a spherical charge and its $1/R^2$ dependence. Another interesting problem is to have the students calculate the number of daylight hours on their birthday in the place where they were born. Other interesting tabular computations, convenient for setting up on a computer, involve the generation of tables of beam, direct or total radiation vs. latitude and date.

Problems to acquaint the student with cell operation are then given. It is especially important for the student to be able to identify the trade-offs, such as when the sun shines brighter, the photocurrent increases, but cells heat up and the open circuit voltage drops.

Then a battery of battery problems is assigned. Problems explore the effects of rate of charging and discharging, temperature effects, depth of discharge effects and characteristics of various types of batteries. Several problems explore the concept of maximum power tracking as irradiance changes and then a few examples of life cycle costing are assigned.

The students are now ready to test their skills at system design. The first design problems involve relatively simple water pumping and d-c refrigeration systems. The water pump has no battery storage, but must be properly sized. The refrigeration system needs battery backup for critical operation. Then an outdoor lighting system is assigned where the students need to perform illumination calculations in order to determine lamp wattage, battery size, and array size.

As a final project, the students design the complete PV system for a mountain cabin located in the mountains of their choice with the loads of their choice and occupancy pattern and system availability of their choice. Students are encouraged to browse the Web to locate PV equipment distributors and to obtain specifications and prices for system components.

The results of the first term included system locations form Nairobi, Kenya to Shanghai, China, to the Pocanos with system life cycle costs ranging from $3,060 to $21,693. The next term, students interpreted “mountain” somewhat more liberally, with one system located at the seashore.

Computer use is encouraged on all design problems. Students are especially encouraged to either set up their own spreadsheets based on the worksheets in the Sandia Workbook[3] or to write their own programs in a scientific language to perform the calculations. The availability of computer worksheets encourages students to experiment with a variety of design configurations to determine the most cost-effective system to meet the design guidelines.

EXAMS

Two mid term exams and a final exam are given. They are open book and open notes and focus on the homework problems. The first exam follows the discussion of solar parameters and system performance, so the exam tends to be analysis oriented. The second exam, however, follows the system design portion of the course, and thus the exam tends to consist of a single, rather comprehensive, design problem, which involves selection of PV modules, batteries and controllers, based on stated loads and location. The final exam is twice as long and comprehensive, with design and analysis components.

SUMMARY

The goal of the course was to stimulate student interest in PV systems design. Evidence that this goal has been achieved is found in the number of capstone senior design projects which have been related to PV systems since the course has been offered. It is particularly encouraging that some of these designs are being put to serious use, such as a water pumping system for a remote area of Haiti and a PV powered fountain which one student has given to his parents as a thank you for their support of his education. Several nicely designed battery charge controllers have also been implemented and the various controllers discussed serve to create an appetite in some students for power electronics. Even though PV power production remains a very small percentage of total electrical power production, and few of the students will actually end up working with PV systems immediately after graduation, the course still serves to challenge the students to think about alternative system designs and life cycle costing, which is useful background for any area of system design.

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