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A 50 KILOWATT DISTRIBUTED GRID-CONNECTED PHOTOVOLTAIC GENERATION SYSTEM FOR THE UNIVERSITY OF WYOMING

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ABSTRACT

The University of Wyoming (UW) campus is serving as the site for a 50 kilowatt solar photovoltaic (PV) system. Three sub-systems were sited and built on the UW campus in 1996. The first sub-system, a 10 kW roof-integrated system of PV roof tiles is located on the roof of the Engineering Building. The second sub-system - a 5 kW rack-mounted, ballasted PV system is on a walkway roof of the Engineering building. The third sub-system is a 35 kW shade structure system and is located adjacent to the parking lot of the university's football stadium. The three sub-systems differ in their design strategy since each is being used for research and education at the university. Each sub-system, being located at some distance away from one another, supplies a different part of the campus grid. Efforts continue at setting up a central monitoring system which will receive data remotely from all locations. A part of this monitoring system is complete. While the initial monitoring data shows satisfactory performance, a number of reliability problems with PV modules and inverters have delayed full functionality of the system.

1. INTRODUCTION

Worldwide, more than 50 megawatts of PV power have been installed in the past decade, mostly for remote applications. The PV market is developing very fast, particularly in developing countries where remote electricity use is increasing. In remote, stand-alone applications, PV has been applied toward pumping water, refrigeration, desalination, lighting remote villages, powering telecommunication equipment, for railroad signals, charging batteries, etc. On the other hand, supplying the electric utility grid from PV sources is also becoming a reality with numerous utility companies already experimenting with innovative customer-oriented programs to generate interest in this form of renewable power [1]. It is strongly believed in the PV community that a significantly large market exists in electric utility systems [2]. However, there are many issues that will need to be resolved before PV becomes an integral part of many utility companies. Some of these issues are cost/economics, reliability and performance. To this end, the University of Wyoming's Electrical Engineering department has embarked on a multi-year, multi-agency project to identify some of these core issues and make strides toward viable solutions of problems. The purpose of this paper is to report on the project's performance thus far.

1.1 PV versus conventional power

Although, PV is not a new technology, it is only recently being considered seriously as an alternative to conventional power generation. There are still many questions that need to be answered, the most important of which is cost. However steady progress is currently being made toward making module manufacturing more cost-effective. PV costs have actually fallen from $100/watt to $5/watt since 1980, with continued cost reduction efforts underway. However, in order for PV to be competitive, the cost has to drop to close to $3-$4/W before it can compete with conventional generation. Besides cost, there are other issues that have to be addressed. Cell efficiency is another hurdle that has to be overcome. The highest efficiencies of crystalline silicon solar cell conversion hover around 10%-18%. Other cell materials provide even less efficiency. Yet, these efficiency figures continue to increase in the laboratory environment and will eventually make its way to the market. Other issues exist: these are, presence of harmonics, a reliable storage technology -- with a good storage mechanism, PV would become more valuable to the electric utility, control aspects -- i.e. having PV power when one wants it. This may not always be possible since PV power depends on sunshine. Other technical issues are reliability and system security.

2. DESIGN AND CONSTRUCTION

PowerLight Corporation of Berkeley, California served as Design/Builder (turn-key system integrator) on the contract. Three sub-systems were sited and built in 1996. The first system, a 10 kW PowerGuard system of PV roof tiles, was sited on the Petroleum Engineering Building of the University. The second system was a 5 kW rack-mounted, ballasted PV system sited on a walkway roof of the College of Engineering building. The third system was a 35 kW shade structure system which was located adjacent to the parking lot for the football stadium.

2.1 PowerGuard™ Photovoltaic Roofing Sub-system

PowerGuard™ is a PV roofing technology which provides multiple benefits as a protected membrane roofing assembly. PowerGuard™ serves as a barrier that insulates the roof and protects the roofing membrane. It incorporates high efficiency PV modules backed with 3" of Styrofoam® brand extruded polystyrene foam, as shown in Fig. 1. It provides additional R10 insulation for improved building thermal performance and increased comfort, thus potentially reducing HVAC load at the site. The PowerGuard system was chosen for its light weight of 3.8 pounds/square foot since this roof could only accommodate a slight additional load. Fig. 2 is a photograph of the PowerGuard system.

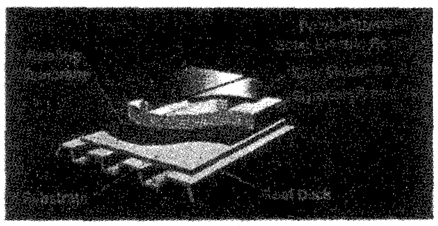

Fig. 1. A PowerGuard tile

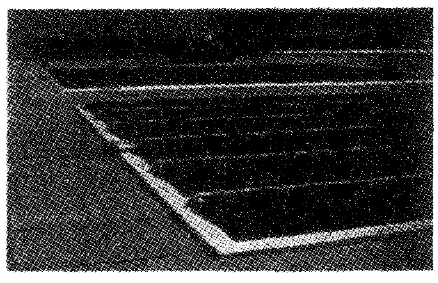

Fig. 2 The roof-mounted 10 kW PowerGuard system. Titled modules are in the foreground

There are a total of 96 PowerGuard roof tiles that have a combined rating of 10 kW(dc). The modules, made of crystalline Silicon cells and manufactured by Atlantis Corporation, are mounted on top of the tiles. Both horizontal and sloped PowerGuard tiles were used for comparative evaluation. Half of the rated capacity of PV tiles are oriented at a 12 degree south facing slope. With this small amount of tilt, about 10% more energy can be captured by these modules compared with the horizontally mounted modules. Table 1 gives specific system information on the two roof-integrated sub-systems.

The PowerGuard™ system requires no support structure other than the roof itself. No roof penetrations are required as the system is placed flat on the roof surface. The system was designed to meet or exceed UBC building code requirements. The system is secured against wind uplift through a combination of perimeter ballast and edge to edge interlocking which has been engineered and tested to strict standards.

2.2 PowerShade™ Photovoltaic Shade Project

The PowerShade™ structure is depicted below in Fig. 3. Each structure is 29'4" in length, has a foot print of 14' 6". Two single piers support the structure, which cantilevers about 5' off each end. Seven modular PowerShade systems of 5 kW each were constructed to provide coverage for the equivalent of 21 automobiles. The PowerShade system was constructed using 336 AstroPower modules which use large area, six inch square, PV cells configured in a prefabricated canopy structure. Beyond optimizing for minimum steel, the structure was designed for attractive aesthetics and easy access to wiring. The project is highly visible to the public with the majority of solar panels providing covered parking at the university's football Stadium. The PowerShade system thus serves as a shade structure as well as energy producer. This PowerShade project is the largest PV structure in the State of Wyoming.

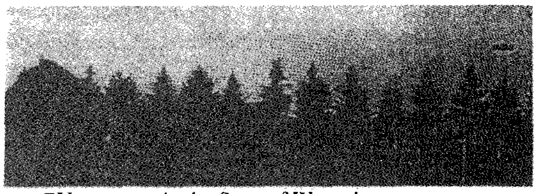

Fig. 3. The 35 kW PowerShade structure

2.3. The Rack-Mounted System

A 5 kW rack-mounted system was constructed on the rooftop of the University's Engineering Building. As with the PowerGuard system, the rack-mounted system did not require penetrations through the roof surface. The structurally engineered system utilized 35 pounds/square foot of ballast to withstand design wind loads up to 90 mph. The rack-mounted system features high-powered PV modules from ASE Americas. This system is shown in Fig. 4.

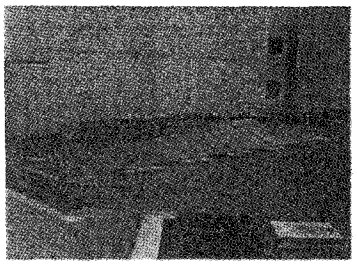

Fig. 4. The 5 kW Rack-mounted PV array

Table 1 gives a summary of specific system information on the sub-systems.

3. MONITORING SYSTEM

Remote data acquisition systems are being designed and implemented, within the EE department, for all three sub-systems. The 35 kW system, because of its longer distance from the department laboratory which contains the computer, presents a number of challenges. The data will have to be transmitted by remote telemetry to a central location in the Engineering building.

The photovoltaic monitoring system collects data, at regular intervals, from each of the three installations to provide performance analysis in the following areas:

1. DC Power output by the photovoltaic panels.
2. AC Power output by the power electronic inverters.
3. Total Harmonic Distortion of the AC output of the inverters.
4. Power Factor of the AC output of the inverters.

In addition, the solar insolation will be measured at two of the panel locations to provide a measure of the efficiency of the panels.

3.1 System Configuration

The monitoring system at each installation consists of two fundamental components:

1. The DAS (Data Acquisition System): a custom data acquisition system based upon the Motorola 68332 Business Card Computer. Signal conditioning and multiplexing is provided for DC voltages (up to +/-300V) and currents (up to +/-25A), as well as AC voltages (up to 170V peak) and currents (up to 50A peak) with passband to 3kHz and 60dB rejection at 10kHz. Simultaneous sampling of from four to twelve separate signals is possible, with effective sampling rates up to 29kHz.
2. The Communication/Control Software: C++ programs, written for Windows NT, which provide data collection, analysis, viewing and archival at each installation. Fig. 5 shows the display screen on the PC monitor of the data acquisition computer.

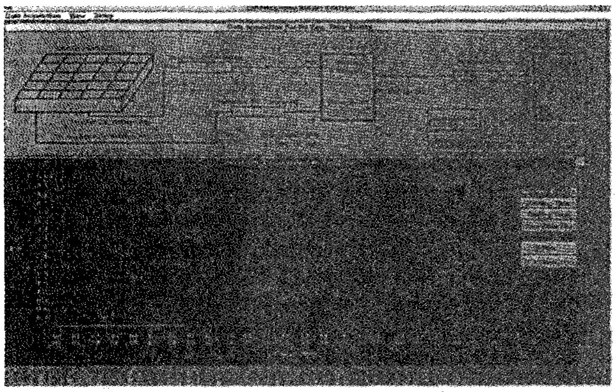

Fig. 5 The display screen on the data acquisition system

3.2 Scope of Measurements

The system as configured provides a great deal of flexibility, which is in-turn demanded by the variety of signal types measured at each installation. Each installation requires measurement of multiple dc and ac voltages and currents and one slowly varying voltage (proportional to solar insolation). The simultaneous sampling, fast sample rate, and lowpass signal conditioning allow for accurate measurement of power factor and total harmonic distortion of the inverter outputs. Panel and inverter efficiencies can be determined via simultaneous DC and AC measurements. These performance monitors provide the essential data for characterization of the PV effect at the grid input, and enable the use of intelligent power factor correction and harmonic filtering.

Table 1. Features of the three sub-system System

	Sloped PowerGuard	Flat PowerGuard	35 kW PowerShade	5 kW Rack-mounted
Modules power	83.2 W	187 W	106 W	285 W
Module Voltage	22.1 Voc	49.4 Voc	20.7 Voc	62 Voc
Module Current	5.5 A	5.5 A	6.6 A	5.7 A
Modules/String	12	6	12	4
No. Strings	6	4	4	4
String Voltage	265.2 V	296.4 V	248.4 V	248 V
String Current	5.5 A	5.5 A	6.6 A	6.2 A
PV Vendor	Atlantis/Sharp Cells	Atlantis/Sharp Cells	AstroPower	ASE Americas
Inverter	Omnion 2400 Series	Omnion 2400 Series	Omnion 2400 Series	Omnion 2400 Series

3.3 Practical Lessons Learned in Data Acquisition

Various parameters of the monitoring system have undergone substantial scrutiny during this initial phase of installation.

- Measurement system calibration has been completed in a "full signal path" form, which incorporates all elements of the specific measurement channels. This step, which includes the effects of signal transducers as well as current shunts and voltage dividers, has greatly improved measurement accuracy.
- Careful selection of sampling rate has proven to be critical to accurate measurement of the total harmonic distortion. The discrete Fourier Transform (in an FFT form) has been implemented for power spectral determination. To minimize leakage and smearing between frequency bins, both the sampling rate and total number of samples of the AC voltage and current channels have been fine-tuned.
- Full sampling of each instrumented installation has been carried out at five minute intervals, leading to a wealth of data. As demonstrated in the plots of inverter power in the next section, this frequency allows for the capture of some of the salient features of the PV system behavior, in particular the effects of party cloudy atmospheric conditions, typical of the Laramie area. However, each data record is fattened substantially by the raw data requirements for harmonic distortion analysis. To lessen the unwieldiness of the archival process, data reduction methods are being investigated.

4. EVALUATION OF SYSTEM PERFORMANCE

This section presents some of the information gathered on the performance of two of the three sub-systems. The third sub-system - the 35 kilowatt PowerShade system - is not being monitored as yet since the monitoring equipment is not in place yet. Figure 6a show the ac power output on June 25, 1997 from the 5 kW rack-mounted PV system. Fig. 6b shows a plot of the total harmonic distortion (THD) present in the ac power output of Fig. 6a. As seen from this figure, the THD is at or below the acceptable limit as recommended by IEEE 519-1992.

Similarly, Fig. 7a and 7b show the ac output power and the THD respectively from the same system for another day. This day was partly cloudy in the morning and changed to clear condition as the day progressed. The ac power output reached 4 kW on this day. From the THD graph, one can see that the harmonic distortion worsens when the ac power reaches more than 3.8 kW. Figures 8a and 8b show similar quantities for the sloped PowerGuard roof-integrated system. The THD for this system seems to be within the IEEE recommended limits most of the times.

4.3 Maintenance and Reliability

Two out of the three sub-systems have experienced some failures on both the dc and the ac sides. These are listed below:

- ♦ Glass laminate fracture on two modules at the 35 kW PowerShade structure. The nature of the breakage leads us to believe that the modules were not able to withstand severe weather conditions. Some other modules are also beginning to bend at the sides.
- ♦ Two inverters at the PowerShade site were damaged by the water sprinkler system on the ground. Water seeped into the inverter boxes and damaged the electronic circuitry. Both inverters were under warranty and were replaced.
- ♦ After 9 months of successful operation, the inverter at the 5 kW rack mounted system failed to turn on. The control board was replaced.
- ♦ After 1 full year of operation, the step down transformer at the same location became overloaded and the windings were damaged. The transformer is awaiting replacement.

5. CONCLUSIONS

The project is proving to very useful from a research standpoint. It is providing beneficial information on performance of PV systems in different orientations in Wyoming's unique weather conditions. At this PV site located about 7,200 feet above sea level, the weather can go from extremely bright conditions with many hours of sunshine in the summer to very cold and short days in the winter. Hence, the performance can vary over a wide range.

- ♦ All monitored performance data from the three distributed PV sub-systems are displayed centrally on a PC screen to accommodate easy access.
- ♦ We are starting to obtain useful data and information on the operation of the PV system. Both the power factor and the harmonic content of the ac power converted from the array dc output are within acceptable limits as long as the power output is above 50% of rated. Below this threshold, both quantities begin to deteriorate.
- ♦ A power factor correction control scheme is currently being put in place. A Programmable Logic Controller-based capacitor switching scheme is being investigated. The control will be initiated from the central computer location.
- ♦ Possible harmonic elimination schemes are being investigated.
- ♦ Some of the inverters from Omnion Power Co. that are being used with our PV systems have had problems and unexpected failures have occurred occasionally. This proves that newer designs of inverter with higher reliability are required for grid-connected operation.

The 35 kW array has experienced two module failures by glass laminate fracture. Vandalism is suspected. However, it is entirely possible that the fractures could have occurred due to excessive warping in the harsh winter weather conditions.

From an educational standpoint also, this project is generating interest among students. Graduate and undergraduate students are learning about distributed PV generation and its impact on the operation of the power grid, the economics involved, the technical problems encountered, their solutions, etc. Several high school students have also been exposed to this system during summer internships. The Electrical Engineering department will be introducing new courses that deal with renewable power production and environmental aspects of bulk power generation.

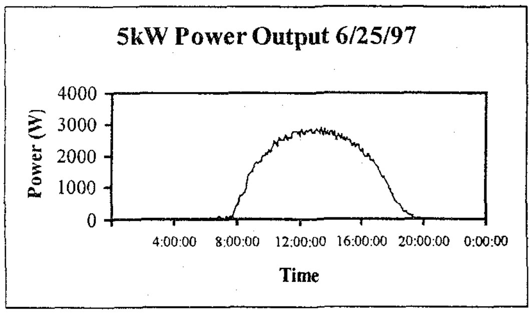

Fig 6a. Ac power output from the rack-mounted system

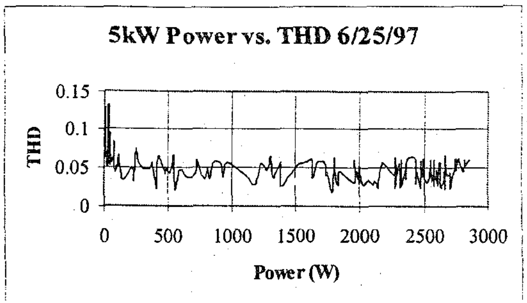

Fig 6b. THD of the ac power output

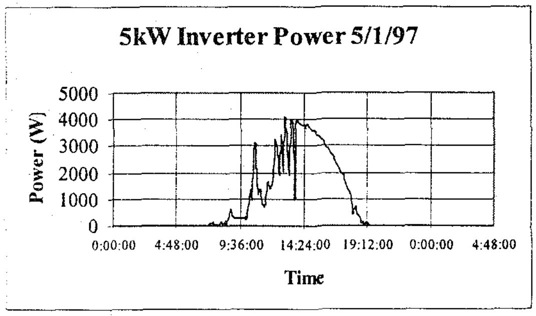

Fig. 7a. Ac power output from the rack-mounted system

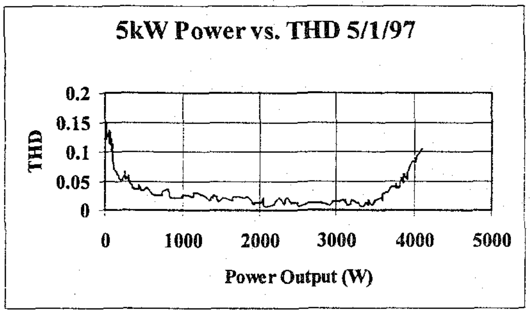

Fig. 7b. THD of the ac power output

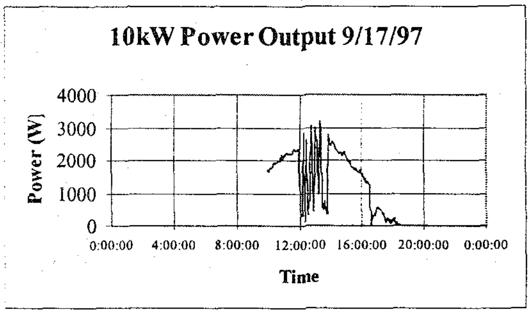

Fig. 8a. Ac power output from the PowerGuard system

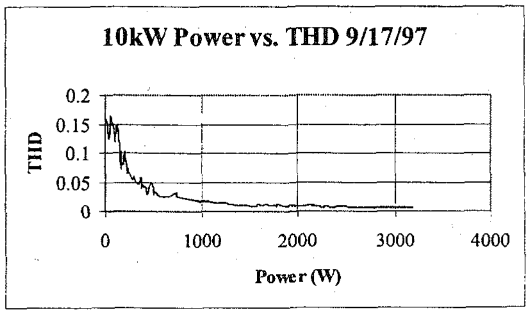

Fig. 8b. THD of the ac power output

6. ACKNOWLEDGEMENTS

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