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Field Tests of a PV-Powered Air Monitoring System

A compact stand-alone PV power system was recently designed and built to run an air sampler for environmental monitoring at the Nevada Test Site. This paper presents an overview of the system design and analysis of some of the recorded daily cycles of various power flows during the summer period. The system long-term performance during both high and low solar resource periods is simulated with the computer code PVFORM using historical weather data. [DOI: 10.1115/1.1562951]

1 Introduction

Off-grid photovoltaic electrical power systems are typically equipped with battery storage in order to provide power at night and during overcast days. One such application is at the Nevada Test Site (NTS) where continuous air monitoring systems are installed at several remote sites on which radioactive fallout was deposited by past nuclear tests. The air sampling is continuously conducted to assess the concentrations of radioactivity in airborne particles to assure that the air is in compliance with federal regulations.

The current stand-alone power systems consist of a PV array, a battery bank, a charge controller, an inverter, and a single-phase AC motor that drives the air pump. The PV array is composed of 60 modules, each rated at 56 W with a total peak power of 3.36 kW. Energy storage consists of eight units of 6-V batteries, each rated at 1400 Ah @ C/8 with a total capacity of 67.2 kWh. DC-to-AC conversion is performed by a modified sine-wave type inverter that is rated at 700 W and converts 24 DC to 110V AC. Finally, the inverter-induction motor-pump load consumes an average power of just over 300 W. These systems are quite large as the PV array covers nearly 34 m² and the batteries weigh over 3,600 kg. Meanwhile, the NTS operators expressed a need for a compact trailer-mounted system (so that it can be easily transported to different locations), but must maintain the same power availability as that of existing systems.

To meet the above need, a compact system that is half the size of current systems in terms of PV array area and battery capacity was designed and built this past Spring. This significant size reduction is reached by using a more efficient electrical load and by selecting the PV array area and battery capacity such that the unused solar energy is minimized. This paper describes this compact stand-alone PV system, and analyzes the daily cycles of some of its parameters including PV and battery power, DC bus voltage and battery State-Of-Charge (SOC) during the month of July, 2000. The long-term performance over several years is conducted through computer simulations using the computer code PVFORM and actual past weather data.

2 PV System Design

Actual measurements on one of the existing PV systems at the NTS show that over 45% of the 310 W supplied by the PV-Battery combination is wasted due to poor efficiency of the inverter, induction motor and pump used in the air monitoring system. Furthermore, the PV array is too large for the existing load as a 34-m² array generates over three times the daily energy demand. The same applies to the existing battery bank that stores over nine days of load energy. To reduce the power loss within the inverter and induction motor, a brushless DC motor is used in the new system to drive an efficient air pump. Such a motor is not only more efficient than the induction motor, but also eliminates the need for an inverter. It is estimated that such a replacement results in a continuous load demand of not more than 150 W, or a daily energy consumption (E_L) of 3.6 kWh.

Step-by-step procedures for sizing stand-alone PV systems are described in several sources such as Refs. [1–3]. With the load demand calculated above, the next step is to select an array that is large enough to furnish the amount of energy needed. The array size depends on several factors including cell efficiency, array position relative to the sun's path, and site-specific factors such as latitude and atmospheric conditions. Furthermore, the intensity and availability of sunlight including ambient temperature and wind speed which all affect the array's energy production vary throughout the day. There are, however, several rules-of-thumb that have been developed for approximating the daily average energy production of a given array size at different sites in North America [3–4].

A common rule is a multiplier Γ that represents the average full sun hours in each region. For the Southern Nevada region, $\Gamma \approx 6$ h [5]. The array size P_A (in peak watts) is found by dividing the daily load energy by this multiplier and battery average efficiency η_B . Finally, a safety factor S_f is often added to account for other system losses and sub-array shedding. Using a round-trip battery efficiency of 68% and a safety factor of 2, the array size is calculated to be

$$P_A = S_f \frac{E_L}{\eta_B \Gamma} \approx 1,760 \text{ W} \quad (1)$$

The above safety factor was chosen to be on the conservative side relative to those recommended by others (e.g., [3]) at the request of the PV system users.

The final step is to calculate the battery storage capacity. One needs to know the minimum allowed state of charge $\text{SOC}_{\min}$, the

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Fig. 1 1760 W PV powered air monitoring system

battery charge and discharge efficiency, and the number of days N the battery is expected to serve the load (starting from full charge) without recharge from the PV panels. For a minimum SOC of 20%, a discharge efficiency of 95%, and $N=7$ days, the battery rating E_B in Amp-hour (Ah) for a DC bus voltage V of 48 volts is

$$E_B = N \frac{E_L}{V \eta_B (1 - SOC_{\min})} \approx 690 \text{ Ah} \quad (2)$$

It is important to note that the above battery rating is at a very low discharge rate (i.e., over C/200), and it is valid only at temperatures within approximately $\pm 10^\circ\text{C}$ of room temperature (i.e., 25°C). This value reduces to around 610 Ah at a discharge rate of C/100, or to 29.3 kW-h on a 48-V system.

In summary, a PV array of 1,760 W (peak) and a battery pack of 610 Ah @ C/100 are expected to serve the 150 W constant load while meeting the power reliability requirements. In May 2000, such a system was built (see Fig. 1) using 14 PV panels each rated at 110 W, and four series-connected 12-V VRLA batteries each rated at 610 Ah. The load consists of a 48-V brushless DC motor that drives a pump that filters air at a rate of 3 cubic-ft/min (CFM) when the speed is set at 1,750 rpm. The system uses Amp-hour counting [6] for charge control, and it is equipped with a data logger which monitors battery and ambient temperatures, PV and load current, and bus voltage. The following section analyzes some of the data collected this past summer.

3 Analysis Of Recorded Data

The new system described above went through several tests to validate the performance of various components as well as the performance of the system as a whole. The system variables were sampled every 15 min for a period of several weeks, from mid June to mid August, 2000. The recorded currents and voltage are then imported to an Excel file for graphical analysis. Figures 2–5 show the power supplied by the battery, battery voltage, load power and PV output power, respectively. Figure 4 shows that the actual load (including the power requirements of the data logger and charge controller) fluctuates between 100–160 W, with an average value of less than 130W. This is due the voltage fluctuations between 48.5–56V as shown in Fig. 3. Figure 6 illustrates a typical daily variation in power produced by the PV array and power consumed by the load, since such details are hard to discern in Figs. 4 and 5.

Note that the PV array was disconnected from the system on July 13, at 6:00 p.m. to determine how many days the batteries will serve the load without recharge, and to verify the automatic load disconnect when the battery reaches a low SOC (corresponding to a voltage of 44.5 V). The load disconnected 7.5 days later

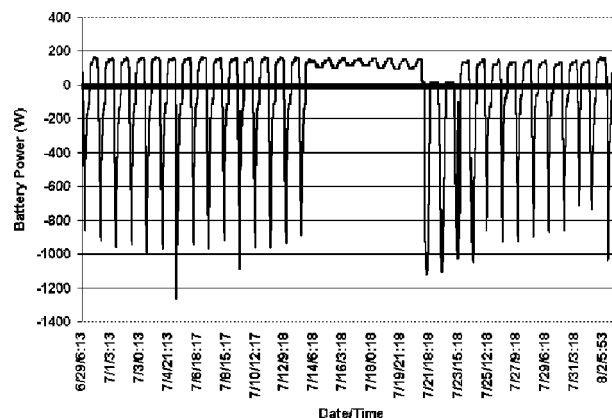


Fig. 2 Power supplied by battery (negative power corresponds to battery charging)

on July 21 as shown in Figs. 2 and 4, after which the PV array was reconnected to the system. The controller was programmed to reconnect the load after the battery regains its state-of-charge to 60%, and this took 2.5 days as can be seen in Figs. 2 and 4. The 15-W reading in Fig. 3, when the load was shut down, corresponds to the power consumption of the charge controller/data logger combination.

Figure 5 shows a nearly repetitive daily PV power production except for the day of July 23, 2000 which appears to be partly cloudy. The peak power production of less than 1,200 W indicates

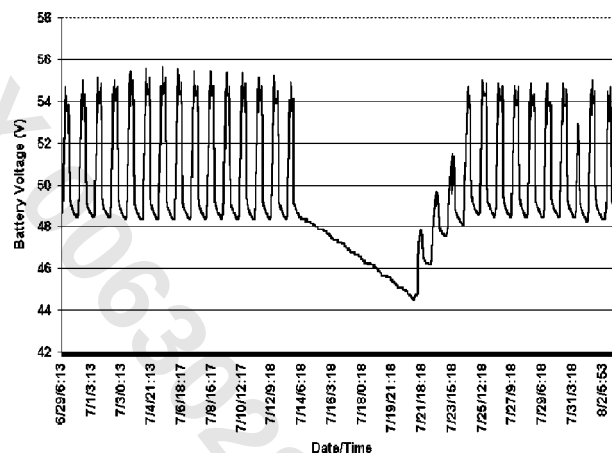


Fig. 3 DC Bus voltage

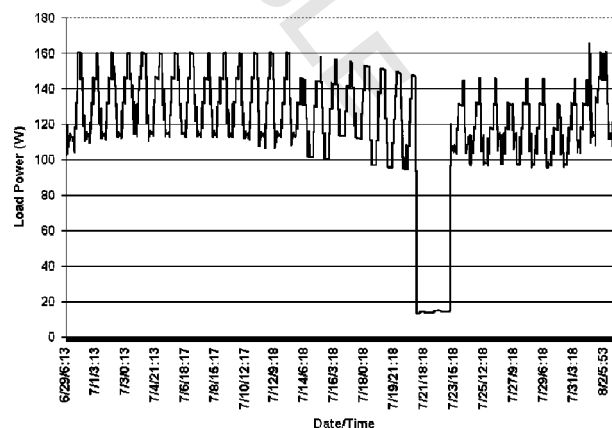


Fig. 4 Load power

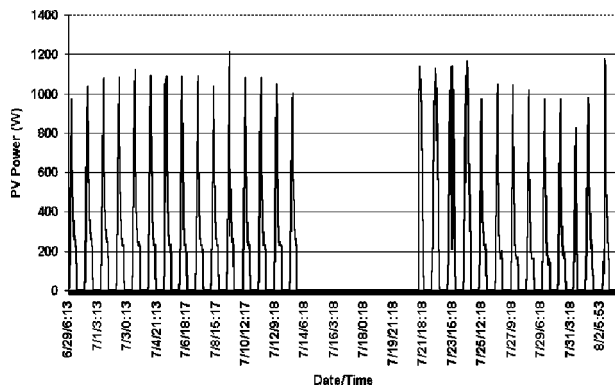


Fig. 5 PV output power

the that the PV array capability is not fully needed during this high solar resource period where the battery continuously operates in a high state-of-charge. It is likely that sub-array shedding is the norm rather than the exception during most of the sunny period except during the early and late afternoon hours where the entire array is expected to be turned on.

The voltage disconnect and reconnect set points for the two sub-arrays are 56.6–55.2 V, and 56.4–55.0 V, but it is important to point out that battery manufacturers rarely recommend similar values due to the industry's unfavorable feelings towards controlling charge through array shedding [7].

The battery state-of-charge is calculated by assuming that the battery efficiency η_B drops linearly from 90 to 10% as the SOC increases from 90 to 100% during charging [8], i.e.,

$$\eta_B = 8.1 - 8SOC \quad (3)$$

for $SOC > 0.9$ while charging. Otherwise, the battery efficiency is constant and equal to 90%. The SOC at time t is then calculated recursively by

$$SOC_i = SOC_{i-1} - \frac{\Delta t P_{Bi}}{C_B \eta_B} \quad (4)$$

where P_{Bi} is the power supplied by the battery during period i , t is the sampling period, and C_B is the battery capacity (i.e., 29.3 kWh). The resulting battery SOC is shown in Fig. 7 below. Note that the above assumptions resulted in a load rejection at a SOC slightly below the minimum value of 20%.

4 Computer Simulation

To analyze the performance of the PV system described above during low solar resource periods and yearly cycles, computer

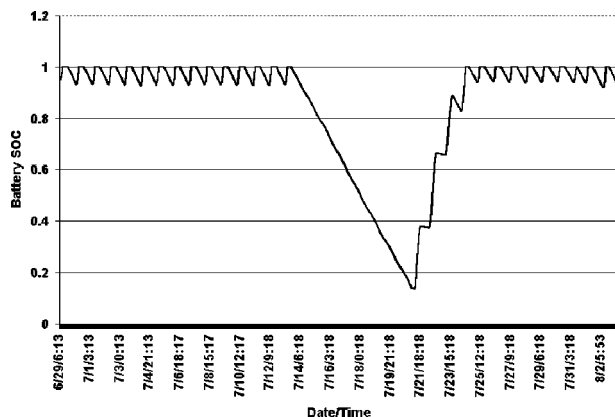


Fig. 7 Calculated battery state-of-charge

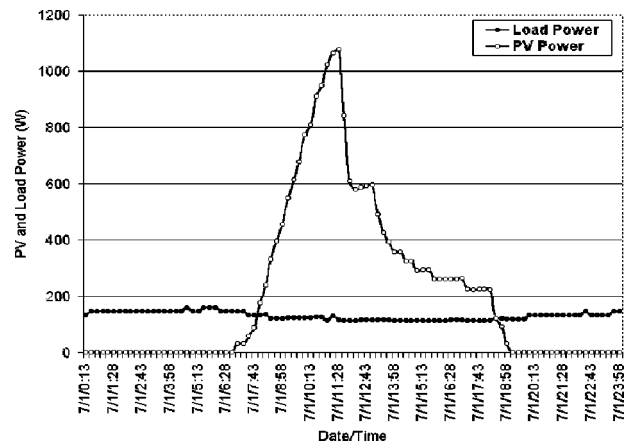


Fig. 6 Typical daily variation in PV output power and load demand

simulations are conducted using computer software known as PV-FORM [8]. This program performs a series of hourly calculations to determine the physical performance of the PV system being simulated. The input data to the program includes the following: a) load hourly data, b) hourly meteorological data, c) array and site description variables, and d) battery information.

The program determines the array hourly output power by first converting the solar insolation data to the array's orientation including radiation that is reflected off the ground. Then it estimates the cell temperature by solving heat transfer equations which are strongly dependent on wind speed. Then it determines the cell efficiency at the current temperature by using a standard degradation technique in which the efficiency is assumed to decrease at a linear rate as a function of temperature rise

The output DC power of the PV array is first applied to the load, and any excess energy is used to charge the battery bank. Energy that is not consumed by either the load or batteries is considered wasted. When the battery reaches its maximum depth of discharge, it is automatically disconnected from the system.

The performance of the above system is evaluated by using actual hourly weather data collected at the NTS over a three-yr period (1/1/81–12/31/83). The values of various parameters used in the simulation are as follows:

- PV array and site: array area = 13.4 m², site latitude = 35°, array tilt angle = 50°, array average height = 1.5 m, ground reflection coefficient = 0.25, $\eta_{ref} = 10\%$, $T_{ref} = 46^\circ\text{C}$, line loss = 1%.

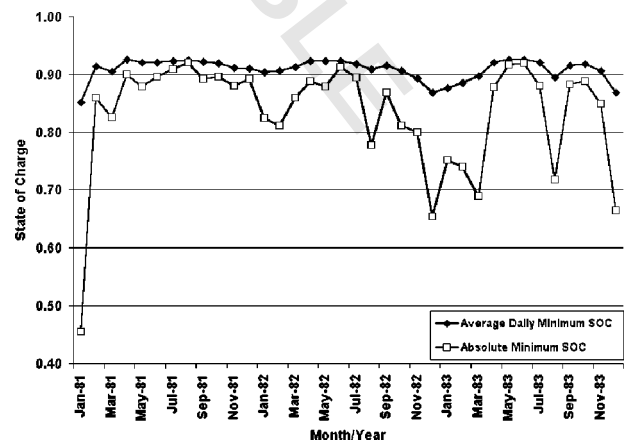


Fig. 8 Simulated battery SOC over 3-yr period

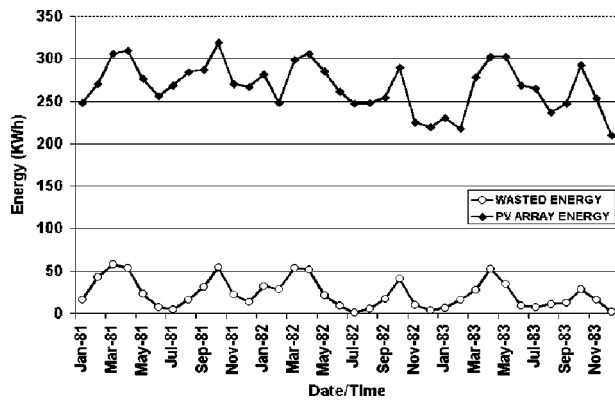


Fig. 9 PV available energy and its unused portion

- Battery $SOC_{min}=0.2$, $SOC_{start}=0.5$, capacity: 29.3 kWh, charge and discharge efficiency varies with SOC according to Eq. (3).
- Load characteristic: 150 W steady over the entire study period.

Figure 8 above shows the resulting average daily minimum battery SOC as well as the absolute minimum battery SOC for each of the 36 months. The graph indicates that the start-up SOC of 0.5 is too low for such a system, and that the battery remains near full charge (i.e., above 90%) most of the time.

Figure 9 shows the variations in the PV array energy availability and the portion of this energy that is not used (i.e., wasted or excess energy). The difference between the two quantities in Fig. 9 is used to serve the load and charge the battery. Note that the excess energy is near zero in July, 1982 and December, 1983, but nevertheless positive over the entire period. This leads to the conclusion that the power will be continuously supplied to the load 100% of the time. It is important to note, however, that PVFORM does not take into account the PV shedding by the battery charge controller, as it assumes that the battery charge rate is unlimited and can absorb all the power available from the entire array till it reaches full SOC. As a consequence, these results may be optimistic since in real life the controller limits the rate at which the battery charges when the SOC typically reaches a state above the 90% range [9].

5 Conclusion

This project successfully demonstrated that the newly designed PV system meets the Nevada Test Site needs. The system size is

50% smaller than the existing ones, small enough to be mounted on a trailer for easy relocation, and meets or surpasses the power availability requirements. Future plans include a) the installation of a voltage regulator to keep the voltage at the load terminals constant, or a feedback loop that maintains constant motor speed under varying supply voltage; and b) installation of the PV system at the NTS to remotely monitor its operation during the winter months.

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Nomenclature

- Γ = Daily average full sun hours
- η_B = Battery efficiency
- C/h = Battery discharge rate at h h
- C_B = Battery capacity
- CFM = Cubic-ft/min
- E_B = Battery energy storage rating
- E_L = Load daily energy demand
- N = Number of days of autonomy
- P_A = PV array size in Watts
- S_f = Design safety factor
- SOC_i = Battery State of Charge at time t_i
- Δt = Sampling period
- V = DC Bus voltage

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