THE 100-kWP PHOTOVOLTAIC POWER SYSTEM AT NATURAL BRIDGES NATIONAL MONUMENT* ** +

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Abstract

The Natural Bridges National Monument in southeastern Utah is the location of the world's largest solar photovoltaic power system. This system, which operates in a stand-alone mode without utility backup, supplies from 300-400 kWh/day of 60-Hz AC electrical energy to the diversified loads in the monument headquarters area. A diesel-powered generator serves as backup for the system.

The solutions to a number of problems encountered in the design, fabrication, testing and early operation of the system are discussed.

Introduction

NBNM Power System

The implementation of the photovoltaic (PV) power system as shown in Figure 1 at Natural Bridges National Monument is a joint project of the Departments of Energy and Interior (through the National Park Service). A central objective is to explore applications of PV power systems for sites which, because of their remoteness, cannot be served economically from a utility grid. Natural Bridges was selected from approximately 60 candidate sites[1,2] based on the present and expected electrical loads, its remoteness from a utility grid, an abundance of sunshine and significant public exposure (approximately 80,000 visitors per year).

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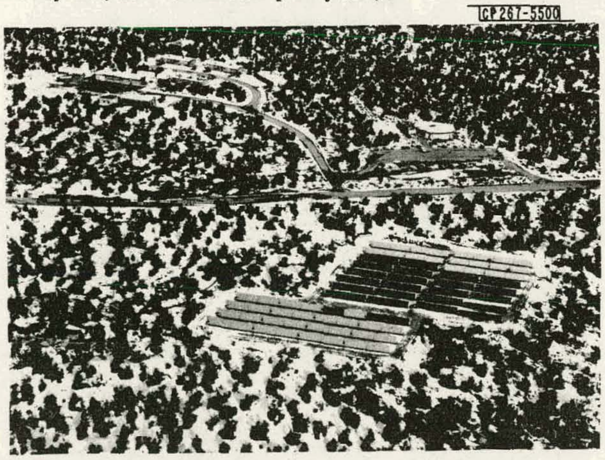

Fig. 1. Aerial view of the 100-kWp photovoltaic power system at NBNM.

As part of the joint project, the National Park Service has provided for all site development work, including the array area and a PV building, and will operate and maintain the system. Acting on behalf of the Department of Energy, the MIT Lincoln Laboratory has managed the design, fabrication and installation of the power system and will monitor its performance over an extended period.

The PV system was designed to power all of the existing site AC loads plus the overhead loads of the PV system itself. Considerable effort was expended to minimize this overhead AC load for the control and data subsystems as well as for the heating and cooling of the PV building. For example, in the winter, waste heat from the inverters is redistributed through the building; in the summer evaporative air conditioners are used to minimize the electrical energy required for cooling the equipment in the building. Although active load management of the site loads is not presently planned, conservation measures are being implemented. These measures are required particularly during January and December to minimize the use of the backup diesel during these cold months.

In addition to engineering factors, aesthetic considerations played a large part in the design process. For example, the desire to preserve the natural setting of the park led to the location of the array on the south slope of a hill across from the Visitor's Center. Thus the array is out of view to casual visitors, but is still easily reached by a short walk from the Visitor's Center.

Array Field

Figure 2 shows a view in the 1.3-acre array area looking to the northeast towards the Bear's Ears Buttes. As can be seen, considerable effort was expended on lightning protection measures. A large number of short lightning rods were used instead of several taller ones for aesthetic reasons. These rods can be seen behind the array frames in the figure.

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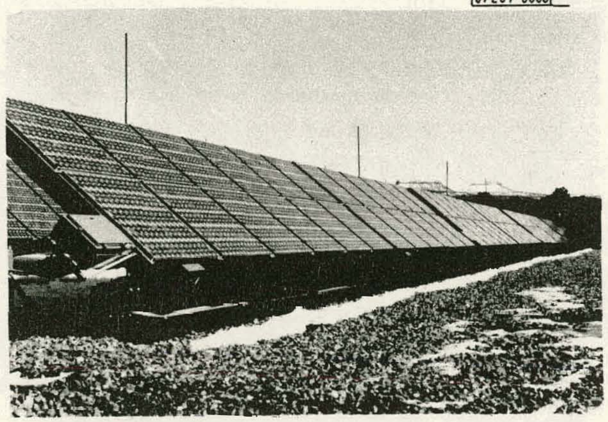

Fig. 2. A row of modules in the array field at NBNM.

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The array field is implemented in twelve rows with a total of 48 subfields of about 2-kW output each. The modules for each subfield are mounted on 4' x 4' aluminum subframes which are in turn mounted on two 8' x 24' steel frames. The use of subframes was dictated by the need to accommodate the three types of PV modules (Arco Solar, Motorola and Spectrolab) used in the array. Eight frames, for a total of 4 subfields, are in each of the twelve rows. The power from each subfield is run to a junction box at the west end of each row through buried conduits and then passes up the hill in an underground cable to the PV building.

The glass-covered PV modules were mounted and wired on approximately 1100 subframes in a "production line" at Salt Lake City, bolted into special shipping racks and shipped to the site over a two-month period. These racks, which hold ten subframes each, eliminated the need to handle packing materials at the site and provided a safe ride for the glass-covered modules. At the site, the shipping racks were removed from the open flatbed trucks with a fork lift mounted on a large farm tractor and driven down into the array field. The subframes were then unloaded and placed directly onto the 8' x 24' steel frames already in place. The subframes plug into a wiring harness mounted in the steel frames for speed of assembly and easy removal of a subframe for inspection and maintenance. The backs of the steel frames are covered with wire-mesh rodent screens to protect the wiring and to provide high-voltage protection for personnel. The array site is fenced as a second protective barrier.

Since one of the primary objectives of this project is to gather performance data on system components, each frame is provided with test wiring, which permits rapid electrical measurements on small groups of modules, as well as the entire frame and the two frames that comprise a subfield. The test connections are available in the junction box on the front of each frame. Although the rodent screens prevent general access from the rear, the open mesh does provide easy access for voltmeter probes which, when combined with the test connectors, permits rapid location of defective modules.

A block diagram of the system is shown in Figure 3. Power from each of the 48 subfields is brought to the PV building by underground cables. The power loss in the cable is about 3%. Lightning arresters were used on both ends of the run to minimize the adverse effects of voltage transients induced in the cable as a result of nearby lightning strikes.

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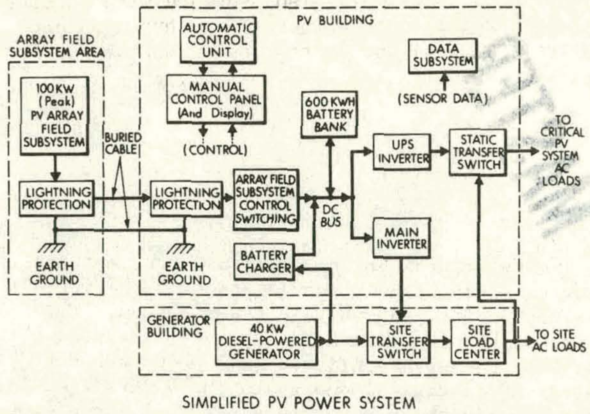

Fig. 3. Block diagram NBNM PV power system.

Battery Storage

The heart of the PV system is a large lead-acid storage battery (see Figure 4) which provides a usable capacity of 600 kWh. This is enough to run the site from 24 to 48 hours, depending on load. Although the battery would normally operate over a wider range, the main inverter design dictated a limited window of 210-280 Vdc. At the upper end of this range, the battery voltage corresponds to 2.5 V/cell, somewhat less than desired for stationary batteries. A high value would increase the gassing at end-of-charge and thus provide a beneficial mixing of the electrolyte. As a consequence of the required upper voltage, an air-lift system, similar to that used in submarine batteries, was employed to permit stirring of the electrolyte at the end of daily charge and thus to prevent stratification within the cells. Mixing the electrolyte reduces the incidence of sulfation at the bottom of the cells and therefore extends battery life.

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Fig. 4. 600-kWh storage battery at NBNM.

The batteries are also provided with catalytic hydrogen recombiners to return the hydrogen and oxygen liberated during recharging to the battery cells as water. This reduces the danger of explosion and minimizes the amount of water that must be added to the cells.

The system control equipment and control panel are shown in Figure 5. Control is accomplished by a microprocessor-based controller.[5,6] The primary task of the controller is to manage the battery and protect it from both overcharge or overdischarge. This is implemented by an algorithm which employes battery voltage and current. In simplified terms, arrays are shed when the battery voltage rises above 280 volts and added when it drops below the shed voltage by about 3 volts.

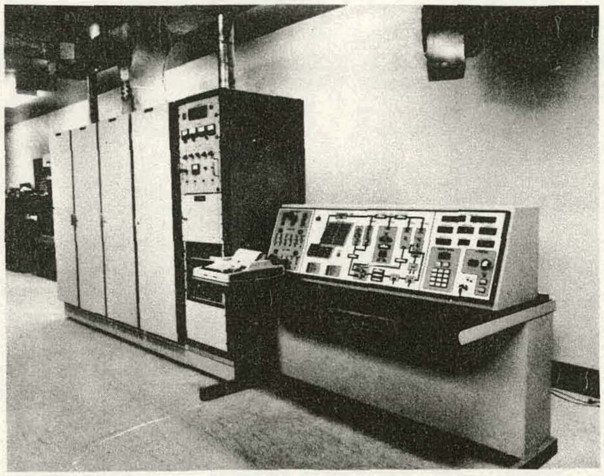

Fig. 5. System control equipment and control panel.

A measure of battery state-of-charge (SOC) is obtained by digitally integrating the battery current. This is then converted to SOC to provide a basis for monitoring depth of discharge. The SOC is effectively reset every two to three weeks when the battery is equalized to full charge. The error in the estimate of ampere hours over a two-week span is expected to be less than 10% of the battery capacity. A backup decision on low SOC can also be made by observing battery voltage. This is used to turn on the diesel generator and battery charger to recharge the batteries during periods of high load or low solar insolation.

In addition to managing the battery, the controller also operates multiplexers for monitoring system parameters and performs daily I-V plots of each of the 48 subfields of the array.

A small thermal printer, shown on the desk in Figure 5, is also driven by the microprocessor to provide a written record of controller actions during the day. This is especially important since some controller actions can completely shut down the system. A written, on-site record has proven to be valuable for troubleshooting and for assuring the operators that all is well.

Data Recording

The data from weather and insolation measurements, as well as test points in the system, are recorded every ten minutes by a data logger (Figure 6). This subsystem also contains a dedicated logger that gathers the I-V data from daily measurements on each of the 48 subarrays. In addition, standard cells are available for temporary installation when standardized array measurements are taken.

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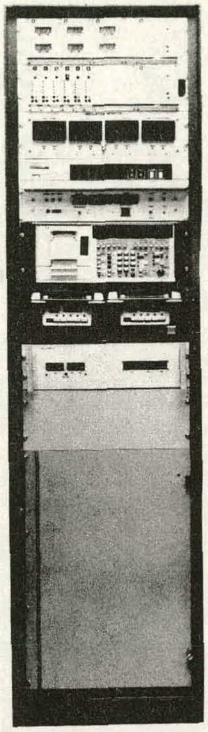

Fig. 6. Data logger.

AC and DC power transducers permit monitoring of the power flow in the system. These are supplemented by Watthour meters which give integrated values of energy flow.

Off-Site Assembly and Test

The control system was tested off-site with an array simulator and mockup for the interfaces to other devices. The power equipment--inverters, battery charger, and 30 tons of batteries--were also set up and tested together. In spite of careful specifications, design, and factor test, each major item in the power-processing subsystem displayed problems requiring significant attention.

For example, the 5-kVA Uninterruptible Power Supply (UPS) inverter, which provides uninterruptible power to critical system loads, operated normally until the first tests employing the system battery. At this point, it consistently tripped itself off-line on under voltage even though the input DC voltage was within limits. The problem was eventually traced to the input DC filter where it was found that the extremely low resistive component of the large battery caused a reduction in damping. This problem had not occurred in prior tests where the inverter had been operated from modestly sized batteries or from a DC power supply.

Inverter Considerations

The main inverter, a 50-kVA single-phase unit, has been found to produce considerable interference to AM broadcast reception for radios powered from site AC power. Most of the interference is conducted on the buried site power wiring and is produced by the power SCR's of the inverter. The fast-switching transients of the SCR's excite the power wiring of the inverter to produce a series of damped sinusoidal bursts with a carrier frequency of about 1 MHz.

Measures being taken to minimize this interference to AM broadcast reception include filtering the inverter output, line filters for radio receivers, and mounting external antennas to improve signal strength relative to noise.

Somewhat more troublesome than the interference problem have been two surge current effects. The first is the result of the high-starting current drawn by AC motors, typically 5-10 times the full-load value. To support these transients, a 50-kVA inverter was selected so as to provide on the order of 25-35 kVA of excess capacity beyond the normal site demand.

An even more troublesome problem was discovered when it was found that inverter input (DC) fuses would occasionally blow when the step-up and step-down transformers (and Visitors' Center loads) at the ends of a modestly long AC power line were reconnected following a shutdown. This event was due to transformer saturation effects, which caused initial inrush currents as high as 10-12 times the full-load kVA rating of the transformers, (600 A was observed). It is a consequence of the residual magnetization left in the core from the last portion of the 60-Hz excitation. Since the removal of AC voltage can occur at any point in the 60-Hz waveform, and since the restoration of voltage can likewise occur at any point, there exists the certainty that on some occasions the remnant flux will be in the same direction as required during the first half cycle of the restored voltage. The result is saturation of the core for the first few cycles with resulting high inrush (magnetization) current. This problem was solved through use of a startup circuit which imposes a 3-ohm series resistor in one side of the 240-VAC line for a period of one second following application of line voltage.

System Loads

The actual observed load and the necessary load can be quite different depending on the local habits of energy usage.[3,4,5] With the diesel generators at this site previously in use 24 hours per day, some of the winter heating requirements were met by electric heaters since the impact on diesel fuel usage was relatively minor and a base load was needed to keep the generator adequately loaded for proper operation. Extra lighting was also left on year-round to load the generator. Lighter loads (compared to diesel capacity of 40 KW) were considered harmful since more carbon builds up if the engine does not reach proper operating temperatures. The PV system was designed with the observed loads and some conservation measures in mind. The minimum necessary load for a remote site is still an elusive quantity but perhaps it can be lower than most expect if a system approach considering both loads and source capability is taken. This site has a 50,000-gallon water storage tank for water storage from the well pump. During the winter season, the pump is run infrequently so pumping can be scheduled for good days to further reduce demands on electrical storage by exploiting storage of another product (water).

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