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A 100 KW PEAK PHOTOVOLTAIC POWER SYSTEM FOR THE NATURAL BRIDGES NATIONAL MONUMENT*

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ABSTRACT

The Department of Energy, in partnership with the National Park Service of the Department of the Interior, is sponsoring the implementation of a 100 kW peak photovoltaic power system for the Natural Bridges National Monument in southeastern Utah. This remote site, which presently obtains all of its electrical energy from a diesel-powered generator, is manned year-round by NPS personnel. Starting in the fall of 1979, the PV system will begin to provide the bulk of the electrical demand at the site. Sunlight will be converted into DC electricity by an array field of glass-covered modules containing three types of silicon solar cells. The 1700 m^2 array, with over a quarter million two- and three-inch cells, will be the largest flat-plate PV field in the world at the time of its dedication. The power system will take DC power from the array, store excess energy in a 750 kWh lead-acid battery, and convert DC to AC in a single 50 kVA inverter. A standby diesel-powered generator will provide backup for the system in the event of extended inclement weather.

1. INTRODUCTION

The application of solar photovoltaic (PV) power at the Natural Bridges National Monument (NBNM) represents a field test of a system designed to displace primary hydrocarbon fuel at a remote site. Such sites, which have in common the fact that they are not connected to any electrical utility grid, can be divided into two types. Type-1 sites, typified by NBNM, have an existing electrical power system usually consisting of a gasoline or diesel-powered generator. In contrast, Type-2 sites are those which presently have no source of electrical power. Tens of thousands of remote villages fall into this category.

The design of a PV power system for NBNM, as for all Type-1 sites, must include the integration of several features. In particular, the system must supply power to an existing small grid feeding established AC loads. Thus one does not generally have an option to incorporate DC loads as might be the case at a Type-2 site. In short, the PV system must be adapted to the existing load-center application. This adaptation has greater impact than would be the case for an unelectrified remote village where use patterns do not exist.

The choice (1,2) of Natural Bridges National Monument (NBNM) in southeastern Utah for a PV power system was based on its remoteness from the public utility grid, the size of its annual electrical consumption, the diversity of the loads and its accessibility to the visiting public. As a general load center (3), the PV system will supply a diverse collection of loads including lighting, appliances, shop tools and machinery, refrigerators, radios, television, and multi- and fractional-horsepower motors. The largest and most troublesome loads are represented by several 3-hp AC induction motors which are used for water pumping from a deep well, pressurization of the water distribution system, and operation of a shop air compressor.

2. THE SITE

Natural Bridges is situated 2000 meters above sea level in an area where prevailing clear skies, abundant solar insolation, dry air and usually moderate temperatures combine to produce an excellent climate for solar applications. On an annual basis, a horizontal surface at NBNM receives an insolation of approximately 2500 kW/hrs/m^2.

At present, all electricity for NBNM is produced as 240/120V 60 Hz single-phase power by a 50 kVA/40 kW diesel-powered generator which operates continuously. Demand varies from 10 to 30 kVA, with short-term peaks to 50 kVA during the starting of any of several 3-hp induction motors. Although the annual consumption is now over 200 MWh, it is believed that energy conservation measures

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DISCLAIMER

will reduce consumption to the vicinity of 150 MWh (5.4×10^{11} joules). However, the PV power system will be required to provide approximately 20 MWh for its own energy requirements in the form of power for the control, data and other subsystems, as well as for the heating and cooling of the PV building.

Following completion of the PV power system, the present diesel-powered generator will be relegated to use as a backup power source which will be activated automatically when the battery state-of-charge (SOC) drops to a predetermined lower limit. Projections have placed the amount of electrical energy to be supplied by the diesel at from 5 to 15% of the annual site consumption.

3. THE PV POWER SYSTEM

Figure 1 shows the layout of the system which is made up of a 100 kW peak array field, an underground cable, and a PV building housing the battery subsystem, power conditioning elements, switchgear, control, data alarm systems and other equipment. The backup diesel is housed in an adjacent building.

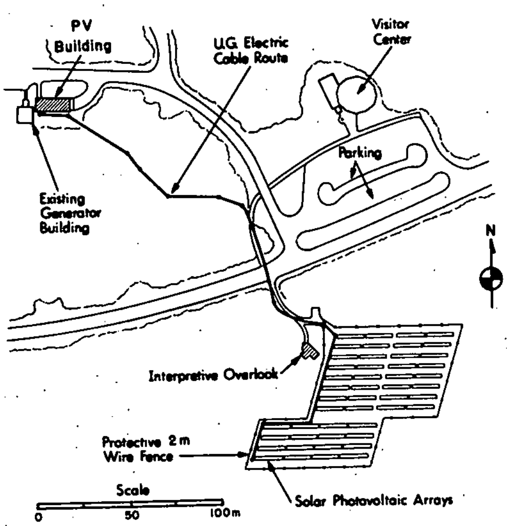

Fig. 1 PV system layout

Figure 2 shows a simplified diagram of the system. The nominal 100 kW peak array field passes DC power through an underground cable to the PV building. A control switching subsystem then combines all subfields and passes the power to the DC bus where a charger, the battery and two inverters are connected. An automatic control unit operating through a manual control and display panel exercises system control while a data subsystem gathers performance data. Site AC power is provided by a main inverter while a small inverter is used to supply critical PV system loads.

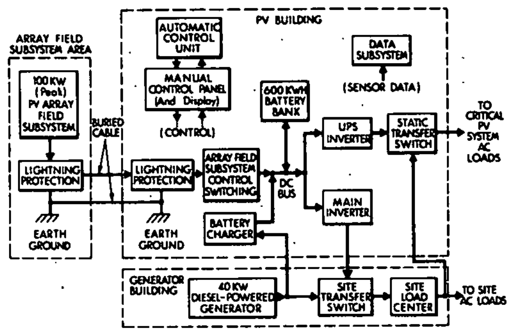

Fig. 2 Simplified PV power system

3.1 Component Efficiencies

The projected net efficiency for energy flow from the PV modules to AC loads is shown in Figure 3. The 60% overall efficiency does not include effects due to mismatch between the array maximum power voltage and the DC bus voltage, haze or dust in the atmosphere, or the system overhead. However, it is typical of present remote AC load-center PV power systems utilizing lead-acid storage batteries. Future systems with storage are expected to reach 65% to 70% energy efficiency, largely as a result of improved inverter designs, while grid-connected AC systems may approach 85%. DC systems without storage could do even better although daytime-only use is not generally compatible with village or community needs.

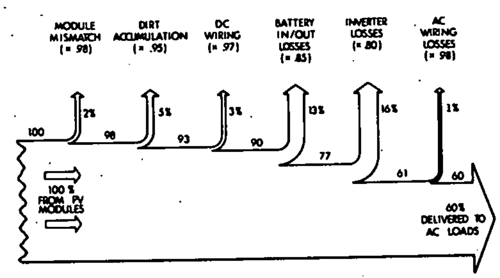

Fig. 3 Projected system efficiency

3.2 The PV Array Field

The nominal 100 kW PV array field, which will occupy a 5600 m^2 cleared area, will be implemented by using 48 array subfields of just over 2 kW each. The total area of glass-covered modules from three manufacturers (Motorola, ARCO Solar and Spectrolab) will be

1700 m² corresponding to 990 m² of actual silicon cells with an average packing factor of 58%

To obtain maximum power from the array, under conditions of a significant array-to-bus voltage mismatch caused by extremes of temperature, insolation and DC bus (battery) voltage, a maximum power tracker (MPT) must be used. However, factors of cost, complexity and the moderate energy benefit have led to the decision not to implement a 100 kW MPT at NBNM. In its place, MPTs rated at 2.5 kW each will be incorporated into three subfields, one of each module type, so that performances may be compared to those of subfields without MPTs.

3.3 The Underground Cable

As a consequence of siting constraints, the array field was located at a considerable distance from the PV building. This necessitated a 335 m underground cable to connect the 48 array subfields to the array field subsystem control and switching box. Economic considerations caused the cable to be sized for roughly 3% peak power loss from array to DC bus.

3.4 The PV Building

The PV building, shown in Figure 4, will incorporate four rooms totaling 134 m². Outside walls will have 15 cm of insulation as well as triple-glazed windows, while the ceiling will contain 25 cm of insulation. For safety reasons, the wall between the battery room and the remainder of the building will be reinforced concrete. In addition, explosion-proof electrical fixtures will be utilized in the battery room.

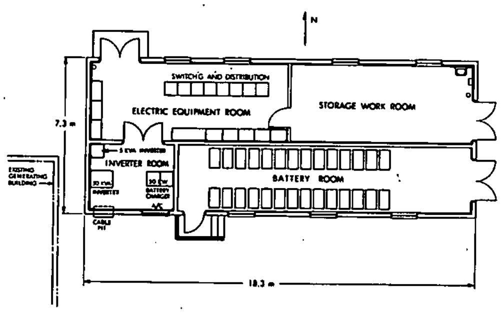

Fig. 4 NBNM PV building

The major heat-producing power conditioning elements will be located in a single room (the inverter room) so that excess heat during warmer periods can be removed by an energy-efficient evaporative (water) cooler. Fans will be used during winter months either to vent to the outside or to redistribute excess inverter heat within the building.

3.5 The Battery Subsystem

Electrical storage will be provided by a 750 kWh (12-hr rate, 25°C) bank of 224 lead-calcium cells. The batteries will be configured as 112 cells in series and 2 in parallel for a bus voltage range of from 210 to 280 VDC. The 1675 AH cells (12-hour rate, 25°C) will be packaged in 28 1105 kg modules of eight cells each. Guaranteed battery life is six years.

Battery life will be improved by limiting the maximum drawdown from full charge to no more than 600 kWh and by employing a continuous air lift system to prevent electrolyte stratification. In addition, catalytic combiners on each of the 224 individual cells will reduce gassing during overcharge. Although hybrid lead-acid batteries would provide roughly 6% more energy than lead-calcium, the latter were chosen in part because of their lower rate of gassing and the suitability of recombiners as well as their significantly lower equalizing current (X 1/5 when new, X 1/30 when old). The batteries will be equalized biweekly in order to reduce divergence in SOC among the cells and to extend the battery life.

3.6 Power Conditioning

Solar energy will be supplied to the site and overhead loads as AC power through a 50 kVA single-phase 60 Hz inverter. The rather high rating of this inverter, relative to the expected range of base loads, results from the need to supply the peak demand during the starting of any of the 3-hp induction motors at the site. This type of transient load, with initial peaks typically six to eight times the rated full-load current, represents the most difficult load for an inverter. It is expected that future inverter designs for PV power systems will incorporate greater momentary overload capability as well as better part-load efficiency, thus allowing the selection of the inverter to be made on the basis of the expected base load rather than the starting peak transients.

The second major power handling device is a 50 kW battery charger. This unit, which utilizes the "controlled ferroresonance" technique, was chosen because of its relatively clean (harmonic free) AC input current waveform. Chargers utilizing phase-controlled silicon controlled rectifiers (SCRs) have a significant harmonic content in their input current waveforms. When supplied from a diesel-powered generator, an adverse interaction between the charger and generator control loops frequently results. Controlled ferroresonant chargers are believed to be free from this problem.

One important feature of the charger will be the inclusion of a constant input current control loop. This feature will cause the charger to draw essentially constant input AC power during battery charging, thereby maintaining a constant load on the diesel-powered generator. Thus the variation of DC bus voltage will not affect the diesel loading.

The final unit to be located in the inverter room will be a small (3-5 kVA) inverter, configured as an uninterruptible power source (UPS), for powering such critical system loads as the control, data and alarm subsystems. A static transfer switch will be incorporated to switch these critical loads to site power in the event of UPS inverter failure.

3.7 Control

Control of the PV power system will be implemented with a two-level approach, including a manual control panel (MCP) and a microprocessor-based automatic control unit (ACU). Although system control may be exercised manually through the MCP, which includes all display functions, routine operation will be handled by the ACU. The ACU will provide for unattended operation, including the following tasks:

1) Battery charge control by shedding of one or more (up to 48) array subfields when the battery SOC reaches 100% and the available solar PV power exceeds the demand of the two inverters.

2) Automatic start-up of the diesel-powered generator when the battery SOC drops to 20% (600 kWh drawdown).

3) Automatic shutdown of the main inverter, thus dropping power to the site, in the event that the diesel fails to start.

4) Automatic shutdown of the UPS inverter, thus eliminating all battery drain, if the battery SOC reaches 15%.

5) Automatic scheduling and operation of a biweekly equalizing cycle utilizing the diesel-powered generator and battery charger.

4. SYSTEM OPERATION

Routine system operation will include the automatic startup of the backup diesel-powered generator (DPG) at 20% SOC. When started, the DPG may supply power to the system in either of two modes. Mode 1, which utilizes the charger constant-power control, is expected to be the normal mode. In this mode the full DPG output (40 kW) will go to the charger which in turn supplies power to the DC bus. Site AC power will continue to be provided from the main inverter. Charger output in excess of the demand from the two inverters will go into recharging the battery.

Mode 2 will differ in that the site AC power will be transferred from the main inverter to the DPG through activation of the site transfer switch.

Following this transfer, the main inverter will be shut down and the battery charger will be used to recharge the batteries. However, since the DPG will be supplying a variable amount of site power, the charger demand must be adjusted continually to consume the excess DPG capacity. This complication makes Mode 2, which otherwise has a slight efficiency advantage over Mode 1, appear less attractive.

4.1 Data Subsystem

One objective of the NBNM field test is to provide comprehensive data on the performance of the PV power system. In addition to the performance data, I-V curves of each of the 48 array subfields will be automatically recorded each day at noon. These data will facilitate the long-term evaluation of array and module degradation including both recoverable losses (e.g., dirt accumulation) and non-recoverable losses from permanent effects.

5. IMPLEMENTATION

The program to implement what will be the largest flat-plate PV power system in the world (for a time) is divided into two parts. The site development work by the National Park Service, which will provide that portion of the array field up through the foundations as well as the underground cable and the PV building, has begun and is expected to be completed during the summer of 1979. Detailed system design under the sponsorship of the United States Department of Energy is well underway and turn-on is scheduled for late 1979.

6. REFERENCES

(1) Jarvinen, P.O., Peatfield, C.R., and Haiges, H., "Photovoltaic Applications for the National Park Service," Proc. of the Twelfth Intersociety Energy Conversion Engineering Conference, pp. 1159-1166, Washington, D.C. August 28-September 2, 1977.

(2) Jarvinen, P.O., and Haiges, H., "Natural Bridges National Monument, Utah - Solar Photovoltaic Power System Design," Proc. of the 1978 National Conference on

Technology for Energy Conservation, pp. 318-325, January 24-27, 1978, Albuquerque, New Mexico.

(3) Lyon, E.F., Bucciarelli, L.L., and Benoit, A.E., "Design of the Natural Bridges National Monument 100 kW PV Power System," 13th IEEE Photovoltaic Specialists' Conference, Washington, D.C., June 5-8, 1978.