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A CONTROL SYSTEM FOR IMPROVED BATTERY UTILIZATION IN A PV-POWERED PEAK-SHAVING SYSTEM

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ABSTRACT

Photovoltaic (PV) power systems offer the prospect of allowing a utility company to meet part of the daily peak system load using a renewable resource. Unfortunately, some utilities have peak system-load periods that do not match the peak production hours of a PV system. Adding a battery energy storage system to a grid-connected PV power system will allow dispatching the stored solar energy to the grid at the desired times. Batteries, however, pose system limitations in terms of energy efficiency, maintenance, and cycle life. A new control system has been developed, based on available PV equipment and a data acquisition system, that seeks to minimize the limitations imposed by the battery system while maximizing the use of PV energy. Maintenance requirements for the flooded batteries are reduced, cycle life is maximized, and the battery is operated over an efficient range of states of charge. This paper presents design details and initial performance results on one of the first installed control systems of this type.

INTRODUCTION

Salt River Project (SRP), a Phoenix, Arizona based utility, has continuing and long-term research and development projects in renewable energy areas including several PV systems. The SRP grid has a Summer peak system-load period from 4 PM to 7 PM. In the Winter, the peak system-load period is from 7 AM to 10 AM. Neither of these periods matches the peak output period of a PV system which is generally between 10 AM and 2 PM. Phoenix has generally clear days with an annual average daily irradiation of 6-7 kWh per square meter. There are few days with consistent morning or afternoon weather conditions that would shift the peak solar period. SRP has expressed a desire to determine the feasibility of using battery storage coupled with a PV system to match the PV output with the peak system-load periods.

A program to address these SRP research objectives was formulated jointly by people from SRP Research and Development, Electric Power Research Institute (EPRI), Sandia National Laboratories (SNL) Photovoltaic Systems Applications Division, and the Southwest Technology Development Institute (TDI).

SRP was aware of the limitations associated with a battery storage system and wanted to minimize these problems while maximizing the system efficiency. Battery charge controllers frequently do not make full use of the available energy from the PV system, nor do they charge the battery in the most efficient manner. The control system maximizes the stored energy from the battery and the direct energy from the PV array delivered to the grid during peak periods. It also minimizes the energy delivered to the grid outside of peak system-load periods.

SYSTEM DESCRIPTION

A 2.4 kW PV array consisting of 20, 120-watt Solarex MSX-120 PV modules was installed on the roof of the SRP Chandler House in Chandler, Arizona. This house has been used extensively for SRP research on PV technologies and systems and exploration of several demand-side management techniques. An SRP employee lives in the house. The PV array is connected in five source circuits that each deliver the PV energy from four modules (connected in a nominal 24-volt configuration) to an Ananda Power Technologies (APT) power center containing overcurrent, disconnect, and charge control devices. Energy is stored in 12 Trojan L-16, 6-volt flooded, lead-acid batteries with a nominal capacity of 25.2 kWh at 24 volts and 1050 amp-hours. Hydrocap Vents are installed on each battery cell to convert evolved hydrogen and oxygen gases back to water. A Trace Engineering 4024 SW inverter is used to convert direct current from the batteries and the PV array to 120 volts alternating current (ac). A data acquisition system (DAS), designed by TDI, provides supervisory control of the other components and collects data for off-site analysis. A 50-amp branch circuit connects the output of the system through utility-grade protective relays (voltage/frequency) to the house load center and then to the SRP grid. Figure 1 shows a one-line diagram of the system which was installed in full compliance with the *National Electrical Code* ®(NEC ®) [1].

BATTERY LIMITATIONS

The theoretical maximum energy efficiency of a flooded lead-antimony battery is about 75% [2]. Under non-ideal operating temperatures and charge and discharge rates, the energy efficiency will be much lower. While the cycle life of lead-acid batteries is relatively well established for conventional uses such as motive power and float applications, the partial, non-periodic charge and discharge cycles in PV usage promote shortened battery life. Charging rates and set points affect both cycle life and maintenance requirements (gas liberation and water usage). Batteries operate with greater efficiencies when operated below the gassing voltage. Charging above this

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voltage results in excessive heating and gas evolution—both of which result in lower efficiency. But, continued operation below the gassing voltage and below full states of charge result in loss of battery capacity which is not recoverable if the batteries are operated for extended periods in this partially charged state. Efficiency, cycle-life, and maintenance requirements present a set of battery use requirements that conflict. Using the above constraints, a new control system was designed to provide better overall performance in this PV/battery/utility-interactive system than has been achieved in other systems.

minimized and most of the available energy is delivered to the grid during the designated peak system-load periods.

Electrical transducers are installed on the system and measure direct current (dc) from the PV array, direct current into and out of the battery, battery voltage, and ac power to and from the utility grid. The outputs of these transducers are used to control the system. For overall system performance assessments, other transducers measure solar irradiance, PV module temperature, ambient air temperature, and battery temperature.

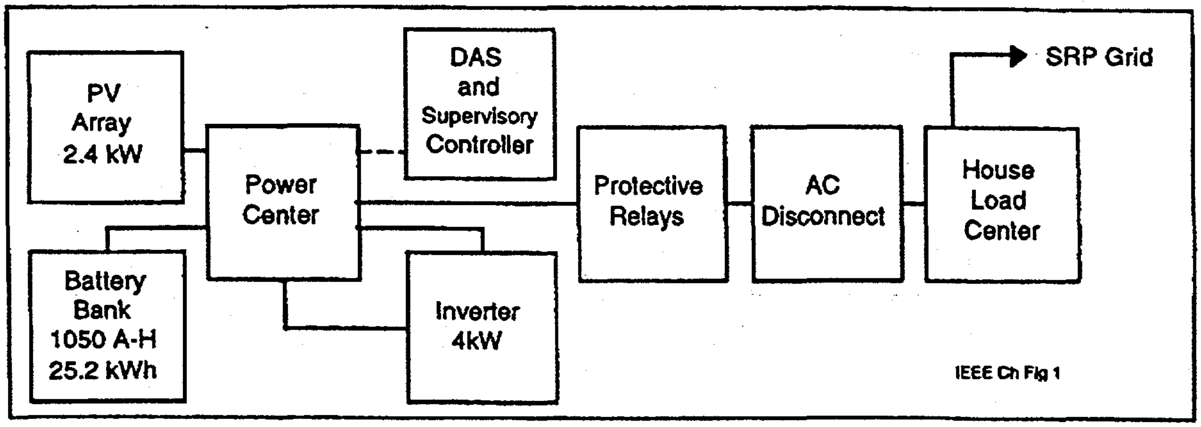

Figure 1. PV/Battery System, One-Line Diagram

CONTROL SYSTEM

The control system consists of the following components and functions.

- APT power center charge controllers: equalizing voltage
- Trace inverter utility-connected float mode: daily voltage
- Trace inverter utility-connected sell mode: stored energy to grid
- DAS computer: equalizing cycles and discharge periods

This control system allows the batteries to be charged by the PV array up to a point just below the gassing voltage. It also allows the batteries to be fully charged and equalized (four hours above the gassing voltage) every other Saturday (no peak system-load requirement) to condition the batteries, maintain capacity, and extend cycle life. The control system discharges a percentage (based on the average battery efficiency and average state of charge) of the energy stored in the batteries during the peak system-load period. The operating state of charge is maintained to a range just below the gassing point which maximizes battery efficiency and contributes to cycle life. Almost all PV energy is delivered to either the battery or the grid with only small losses associated with the equalizing cycle. Energy is lost in the system due to unavoidable battery and inverter losses. Energy delivered to the grid outside the peak system-load periods is

The change-over between Summer and Winter operation is accomplished by manually resetting two parameters in the inverter microprocessor. The control system parameters in the DAS are automatically reset at the proper time.

OPERATING MODES

There are two modes of operation of the system. One is the daily cycling mode and the other is the every-two-week equalization mode.

Daily

During daily periods of PV array output, the energy into the battery is measured. During the SRP peak system-load time periods, a percentage of the energy that was stored in the battery the previous 24 hours is discharged into the SRP grid along with any PV energy being delivered by the array over the peak system-load period. The discharge percentage is a system variable that roughly equals the short-term battery energy efficiency. This percentage discharge factor is used to control the operating-state-of-charge range of the battery.

As a lead-acid battery is operated at states of charge (SOC), charging currents, and voltages that allow the cell voltage to rise above 2.38 volts per cell (at 25-27°C), the battery begins to evolve hydrogen gas. Above this cell voltage, the charging efficiency becomes lower as more and more of the charge is used to liberate hydrogen gas through electrolysis. Operation below the gassing voltage represents the most efficient operating range for the battery.

The control system monitors the battery voltage continually. When the PV array charges the battery to just below the gassing voltage, the control system connects the inverter to the grid and sends excess PV energy to the grid. Since this activity will usually occur outside the SRP peak system-load period, it is desirable to minimize the energy delivered in this manner. By adjusting the percentage discharge factor, the control system attempts to hold the out-of-peak grid connection time to 20 minutes each day. On a typical day, this represents about 300 watt-hours of energy being fed to the grid outside of the peak system-load period. A four-day averaging process is used that compares the actual out-of-peak time of connection with the desired 20 minutes. The control system adjusts the percentage discharge factor to discharge more energy from the batteries during the peak system-load period when the out-of-peak time exceeds the desired 20 minutes. The averaging process allows the effects of daily variations in the weather to be smoothed out. Figure 2 shows the time shifting of solar energy.

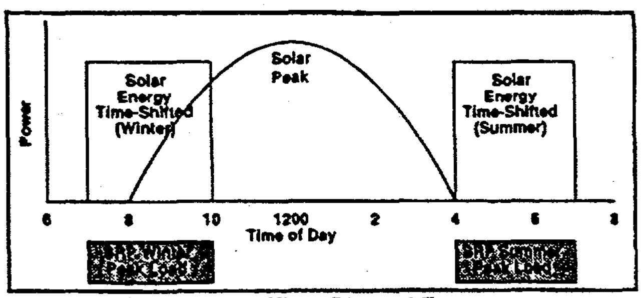

Figure 2. Time-Phased Energy

The measurements of battery voltage and the charge algorithms are temperature compensated since the batteries are located in an area that is not temperature controlled. Ambient temperatures in the battery room may range from near 0°C on Winter nights to 45°C on Summer days.

This closed-loop system keeps the batteries operating in a range of states of charge that has a maximum state of charge (85-95%) just below the gassing voltage. The lower limit on the state of charge depends on the season and the average weather over the past four days. The battery bank is sized so that the state of charge swings over about a 40 percent range in the Summer and about a 25 percent range in the Winter.

Equalization

Unfortunately, continued daily operation below the gassing voltage allows the water-sulfuric acid electrolyte to stratify. Stratification of the electrolyte causes the upper portion of the lead plates in the battery (where the specific gravity of the electrolyte is lowest) to develop large lead-sulfate crystals. The higher specific gravity of the electrolyte in the bottom of the batteries allows a more active charge/discharge process, and the active material is consumed at a greater rate on the lower portion of the lead plates. This stratification results in a loss of capacity (sulfation) and a loss of cycle life (active material consumed).

The computer in the DAS keeps track of the days of the week. Every other Saturday, the daily cycle is inhibited, and the inverter is not connected to the grid until the batteries have been charged at voltages over the gassing voltage for four hours. This process is accomplished by allowing the charge controllers in the APT power center to regulate the PV charging process at about 30.0 volts (2.5 volts/cell). The series relays in the power center cycle open and closed during this time so some of the PV energy is lost.

During the period that the batteries are operated over the gassing voltage, the evolved hydrogen and oxygen gas bubbles stir the electrolyte and create a uniform electrolyte density throughout each cell. Stratification is eliminated and the resulting problems of sulfation and excessive consumption of active material are minimized. Equalization charging also helps to break up any large lead-sulfate crystals that may have formed between equalization cycles.

The control system counts only 20% of the measured energy into the batteries when the battery voltage exceeds the gassing voltage. This is an approximation of the inefficiency of the battery in this charging region.

In the Summer on clear days, the battery will normally complete the four hours of equalization before 4 PM and will then discharge the stored energy into the grid, even though there is no peak-load period defined on Saturdays. In the Winter, there is no morning peak-load defined on Saturdays, and the system does not connect to the grid. The energy collected on Friday allows a very fast charge to the gassing range and the batteries are well charged for the grid-connection period on Sunday morning—again without a defined peak-load period. Sunday gives a back-up day for the equalization charge, should the weather on Saturday prove poor.

The system controller will not connect the inverter to the grid on successive poor-weather days until four hours of charging above the gassing voltage have been accumulated.

PERFORMANCE

The system was installed in mid September 1995 and has been operating continually. No repairs or homeowner involvement have been required. The equations and constants used in the control system have been adjusted slightly to allow for unexpected transients due to weather and unforeseen external perturbations (e.g. loss of ac grid power). The peak current discharged into the grid was increased from 25 amps (3000 watts) to 30 amps (3600 watts) to allow for higher-than-predicted collected energy to be discharged into the grid during the three-hour peak periods.

Energy collection, storage, and delivery to the SRP grid have exceeded predicted amounts by 10-20%.

Projections were based on average insolation values for Phoenix, Arizona, anticipated module heating, and system electrical efficiencies. The PV modules have been operating slightly cooler than projected due to higher than average winds. The Inverter is operating at slightly higher than advertised efficiencies.

The system has, on long sunny days, been able to deliver energy to the grid even after completing an equalizing period on the same day. Water usage, checked twice at 90-day intervals, has only been about four ounces per cell per 90-day period and is minimized by the use of Hydrocap Vents on each cell. Sufficient water exists above the plates, at this rate of water usage, to allow battery watering at one year or longer intervals. However, unanticipated loss of ac power to the system causes the system to be in the equalization mode with higher water losses and a 90-day watering check period is considered prudent.

Future Modifications

The control system time constants and gains are being adjusted slightly to improve the system transient response to daily changes in the weather. This is a relatively slow process and may necessitate a different set of constants for Winter and Summer operation.

Production enhancements in the microprocessor that controls and is embedded in the Trace Inverter may reduce the necessity for extra controls such as those in the data logger. When the improved controllers are available, they will be investigated for possible inclusion in this system.

New systems designs and packaging by Ananda Power Technologies, Trace Engineering, and others may reduce the component count and complexity allowing smaller, more designer-friendly systems. Costs will decrease as component count decreases.

New technology batteries with lower costs, higher efficiencies, longer cycle life, and lower maintenance requirements would enhance the attractiveness of the system.

SUMMARY

The control system has performed as designed and installed. Higher than anticipated energy is being collected and delivered to the SRP grid that necessitated slight changes in the control system parameters. Maximum energy from the PV system is being delivered to the SRP grid during the peak-load periods while minimal amounts of energy are being delivered to the grid outside of the peak-load periods. The batteries are being operated at states of charge in the region just below gassing. Although the amounts of energy are small compared to the SRP peak load, the installation proves that the control system concept and implementation are valid and well within the state of the art. There have been no failures of the control system, and there have been no maintenance requirements other than checking the battery water every 90 days and changing the system from Winter to Summer Peak operation and back.

ACKNOWLEDGMENTS

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2. D. Linden, editor. *Handbook of Batteries & Fuel Cells*, McGraw-Hill, NY 1984, p. 13-21.