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PVSS-A Photovoltaic System Simulation Program Users Manual

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Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
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Printed June 1977

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SF 1004-DF (3-75)

Printed in the United States of America
Available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Per Copy \$5.00
Microfiche \$2.25

SAND77-0814
Unlimited Release
Printed June 1977

PVSS - A PHOTOVOLTAIC SYSTEM SIMULATION PROGRAM

USERS MANUAL

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ABSTRACT

The PVSS code has been developed to accurately simulate the performance of a photovoltaic system. Sixteen system configurations can be modeled using such components as batteries, inverters, dc-voltage regulators, and maximum power point trackers. When the user supplies data describing incident light intensity and load demand, the PVSS program computes the power available at the output terminals of each system component, the energy surplus produced or deficit incurred by the system as a whole, and the battery state of charge for systems possessing battery storage.

In this report, procedures for defining a photovoltaic system and specifying a simulation are discussed. The theory used in developing simulation models is explained to the extent necessary to understand the accuracy of the models used. Finally, several sample runs are discussed to illustrate the behavior of the program in simulating various photovoltaic systems.

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Chapter I. Introduction

The Photovoltaic System Simulation Program, PVSS, has been written to simulate the performance of any one of sixteen photovoltaic system configurations assembled from such components as batteries, inverters, dc-voltage regulators, and maximum power point trackers. When the user supplies data describing incident light intensity and load demand, the PVSS program computes the power available at the output terminals of each system component, the energy surplus produced or deficit incurred by the system as a whole, and the battery state of charge for systems with battery storage. PVSS can be used to evaluate proposed system designs under a variety of simulated environments, to verify performance predictions obtained from analytical calculations, to optimize a photovoltaic system for specified conditions of insolation and load demand, and to aid in the economic analysis of power systems utilizing photovoltaics. Furthermore, in addition to its use as a stand-alone code, PVSS can be integrated into a solar-thermal energy system simulation code to provide it with a photovoltaic capability.

PVSS consists of an executive program and a series of subroutines. The executive program sets up the photovoltaic system description and simulation parameters. The 16 nonredundant system configurations that can be simulated by this code are indicated in Fig. 1. Each distinct system can be formed by selecting a component option from each block and connecting them as indicated. For example, a system consisting of a maximum power tracker, battery, and inverter may be used, or the array may be attached directly to the load by selecting open circuits for blocks A, B, and C.

Subroutines which accurately model the behavior of a solar cell array, maximum power point tracker, battery array, inverter, and DC voltage regulator are available to the executive program. When parameters are specified for these

FIGURE 1. PHOTOVOLTAIC SYSTEM

devices, data are provided to describe the insolation incident on the solar cell array, and the load demand is given, the executive routine will configure the required system and simulate its behavior for the specified number of days and update interval under the conditions supplied.

The output from a PVSS run is an accounting performed at every update interval, of the maximum available solar cell array power, the power available at the output terminals of each piece of power conditioning equipment, the battery array state-of-charge if a battery array is present, and the energy surplus available at the terminals of the load if the system produces more than enough energy to satisfy the load demand, or the energy deficit if the system cannot supply the load demand.

PVSS is written entirely in Fortran for the CDC6600, although it should be transferrable to any machine with a Fortran compiler. The code requires 16K₈ central memory and executes a simulation at the rate of 1 second/day, updating every half-hour.

This report describes the use of PVSS to simulate a photovoltaic system. Chapter II explains the theory for the models used in the simulation subroutines. Chapter III discusses the input required from the user to specify the system configuration, component characteristics, and simulation parameters desired. Finally, Chapter IV provides sample runs illustrating program performance for the different system configurations. Tradeoffs between the speed of execution and the accuracy of the simulation models are also mentioned.

Chapter II - Theory

This chapter describes the theoretical models used to represent the components of a photovoltaic system. Models for a solar cell, solar cell array, maximum power point tracking device, inverter, dc-voltage regulator, and battery array are presented; the model descriptions include equations and figures specifying component performance, and a discussion relating the component interaction in an overall system environment.

Solar Cell Model

A solar cell is a photovoltaic device designed to convert sunlight into electrical power and to deliver this power into a suitable load in an efficient manner. Virtually all solar cells now in use consist of a Si single crystal wafer 12-18 mil thick having a very thin (0.2-0.5 μm) diffused region at the surface to form a p-n junction. Electrical contact is made to the diffused region in such a way that a maximum amount of light is allowed to fall on the Si. Ohmic contact is also made to the back of the wafer. A sputtered or evaporated anti-reflection coating is applied to reduce the amount of light lost by reflection from the surface. Finally, a cover glass of quartz, sapphire, or specially treated glass, with additional antireflection and ultraviolet rejection filters, is bonded to the cell with transparent adhesive to prevent high energy particles from reaching and degrading the device. The heavily doped side of the junction is called the top region of the solar cell. The other side of the junction, consisting of the remainder of the substrate except for the depletion region, is called the base.

If reverse voltages in excess of a few tenths of a volt are applied to the p-n junction, an almost constant current (independent of the magnitude of the reverse bias) is obtained. The dark current corresponds to the reverse saturation

current due to thermally generated minority carriers. When light falls upon the surface, additional electron-hole pairs are formed. Since the concentration of majority carriers greatly exceeds that of minority carriers, it is justifiable to ignore the increase in majority density and to consider the radiation solely as a minority-carrier injector. These injected minority carriers diffuse to the junction, cross it, and contribute to the current.

An equivalent circuit of a solar cell under radiation is shown in Fig. 2.

FIGURE 2. SOLAR CELL MODEL

where R_S is the series resistance of the cell
 I_L is the light-generated current
 I_D = dark current
 V_D = diode voltage (positive for a forward-biased diode)
 I = total cell current
 and V = cell voltage.

From Fig. 2, it can be seen that

$$I = I_L + I_D \quad (1)$$

and

$$V_D = IR_S + V \quad (2)$$

The dark current I_D is simply the current through a diode with voltage V_D across it

$$I_D = I_0 \left(1 - e^{-\frac{q}{kT} V_D} \right) \quad (3)$$

where I_0 is the reverse saturation current, and T is the temperature in $^{\circ}\text{K}$. Note that I_0 is actually a function of T .

Combining Eqs. 1, 2, and 3, we obtain the current-voltage relation for a solar cell

$$I = I_L + I_0 \left[1 - e^{-\frac{q}{kT} (V + IR_S)} \right] \quad (4)$$

Equations for short-circuit current, I_{SC} , and open-circuit voltage, V_{OC} , can be derived from Eq. (4).

$$I_{SC} = I_L + I_0 \left[1 - e^{-\frac{q}{kT} I_{SC} R_S} \right] \quad (5)$$

and

$$V_{OC} = \frac{kT}{q} \ln \left[1 + I_L / I_0 \right] \quad (6)$$

It will be assumed that only a limited amount of information will be available to describe the solar cells. Specifically, I_{SC} and V_{OC} at four conditions of temperature and insolation:

low insolation, C_L , and low temperature, T_L ,

low insolation, C_L , high temperature, T_H

high insolation, C_H , low temperature, T_L

high insolation, C_H , high temperature, T_H

Typical values for C_L and C_H are 1 and 50 suns, respectively; and for T_L and T_H are 25°C and 100°C, respectively. The series resistance, R_S , can be calculated by measuring the cell voltage at two additional values of current [1]:

$$V = V_{\Delta}^{LL} \text{ at } I = I_{SC}^{LL} - \Delta I \text{ for } C = C_L, T = T_L$$

and
$$V = V_{\Delta}^{HL} \text{ at } I = I_{SC}^{HL} - \Delta I \text{ for } C = C_H, T = T_L,$$

where ΔI is typically 10 to 30 mA, I_{SC}^{LL} is short circuit current at low insolation and low temperature, and I_{SC}^{HL} is short circuit current at high insolation and low temperature.

Using this information about the I-V curves, the series resistance of the solar cell can be computed by

$$R_S = \left| \frac{V_{\Delta}^{LL} - V_{\Delta}^{HL}}{I_{SC}^{HL} - I_{SC}^{LL}} \right| \quad (7)$$

For modern solar cells, R_S usually lies between 0.05Ω and 0.2Ω.

I_0 in Eq. (4) is of the form

$$I_0(T) = K_{dev} n_i^2(T) \quad (8)$$

where

K_{dev} is a device-specific constant, independent of temperature and insolation,

and

$n_i^2(T)$ is the square of intrinsic carrier concentration, and is a function of temperature and device material.

An accurate equation for $n_i^2(T)$ over a temperature range from 200°K to 500°K is:

$$n_i^2(T) = A_0 T^3 e^{-E_{GO}/kT}, \quad (9)$$

where T is the temperature of the solar cell in °K

k is Boltzman's constant

E_{GO} is the band-gap at 0°K

and A_0 is a material-specific constant.

For silicon,

$$n_i^2(T) = 1.54 \times 10^{33} T^3 10^{-6080/T} \quad (10)$$

Solving Eqs. (5) and (6) for I_L and equating the results, we obtain

$$I_0 \left[e^{\frac{qV_{OC}}{kT}} - 1 \right] = I_{SC} + I_0 \left[e^{\frac{q}{kT} I_{SC} R_s} - 1 \right] \quad (11)$$

Using Eq. (11) to derive an expression for I_0 and substituting in Eq. (8), an expression for K_{dev} in terms of measurable and computable quantities results.

$$K_{dev} = \frac{1}{n_i^2(T)} \cdot \frac{I_{SC}}{e^{\frac{qV_{OC}}{kT}} - e^{\frac{qI_{SC}R_s}{kT}}} \quad (12)$$

The only quantity remaining in the solar cell description whose dependence upon insolation and temperature is incompletely known is the light-generated current. However, it is known that for well designed solar cells under low to moderate insolation and temperature conditions, the light-generated current is

proportional to insolation. At high insolation and temperature, deviations from linearity are observed. Therefore, the light-generated current is represented as a bivariate series expansion in temperature and insolation in which higher-order terms are dropped,

$$I_L = I_{LL} C \left[1 + \delta_C (C - C_L) + \delta_T (T - T_L) + \delta_{CT} (C - C_L) (T - T_L) \right] \quad (13)$$

The parameters I_{LL} , δ_C , δ_T , and δ_{CT} are determined from measured short-circuit currents as follows:

$$I_{LL} = \frac{I_{SC}^{LL} + I_o(T_L) \left[e^{\frac{q}{kT_L} \frac{I_{SC}^{LL} R_S}{I_{SC}^{LL}}} - 1 \right]}{C_L}, \quad (14)$$

where the first I_{SC} superscript H or L represents high or low insolation, respectively, and the second superscript pertains to temperature.

Expressions for the remaining light-generated current parameters are:

$$\delta_C = \frac{I_{SC}^{HL} + I_o(T_L) \left[e^{\frac{q}{kT_L} \frac{I_{SC}^{HL} R_S}{I_{SC}^{HL}}} - 1 \right] - I_{LL} C_H}{I_{LL} C_H (C_H - C_L)}, \quad (15)$$

$$\delta_T = \frac{I_{SC}^{LH} + I_o(T_H) \left[e^{\frac{q}{kT_H} \frac{I_{SC}^{LH} R_S}{I_{SC}^{LH}}} - 1 \right] - I_{LL} C_L}{I_{LL} C_L (T_H - T_L)}, \quad (16)$$

and

$$\delta_{CT} = \frac{I_{SC}^{HH} + I_o(T_H) \left[e^{\frac{q}{kT_H} \frac{I_{SC}^{HH} R_S}{I_{SC}^{HH}}} - 1 \right] - I_{LL} C_H - I_{LL} C_H \delta_C (C_H - C_L) - I_{LL} C_H \delta_T (T_H - T_L)}{I_{LL} C_H (C_H - C_L) (T_H - T_L)} \quad (17)$$

The behavior of the solar cell may be described more exactly by using a larger number of terms in the bivariate series expansion. However, Equation (13) represents a compromise between accuracy and efficiency that fits observed solar cell characteristics with an error of less than 5% at high temperatures and insolation and an error less than 1% under more moderate conditions [2]. Equations for current and voltage in a solar cell at a given temperature and insolation are:

$$I = I_L(C,T) + I_O(T) \left[1 - e^{\frac{q}{kT}(V+IR_S)} \right] \quad (18)$$

and

$$V = \frac{kT}{q} \ln \left[1 + \frac{I_L(C,T) - I}{I_O(T)} \right] - IR_S \quad (19)$$

where $I_O + I_L > I$ is required.

Determination of Solar Cell Current

Equation 18 is an implicit expression for solar cell current in terms of cell terminal voltage. The Newton-Raphson method is an efficient mechanism for solving this equation.

Define:

$$f(I) = I_L + I_O - I_O e^{\frac{qV}{kT}} e^{\frac{qR_S}{kT} I} - I \quad (20)$$

Solve: $f(I) = 0$

Let: $c_1 = I_L + I_0 > 0$

$$c_2 = I_0 e^{\frac{qV}{kT}} > 0$$

$$c_3 = \frac{qR_S}{kT} > 0$$

$$f(I) = c_1 - c_2 e^{c_3 I} - I \quad (21)$$

$$f'(I) = -c_2 c_3 e^{c_3 I} - 1 < 0 \quad (22)$$

$$f''(I) = -c_2 c_3^2 e^{c_3 I} < 0 \quad (23)$$

FIGURE 3. NEWTON-RAPHSON METHOD

The Newton-Raphson method generates the $n+1^{\text{st}}$ approximation to the solution of $f(I) = 0$ from the previous approximation I_n , and the values of $f(I_n)$ and $f'(I_n)$ as follows:

$$I_{n+1} = I_n - \frac{f(I_n)}{f'(I_n)} \quad (24)$$

Specifically,

$$I_{n+1} = I_n + \frac{I_L(C,T) + I_0(T) \left[1 - e^{-\frac{q}{kT} (V + I_n R_S)} \right] - I_n}{\frac{I_0(T) R_S}{q \frac{q}{kT} e^{-\frac{q}{kT} (V + I_n R_S)} + 1}} \quad (25)$$

This technique provides a contraction mapping on the interval of uncertainty in the current domain, and hence converges rapidly to the true current.

Solar Cell Array Model

The solar cell array consists of a series connection of n groups of cells, each of which contains m solar cells connected in parallel. I-V characteristics of the array as a function of insolation and temperature are approximated by scaling the characteristics of a single solar cell by a factor m in current and a factor n in voltage. This approach provides a quickly computable approximation to cell array performance without considering distributed resistance effects. The solution to the multidimensional nonlinear minimization problem resulting from taking into account distributed resistance requires much longer execution times than the procedure described above.

Maximum Power Tracker

This device imposes on the solar cell array an effective load that causes the cells to operate at their maximum power point. The maximum power point of a cell is located by a subroutine which performs a sequential dichotomous search on the unimodal power vs voltage curve. The search usually arrives at within .01% of the maximum power point within ten iterations.

The maximum power tracker is specified by a power rating and an efficiency that is a quadratic function of load. If $\eta(f)$ represents the efficiency at fractional load f , $0 \leq f \leq 1$, then

$$\eta(f) = \eta_1 \frac{(f-f_1)(f-f_2)}{(1-f_1)(1-f_2)} + \eta_{f_1} \frac{(1-f)(f-f_2)}{(1-f_1)(f_1-f_2)} + \eta_{f_2} \frac{(1-f)(f_1-f)}{(1-f_2)(f_1-f_2)} \quad (26)$$

where η_1 is the efficiency at full load, η_{f_1} is the efficiency at fractional load f_1 , and η_{f_2} is the efficiency at fractional load f_2 .

If feeding a battery, the maximum power tracker adjusts its output to provide up to full charge. If not, the output voltage is constant. Current can be drawn up to a maximum value such that power out equals power in times $\eta(f)$ specified in Equation (26). Usually $\eta(f)$ is between 85% and 95%. The maximum power tracker will readjust the operating point of the solar cell array to reduce generated power if either the rated load is exceeded or a net energy surplus is being produced by the system.

Power Conditioning Equipment (Inverter and DC Voltage Regulator)

An inverter is assumed to have a nominal AC output voltage for a nominal DC input voltage with the output fluctuating proportionally to the input. A DC regulator provides a constant output voltage and series resistance over a specified range of input voltages. Both the inverter and dc-voltage regulators are described by a power rating and an efficiency that is a quadratic function of load, Eq. (26). The power available at the output terminals of the inverter is always assumed equal to the load demand, while the demand on the system is greater than the actual load demand by a factor related to the inefficiency of the power conditioning equipment. Energy surpluses or deficits at the load terminals are monitored by an energy accounting subroutine.

Battery

It is assumed that the battery charges and discharges along a set of curves of the form illustrated in Fig. 4. These curves are typical of the charge/discharge characteristics of hybrid lead-acid battery cells [3]. The terminal voltage of a battery cell decreases linearly with state-of-charge at a given discharge rate and increases linearly with state-of-charge at a given charge rate until a specified breakpoint is reached. After this, the terminal voltage increases at a different linear rate from the breakpoint state-of-charge to full charge.

The battery model assumes a constant series resistance and charge efficiency, in addition to a specified minimum and maximum state-of-charge. No model is included for state-of-charge greater than 100%, since in practice this condition causes deterioration of the battery, and it is assumed that a circuit has been included to prevent overcharging. The battery array is constructed by connecting cells in series and parallel until the desired terminal voltage and battery capacity in amp-hrs are achieved.

FIGURE 4. BATTERY CHARGE/DISCHARGE CURVES

Insolation and Load Demand Profiles

Both insolation and load as a function of time are supplied to the simulation subroutines through function subprograms. These may be altered to any desired profile by the user.

The profiles utilized in the simulations described in this report are illustrated in Fig. 5 (insolation) and Fig. 6 (load demand).

FIGURE 5. INSOLATION PROFILE - DESCRIBES A SUN RISE AT HOUR 6 WITH A LINEAR INCREASE TO HOUR 10, MAINTAINING 1 SUN FROM HOUR 10 TO HOUR 14, AND A LINEAR DECREASE TO HOUR 18, SUNSET.

FIGURE 6. LOAD DEMAND PROFILE - REFLECTS A STEADY ENERGY DEMAND DURING THE DAY WITH DECREASED USAGE DURING SLEEPING HOURS AND INCREASED USAGE IN THE EARLY EVENING.

Chapter III. Use of PVSS

Specification of System and Simulation Parameters

Program PVSS maintains two labelled common blocks for transferring system specifications and simulation parameters to the program. Subroutines SETD and SETS initialize these parameters. Common block ELEI contains the specifications for the solar cell array, battery array, and power conditioning equipment. It consists of arrays SOCEL, RMPT, BATT, RINV, VR1, and VR2, which pertain to the solar cell array, maximum power point tracker, battery array, inverter, and first and second voltage regulators, respectively. Common block SIMUL contains the variables TIMSTP, NDAY, and ISIM, which indicate the simulation update time interval in minutes, duration of the simulation in days, and the configuration of the system to be simulated, respectively.

One of the 16 nonredundant system configurations in Figure 1 can be chosen by assigning to ISIM an integer value between 1 and 16. These values and the systems corresponding to them are listed in Table I of the Appendix (note that every system is assumed to possess a solar cell array and a load demand - the other elements are specified by ISIM).

The characteristics of the solar cell array are specified in the array SOCEL (30). Array elements, descriptions, and sample values are listed in Table II of the Appendix, together with the information that a particular array element is either supplied by the user or computed by the program.

The maximum power point tracker characteristics are described in array RMPT (30). They are listed in Table III of the Appendix. Array VR1(30), summarized in Table IV of the Appendix, lists the specifications of the first dc voltage

regulator; that is, the dc voltage regulator whose input terminals are connected to the solar cell array. Battery characteristics are enumerated in array BATT(30) (Appendix Table V). The inverter is described in array RINV(30) (Appendix Table VI). Finally, the second dc voltage regulator; that is, the regulator whose output terminals are connected to the load, is specified by array VR2(30) (Appendix Table VII).

In order to completely specify a simulation, the user must supply PVSS with four subprograms: SUBROUTINE SETS, SUBROUTINE SETD, FUNCTION RLOAD(TIME), and FUNCTION SUN(DAY,TIME). Listings of the subprograms used to generate the simulations discussed in Chapter IV are given in the Appendix.

Chapter IV. Sample Runs

This chapter presents and discusses simulation runs for each of the 16 nonredundant photovoltaic systems. Sample values listed in the Appendix were used to specify the solar cell array, battery array, and each piece of power conditioning equipment. Every simulation was conducted for a three day period with updating every half-hour. The temperature of the array was maintained at a constant 28°C, and the insolation and load demand profiles were kept constant from day to day. These profiles are illustrated in Figs. 5 and 6, respectively. Although these profiles were used exclusively in the simulations presented, any desired insolation or load can be easily inserted into the program.

For each system using a maximum power tracker (1-6), the power drawn from the solar cell array is maximized. However, the actual power available at the output terminals of the maximum power tracker is less than the array power by a factor indicating the power tracker efficiency at the given load. Fig. 7 shows the solar array output power and power tracker output power for systems 1-6 under the insolation conditions defined by Fig. 5.

The systems utilizing a dc voltage regulator connected across the output terminals of the solar cell array ascertain the voltage across the array by accessing VR1(10). That is, the voltage regulator specifies a nominal operating point for the solar array. In general, this point will be different from the maximum power point. Simulations conducted of systems 7 through 11 set VR1(10) = 240 v, generating the curves for array output power and regulator output power illustrated in Fig. 8. Notice that the solar cell array when dark and biased nonoptionally will dissipate power instead of generating power. However, this power loss is less than 1% of the array power when the insolation is nonzero. Since the solar cell array is biased nonoptimally by the dc voltage regulator

FIGURE 7. SOLAR CELL ARRAY OUTPUT POWER AND MAXIMUM POWER TRACKER OUTPUT POWER FOR EACH OF THE THREE DAYS SIMULATED (SYSTEMS 1-6)

FIGURE 8: SOLAR CELL ARRAY OUTPUT POWER AND DC VOLTAGE REGULATOR 1 OUTPUT POWER FOR EACH OF THE THREE SIMULATED (SYSTEMS 7-11)

(DCVR), the power drawn from the array by these systems under identical conditions of insolation and temperature is less than for those systems using a maximum power tracker (MPT). A tradeoff exists between the added complexity of a maximum power tracker and the increased power available from the system in this configuration. An additional factor to consider is the difference in efficiency between an MPT and a DCVR. This difference may either negate or enhance the theoretical advantages of an MPT.

If the solar cell array is connected directly across the terminals of the battery array, the operating point of the solar cells is determined by the terminal voltage of the battery. In this system configuration, the solar cells are not optimally biased, but this is compensated for to some extent by the elimination of the inefficiencies associated with a maximum power tracker or a dc-voltage regulator. The power available from the solar cell array in systems 12 through 14 under these conditions is plotted as a function of time for the first day of simulated system performance in Fig. 9.

For systems using battery storage, two quantities are important: battery state of charge and power either delivered to the load while discharging or absorbed from the solar cell array while under charge. Fig. 10 illustrates these two quantities for Systems 1 and 2 (MPT-BATT-INV and MPT-BATT-REG) under the simulation conditions specified earlier in this chapter. Battery power is defined as positive when the battery is supplying energy to the load (i.e., the battery is discharging). When the battery is absorbing energy from the solar cell array, battery power is defined as negative. For Systems 1 and 2 under these conditions, the power supplied by the inverter and the dc-voltage regulator, respectively, equals the load demand over the three day period. The battery array neither completely charges nor discharges during this interval, and the system neither produces excess power nor does it need power from a utility to satisfy the load demand.

FIGURE 9. POWER AVAILABLE FROM SOLAR CELL ARRAY - (SYSTEMS 12-14) - FOR FIRST DAY OF SIMULATED SYSTEM PERFORMANCE.

FIGURE 10. BATTERY STATE OF CHARGE AND BATTERY POWER (+ FOR SUPPLIED, - FOR ABSORBED) FOR SYSTEMS 1 AND 2. (NOTE THAT BATTERY POWER SHOULD BE PERIODICALLY EXTENDED OVER THE THREE DAY PERIOD.)

System 3 consists of a maximum power tracker and a battery array connected directly to a load. With the inefficiency of an inverter or a dc-voltage regulator eliminated from the system, the battery array achieves full charge by the 14th hour on the 3rd day. Since the battery can no longer absorb the excess energy produced by the solar cell array, there is a net energy surplus at the load terminals. This surplus is graphed for the third day of the simulation in Fig. 11.

Systems 4 and 5 (MPT-INV and MPT-REG) have no battery storage to buffer the variations between solar array power output and load demand. Therefore, the energy surplus/deficit accounting reflects the difference between available solar array power and load demand reflected through the inefficiencies of the intervening power conditioning equipment. Fig. 12 plots this energy difference computed half-hourly for Day 1 of the simulated runs. Conditions for Days 2 and 3 are identical. The operation of System 6 (MPT) is similar to Systems 4 and 5 without the inefficiency of an inverter or regulator connected to the load. The result is a slightly larger energy surplus during periods of nonzero insolation.

Systems 7 through 10 are similar in structure to systems 1 through 4, respectively, with the maximum power tracker replaced in each case by a dc-voltage regulator. The configuration obtained when the maximum power tracker in System 5 is replaced by a voltage regulator is two voltage regulators connected in series. Although this arrangement is physically possible, it is not practically meaningful, and was not analyzed. Finally, System 11 is similar to System 6 with a voltage regulator instead of a maximum power tracker.

The battery state of charge and battery power curves for Systems 7 and 8 (REG-BATT-INV and REG-BATT-REG, respectively) are similar to those presented in Fig. 7 with the major difference being the slower rate of battery charge due to nonoptimal biasing of the solar cell array by the dc-voltage regulator. This difference can also be seen between System 9 (REG-BATT) and System 3 (MPT-BATT). While System 3 begins producing surplus power on the 14th hour of the 3rd day, System 9 does not produce a surplus until 14:30. Furthermore, as expected, the total surplus energy generated by System 9 is less than that produced by System 3.

FIGURE 11. ENERGY SURPLUS (KWH) GENERATED BY SYSTEM 3 DURING EACH HALF-HOUR INTERVAL ON DAY 3.

This same effect can be seen in Systems 10 and 11 (REG-INV and REG) as a slightly lower energy surplus than System 4 and 6, respectively.

Systems 12 through 14 (BATT-INV, BATT-REG, and BATT) eliminate the maximum power tracker from Systems 1 through 3. Although this removes one source of power loss, the solar array is nonoptimally biased in these systems by the terminal voltage of the battery array. The resulting loss in available power from the solar cell array degrades the overall system performance more than the inefficiencies associated with a maximum power tracker.

System 15 places an inverter between the solar array and the ac-load. It is similar in performance to System 7. In System 16, the solar array is connected directly to the load without any intervening power conditioning equipment. It produces slightly more energy during periods of nonzero insolation because of the absence of power conditioning equipment inefficiencies. However, some power conditioning will probably be necessary in a practical situation, making System 16 unrealistic as a potential configuration, although interesting for the purposes of comparison.

In a photovoltaic system with battery storage, the battery state of charge describes the state of the system at any specified time. The force driving the system is insolation converted to electricity through the solar cell array and its associated power conditioning equipment minus the load demand increased by a factor equal to the reciprocal of the efficiency of the power conditioning equipment between battery and load. The battery charges or discharges depending upon the sign of the power difference presented to it. Basically, the battery attempts to buffer fluctuations in insolation in order to smoothly supply the time-varying load demand. Enough battery capacity must be provided to reduce the probability of complete discharge to acceptably small levels without overall system cost becoming too high. Determination of the optimal battery capacity for a given environment can be made by simulating photovoltaic systems with varying quantities of battery storage.

Appendix

Table I - System Configurations

<u>ISIM</u>		<u>SYSTEM</u>		
1	Maximum Power Tracker	-	Battery	- Inverter
2	Maximum Power Tracker	-	Battery	- DC Voltage Regular
3	Maximum Power Tracker	-	Battery	- Open Circuit
4	Maximum Power Tracker	-	No Battery	- Inverter
5	Maximum Power Tracker	-	No Battery	- DC Voltage Regulator
6	Maximum Power Tracker	-	No Battery	- Open Circuit
7	DC Voltage Regulator	-	Battery	- Inverter
8	DC Voltage Regulator	-	Battery	- DC Voltage Regulator
9	DC Voltage Regulator	-	Battery	- Open Circuit
10	DC Voltage Regulator	-	No Battery	- Inverter
11	DC Voltage Regulator	-	No Battery	- Open Circuit
12	Open Circuit	-	Battery	- Inverter
13	Open Circuit	-	Battery	- DC Voltage Regulator
14	Open Circuit	-	Battery	- Open Circuit
15	Open Circuit	-	No Battery	- Inverter
16	Open Circuit	-	No Battery	- Open Circuit

Table II - Solar Cell Array

User Supplied (U) or Computed (C)	Array Element	Element Description	Sample Value
U	SOCEL(1)	A_0 = constant factor in n_1^2 computation	1.5×10^{33} for Si
U	SOCEL(2)	E_{GO}/K	14000 °K for Si
U	SOCEL(3)	C_L = low insolation value, suns	1 sun
U	SOCEL(4)	C_H = high insolation value, suns	25 suns
U	SOCEL(5)	T_L = low temperature value, °C	28°C
U	SOCEL(6)	T_H = high temperature value, °C	120°C
U	SOCEL(7)	I_{SC}^{LL} = short circuit current at C_L & T_L , amps	0.06 amps
U	SOCEL(8)	I_{SC}^{HL} = short circuit current at C_H & T_L , amps	1.5 amps
U	SOCEL(9)	I_{SC}^{LH} = short circuit current at C_L & T_H , amps	0.06 amps
U	SOCEL(10)	I_{SC}^{HH} = short circuit current at C_H & T_H , amps	1.56 amps
U	SOCEL(11)	V_{OC}^{LL} = open circuit voltage at C_L & T_L , volts	0.6 v
U	SOCEL(12)	V_{OC}^{HL} = open circuit voltage at C_H & T_L , volts	0.68 v
U	SOCEL(13)	V_{OC}^{LH} = open circuit voltage at C_L & T_H , volts	0.4 v
U	SOCEL(14)	V_{OC}^{HH} = open circuit voltage at C_H & T_H , volts	0.52 v
U	SOCEL(15)	V_{Δ}^{LL} = load voltage at $I = I_{SC}^{LL} - \Delta I$, C_L & T_L , volts	0.57 v
U	SOCEL(16)	V_{Δ}^{HL} = load voltage at $I = I_{SC}^{HL} - \Delta I$, C_H & T_L , volts	0.4 v
C	SOCEL(17)	R_s = series resistance of solar cell	
C	SOCEL(18)	$K_{dev}^{I_0}$ = device dependent constant in I_0 equation	
C	SOCEL(19)	I_{JL} in light generated current equation, amps.	
C	SOCEL(20)	δ_c in light generated current equation	
C	SOCEL(21)	δ_T in light generated current equation, /°C	
C	SOCEL(22)	δ_{CT} in light generated current equation, /°C-sun	
U	SOCEL(23)	# of solar cells in array in parallel	300
U	SOCEL(24)	# of parallel cell groups in series	513
C	SOCEL(25)	voltage across entire array, volts	
C	SOCEL(26)	temperature of array, °C	
C	SOCEL(27)	insolation on array, suns	
C	SOCEL(28)	current out of array, amps	
C	SOCEL(29)	power out of array, watts	
U	SOCEL(30)	default terminal voltage of array, volts	240 v

Table III - Maximum Power Point Tracker

<u>User Supplied (U) or Computed (C)</u>	<u>Array Element</u>	<u>Element Description</u>	<u>Sample Value</u>
C	RMPT(1)	Efficiency of MPT	
U or C	RMPT(2)	Output terminal voltage of MPT, volts	192v = default option
C	RMPT(3)	Output power, watts	
C	RMPT(4)	Output current, amps	
U	RMPT(5)	Power rating, kw (input power it can handle)	4.5 kw
U	RMPT(6)	Efficiency at full load	0.90
U	RMPT(7)	Efficiency at fractional load f_1	0.95
U	RMPT(8)	f_1	0.50
U	RMPT(9)	Efficiency at fractional load f_2	0.85
U	RMPT(10)	f_2	0.20

Table IV - First DC-Voltage Regulator

<u>User Supplied (U) or Computed (C)</u>	<u>Array Element</u>	<u>Element Description</u>	<u>Sample Value</u>
U	VR1(1)	Power rating in kw	5 kw
U	VR1(2)	Efficiency at full load	0.90
U	VR1(3)	f_1	0.80
U	VR1(4)	Efficiency at fractional load f_1	0.95
U	VR1(5)	f_2	0.20
U	VR1(6)	Efficiency at fractional load f_2	0.85
C	VR1(7)	Efficiency	
C	VR1(8)	Power output, watts	
C	VR1(9)	Power input, watts	
U	VR1(10)	Input terminal voltage, volts	240 v

Table V. - Battery

<u>User Supplied (U) or Computed (C)</u>	<u>Array Element</u>	<u>Element Description</u>	<u>Sample Value</u>
U	BATT(1)	battery cell capacity, amp-hrs	250
U	BATT(2)	# battery cells connected in series	100
U	BATT(3)	minimum state of charge	0.0
U	BATT(4)	maximum state of charge	1.0
U	BATT(5)	initial state of charge	0.5
U	BATT(6)	internal resistance of battery cell, Ω	0.04
U	BATT(7)	charge efficiency	0.90
U	BATT(8)	cell voltage at full charge with charge rate f_f , v	2.75
U	BATT(9)	breakpoint in charge curve at rate f_f	0.90
U	BATT(10)	cell voltage at breakpoint, with charge rate f_f , v	2.25
U	BATT(11)	cell voltage at no charge, charge rate = f_f , v	2.08
U	BATT(12)	cell voltage at full charge, charge rate = f_s , v	2.50
U	BATT(13)	breakpoint in charge curve, charge rate = f_s	0.90
U	BATT(14)	cell voltage at breakpoint, charge rate = f_s , v	2.10
U	BATT(15)	cell voltage at no charge, charge rate = f_s , v	2.08
U	BATT(16)	cell voltage at full charge, discharge rate = f_s , v	2.10
U	BATT(17)	cell voltage at no charge, discharge rate = f_s , v	1.95
U	BATT(18)	cell voltage at full charge, discharge rate = f_f , v	2.06
U	BATT(19)	cell voltage at no charge, discharge rate = f_f , v	1.83
C	BATT(20)	battery state of charge = BATT(5) initially	
C	BATT(21)	terminal voltage of battery array = 200 default	
C	BATT(22)	series resistance of battery array = BATT(2)*BATT(6)	
C	BATT(23)	total capacity of battery array = BATT(1)*BATT(2)	
U	BATT(24)	fast charge/discharge rate, f_f	0.2/hr.
U	BATT(25)	slow charge/discharge rate, f_s	0.02/hr.
U	BATT(26)	maximum charge rate	0.5/hr.
U	BATT(27)	maximum discharge rate	0.5/hr.

Table VI - Inverter

<u>User Supplied (U) or Computed (C)</u>	<u>Array Element</u>	<u>Element Description</u>	<u>Sample Value</u>
U	RINV(1)	Power rating, kw	5.0
U	RINV(2)	Efficiency at full load	0.90
U	RINV(3)	f_1	0.80
U	RINV(4)	Efficiency at fractional load f_1	0.95
U	RINV(5)	f_2	0.20
U	RINV(6)	Efficiency at fractional load f_2	0.85
C	RINV(7)	Efficiency	
C	RINV(8)	Power Output	
C	RINV(9)	Power Input	
U	RINV(10)	Input terminal voltage - default - 210 v	

Table VII - Second DC Voltage Regulator

<u>User Supplied (U) or Computed (C)</u>	<u>Array Element</u>	<u>Element Description</u>	<u>Sample Value</u>
U	VR2(1)	Power rating, kw	5.0
U	VR2(2)	Efficiency at full load	0.90
U	VR2(3)	f_1	0.80
U	VR2(4)	Efficiency at fractional load f_1	0.95
U	VR2(5)	f_2	0.20
U	VR2(6)	Efficiency at fractional load f_2	0.85
C	VR2(7)	Efficiency	
C	VR2(8)	Power output, watts	
C	VR2(9)	Power input, watts	

SUBROUTINE SETS

CDC 6600 FTH V3

SUBROUTINE SETS

C

C

C

SETS SIMULATION PARAMETERS.

COMMON/SIMUL/TIMSTEP,NDAY,ISIM

TIMSTEP=30.

NDAY=3

ISIM=12

RETURN

END

10

SUBROUTINE SETD		CDC 6600 FTN V3.0-V34A OPT=1
SUBROUTINE SETD		
	C	
	C	DEVICE CONSTANTS ARE ENTERED OR COMPUTED AND PLACED IN SOCEL
	C	ARRAY
5	C	COMMON/ELEI/SOCEL(30),RMPT(30),BATT(30),RINV(30),VR1(30),VR2(30)
		COMMON/DIAG/NDIAG(30)
		COMMON/PCON/BK
		BK=8.62E-9
10		DO 110 I=1,30
	110	NDIAG(I)=0
		RMPT(1)=0.9
		RMPT(2)=192.
		RMPT(5)=4.5
15		RMPT(6)=0.9
		RMPT(7)=0.95
		RMPT(8)=0.5
		RMPT(9)=0.85
		RMPT(10)=0.2
20		SOCEL(1)=1.5E33
		SOCEL(2)=14000.
		SOCEL(3)=1.
		SOCEL(4)=25.
		SOCEL(5)=28.
25		SOCEL(6)=120.
		SOCEL(7)=0.06
		SOCEL(8)=1.5
		SOCEL(9)=0.06
		SOCEL(10)=1.56
30		SOCEL(11)=0.6
		SOCEL(12)=0.68
		SOCEL(13)=0.4
		SOCEL(14)=0.52
		SOCEL(15)=0.57
35		SOCEL(16)=0.4
		SOCEL(23)=300.
		SOCEL(24)=513.
		SOCEL(30)=240.
		CALL XRS
40		IF(NDIAG(1).NE.0) WRITE(6,11) SOCEL(17)
	11	FORMAT(//10X,*UNEXPECTEDLY LARGE OR SMALL SERIES RESISTANCE*,
		1* RS=*,E13.6,5X,* EXECUTION CONTINUING*)
		CALL XKIO
		IF(NDIAG(2).NE.0) WRITE(6,12) SOCEL(18)
45		12 FORMAT(//10X,*LARGE DEVIATIONS IN COMPUTED KIO VALUES, KIO=*,
		1E13.6,5X,*EXECUTION CONTINUING*)
		CALL XPAR
		IF(NDIAG(3).NE.0) WRITE(6,13)
50		13 FORMAT(//10X,*DENOMINATOR IN XPAR ROUTINE .LE. 0. EXECUTION*,
		1* TERMINATING*)
		BATT(1)=250.
		BATT(2)=100.
		BATT(3)=0.
		BATT(4)=1.
55		BATT(5)=0.5

SUBROUTINE SETD

CDC 6600 FTN V3.0

```

      BATT(6)=0.04
      BATT(7)=0.9
      BATT(8)=2.75
      BATT(9)=0.9
60      BATT(10)=2.25
      BATT(11)=2.08
      BATT(12)=2.5
      BATT(13)=0.9
      BATT(14)=2.10
      BATT(15)=2.08
65      BATT(16)=2.10
      BATT(17)=1.95
      BATT(18)=2.06
      BATT(19)=1.83
      BATT(20)=BATT(5)
70      BATT(21)=200.
      BATT(22)=BATT(2)*BATT(6)
      BATT(23)=BATT(1)*BATT(2)
      BATT(24)=0.2
75      BATT(25)=0.02
      RINV(1)=5.
      RINV(2)=0.9
      RINV(3)=0.8
      RINV(4)=0.95
80      RINV(5)=0.2
      RINV(6)=0.85
      RINV(10)=240.
      VR2(1)=5.
      VR2(2)=0.9
85      VR2(3)=0.8
      VR2(4)=0.95
      VR2(5)=0.2
      VR2(6)=0.85
      VR1(1)=5.
90      VR1(2)=0.9
      VR1(3)=0.8
      VR1(4)=0.95
      VR1(5)=0.2
      VR1(6)=0.85
95      VR1(10)=240.
      RETURN
      END

```

FUNCTION	RLOAD		CDC 6600 FTN V3.0-V34A OPT=1
		FUNCTION RLOAD(TIME)	
	C		
	C	PRODUCES A DIVERSIFIED LOAD DEMAND PROFILE AS A FUNCTION	
	C	OF TIME.	
5	C		
		IF(TIME.LE.6.) RLOAD=0.5	
		IF(TIME.GT.6..AND.TIME.LE.17.) RLOAD=1.	
		IF(TIME.GT.17..AND.TIME.LE.21.) RLOAD=1.5	
		IF(TIME.GT.21.) RLOAD=0.5	
10		RLOAD=RLOAD*1000.	
		RETURN	
		END	

FUNCTION SUN

CDC 6600 FTM V3.0-V34A OPT=1

FUNCTION SUN(DAY,TIME)

C

C

C

C

GIVEN THE DAY, A POSITIVE INTEGER, AND THE HOUR, 1 TO 24,
INSOLATION IN SUNS IS RETURNED.

5

IF(TIME.LE.6.) SUN=0.

IF(TIME.GT.6..AND.TIME.LE.10.) SUN=-1.5+0.25*TIME

IF(TIME.GT.10..AND.TIME.LE.14.) SUN=1.

IF(TIME.GT.14..AND.TIME.LE.18.) SUN=4.5-0.25*TIME

10

IF(TIME.GT.18.) SUN=0.

RETURN

END

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