PHOTOVOLTAIC ARRAY--POWER CONDITIONER INTERFACE REQUIREMENTS[1]

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ABSTRACT

The electric output of flat-plate arrays changes constantly, due primarily to changes in cell temperatures and irradiance levels. As a result, array loads such as dc-to-ac power conditioners must be able to accommodate widely varying input levels while maintaining operation at or near the array maximum power point. The results of an extensive computer simulation study used to define the parameters necessary for the systematic design of array-load interfaces, including optimum operating voltage, voltage tracking width, maximum power and current limits, and maximum open-circuit voltage are presented as normalized ratios of power-conditioner parameters to array parameters to make the results universally applicable to a wide variety of system sizes, sites and operating modes.

1. INTRODUCTION

The electric output of photovoltaic (PV) arrays is unique, in contrast with conventional electric-power generators.

It requires careful consideration if efficient and reliable performance is to be achieved.

Figure 1 illustrates the typical current-voltage (I-V) characteristic of an array and the way it varies with changing cell temperature and irradiance level. In general the short-circuit current of the array is directly proportional to the irradiance level, and the voltage at the maximum power point is linearly dependent upon cell temperature, decreasing about 0.5% of its 25°C value for each degree centigrade of increasing cell temperature. Maximum power output is generated at a point on the knee of the curve called the maximum power point.

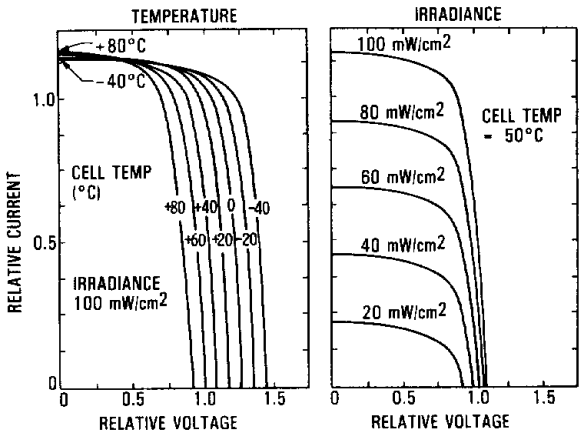

Fig. 1. Influence of Irradiance Level and Cell Temperature on Array I-V Curve

Because of strong dependence on irradiance level and cell temperature, the output of a PV array is dependent on weather conditions and on array construction practices that influence these parameters. If maximum energy is to be drawn from the array, the array load must accommodate these site-specific and time-dependent changes in array output. Also maximum current, voltage and power ratings of the load must be compatible with the maximum levels that the array can deliver. In many applications the load for the PV array will be a power conditioning subsystem (PCS) designed to convert the direct-current (dc) array output into alternating current (ac), which is the form supplied by utilities.

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To aid the designer in making proper system tradeoffs, this paper summarizes an extensive study conducted by the Jet Propulsion Laboratory (Ref. 1) to characterize the output of flat-plate PV arrays under a variety of operating conditions typical of sites throughout the United States. The limitation to flat-plate arrays results from the use of weather data for total irradiance on fixed-tilt flat surfaces, as opposed to the direct-normal irradiance that would be used for tracking concentrator arrays.

After the next section, which provides an overview of the general analysis approach, each of the remaining sections treats one aspect of array performance and its influence on the design of array loading systems.

2. GENERAL ANALYSIS APPROACH

To define the relationships between typical array performance and various loading means, it was necessary to simulate typical array performance for a variety of representative long-term operating conditions. This was done using a computer to calculate hourly electric output for a period of a year at each of 26 sites in the United States. Hourly weather data were obtained using SOLMET TMY weather data tapes containing historical measurements for a typical meteorological year at each site.

The hourly irradiance level on the array was derived from the SOLMET irradiance data using an algorithm developed by Klucher and based on the work of Liu-Jordan (see Ref. 2). The array was assumed to be a flat, south-facing surface tilted up from the horizontal at an angle equal to the latitude of the site. The hourly cell temperature was then computed based on the irradiance level incident on the array, and the hourly ambient air temperature from the SOLMET data tape. For a detailed description of the algorithms, see Ref. 2.

Hourly electrical performance was derived using a baseline curve selected as representative of a present-day silicon-cell array. This I-V curve defined the normalized output of the typical array at standard reporting conditions (100 mW/cm^2, 25°C), and was used to derive the appropriate I-V curve for each hourly irradiance level and cell temperature.

Because the shape of solar-cell I-V curves varies somewhat in cells of different manufacture, and with different degrees of degradation with age, other I-V curves were also used to define the sensitivity of the simulation results to curve shape. The shape, or squareness, of I-V curves is generally quantified by the parameter fill factor, which is defined as the ratio of maximum power to the product of open-circuit voltage and short-circuit current. Typical curves for new arrays have fill factors averaging around 0.70, and ranging from 0.60 to 0.76. As an array ages its fill factor often decreases, reflecting degradation associated with increased series resistance. Fill factors ranging from 0.45 to 0.75 were used in the sensitivity studies.

To make the results as generally applicable as possible, the data are presented as normalized ratios of load characteristics to array characteristics at Standard Operating Conditions (100 mW/cm^2, NOCT). Standard Operating Conditions (SOC) are a set of recognized reference conditions for rating PV arrays and are different from peak rating conditions (100 mW/cm^2, 25°C) in that they use the Nominal Operating Cell Temperature (NOCT) for the chosen PV modules in the intended mounting configuration, instead of the fixed 25°C cell temperature that is selected for ease in laboratory measurements. Use of NOCT makes the results of this study generally independent of operating temperature differences associated with modules and arrays with different thermal properties. Site-to-site weather-related operating-temperature differences are included separately through the presentation of site-specific results.

The NOCT for any particular array is defined as the operating temperature of the cells in the intended mounting configuration with an incident irradiance level of 80 mW/cm^2, an air temperature of 20°C, a wind velocity of 1 m/s, and the array open-circuited. This set of conditions yields a temperature that accurately represents the average cell temperature in the field during periods of significant energy production (Ref. 2). Roughly 50% of the energy will be produced above and 50% below this temperature.

Typical values of NOCT for ground-mounted arrays range from 45°C to 50°C, and for roof-mounted arrays from 60°C to 70°C.

The I-V curve at SOC for an array of interest can be closely approximated from the I-V curve at peak rating conditions by subtracting a voltage offset (shifting the curve to the left, parallel to the voltage axis) by an amount equal to 0.5% of the maximum power voltage at 25°C times the temperature difference (NOCT 25°C).

The majority of the results that follow are presented in terms of the current, voltage or power produced by the array at its maximum power point under SOC.

3. MAXIMUM POWER TRACKING

To achieve maximum energy output from the array under field operating conditions requires that the PCS operation at, or track, the maximum power point. Various strategies are available.

(1) Operation at constant voltage.

(2) Seasonally, or frequently, adjusted constant-voltage operation based on temperature sensing.

(3) Continuous closed-loop feedback sensing of the PCS output power to achieve continuous operation at the maximum power point.

A key consideration in the tradeoff between fixed-voltage operation or some form of periodic or continuous voltage tracking is the gain in array energy that can be achieved. A second consideration is selection of the optimum fixed voltage or voltage window limits with respect to the array voltage rating.

To provide a data base for these decisions, the annual energy output from the baseline array was determined for each of the 26 sites for a large number of fixed-voltage systems with different fixed voltages, and for an ideal continuous tracking system. Sensitivity studies were then conducted using other array fill factors.

3.1 Fixed-Voltage Operation

Fig. 2 presents an example plot of normalized energy output vs normalized PCS voltage for Albuquerque NM. The ordinate scale in this plot is the fraction of available energy drawn from the array during the indicated period of the year (spring and fall, summer, winter and full year) by a constant-voltage system. The ratio of the PCS operating voltage to the array maximum-power voltage (V_{mp}) at SOC is indicated on the abscissa. This plot for Albuquerque indicates, for example, that the optimum voltage without seasonal adjustment is approximately 96% of the array V_{mp} at SOC, and that this fixed voltage system will lose about 2% of the available energy.

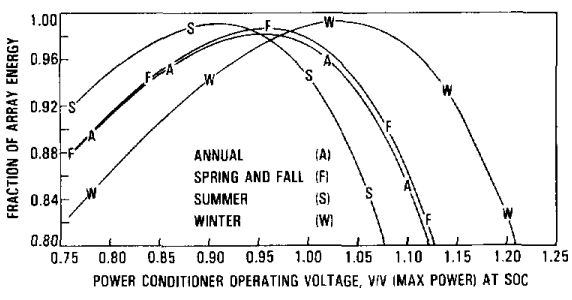

Fig. 2. Fraction of Annual Array Available Energy Obtained vs PCS Fixed Operating Voltage (Albuquerque NM)

Table 1 summarizes the key findings for 12 representative sites selected out of the 26 analyzed. It can be seen that the optimum fixed-voltage ranges from about 92% of the array voltage for hot climates, such as that of Phoenix AZ, to 100% of the array voltage for colder climates, such as that of Caribou ME. In addition, it can be seen that the fraction of annual available energy that is lost by a fixed-voltage system ranges from 0.7 to 2.5%, with few sites over 2%.

TABLE 1. SIMULATION RESULTS FOR FIXED-VOLTAGE POWER CONDITIONER

SITE	OPTIMUM OPERATING VOLTAGE (V_{op}/V_{mp} at SOC)	% LOSS IN ENERGY (FIXED VOLTAGE) (NO SEASONAL ADJUSTMENT)
ALBUQUERQUE NM	0.96	1.7
BISMARCK ND	0.97	2.5
BOSTON MA	0.97	2.0
BROWNSVILLE TX	0.92	0.8
CARIBOU ME	1.00	2.2
CHARLESTON SC	0.95	1.1
FORT WORTH TX	0.93	1.5
FRESNO CA	0.94	1.3
MIAMI FL	0.93	0.7
OMAHA NB	0.96	2.1
PHOENIX AZ	0.92	1.4
SEATTLE WA	0.97	1.4

Although these results are useful for the sites analyzed, relatively few sites have the data base required to perform the analyses. Therefore a regression analysis was performed to examine possible correlations between historical site daily maximum temperatures and the observed optimum operating voltage and annual energy loss. Figs. 3 and 4 show the results obtained when the simulation results for the 26 SOLMET sites investigated were correlated with the maximum-temperature data from a standard atlas (Ref. 3). The

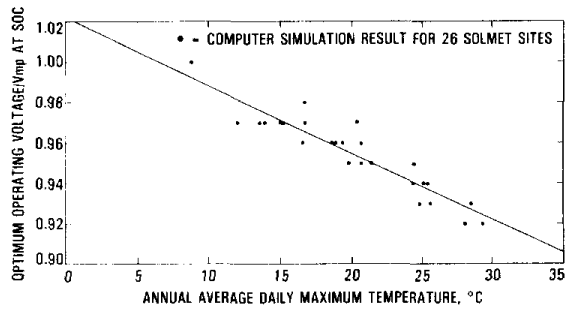

Fig. 3. Array Optimum Operating Voltage vs Average Daily Maximum Temperature

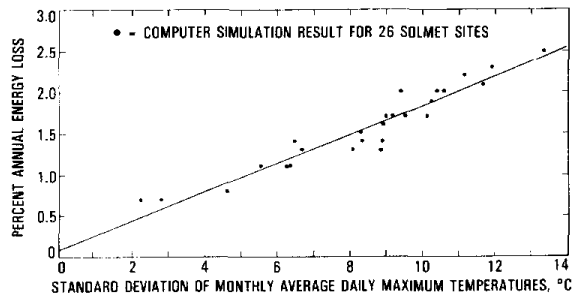

Fig. 4. Array Annual Energy Loss with Fixed Voltage Operation vs Standard Deviation of Daily Maximum Temperature

optimum operating voltage is seen to correlate well with the annual average maximum temperature and the percentage of energy lost with the standard deviation of the monthly averages of daily maximum temperature. The curves provide a ready means of estimating optimum voltage and annual energy loss with the use of monthly average daily maximum temperatures obtained from any weather atlas or from long-term recorded weather data.

Table 2 describes the sensitivity of the above results to array I-V curve fill factor for two representative sites. These results indicate a modest trend toward increasing power-conditioner voltages with higher fill factors, and small changes in annual energy losses.

TABLE 2. EFFECT OF FILL FACTOR ON FIXED-VOLTAGE PCS OPERATION RESULTS

FILL FACTOR	OPTIMUM OPERATING VOLTAGE		% LOSS IN ENERGY	
	ALBUQUERQUE	BOSTON	ALBUQUERQUE	BOSTON
0.45	0.90	0.85	2.4	3.5
0.50	0.91	0.88	2.0	3.4
0.55	0.93	0.90	1.8	3.3
0.60	0.94	0.92	1.8	3.2
0.65	0.95	0.94	1.7	2.8
0.70	0.96	0.97	1.7	2.0
0.75	0.96	0.99	2.2	1.9

3.2 Continuous Voltage Tracking

With ideal maximum-power tracking, closed-loop feedback is used to capture the maximum available energy from the array by continuously tracking the array maximum-power voltage. This is one means of dealing with the site and fill-factor dependencies just described. The degree of voltage movement required to obtain most of the available energy is an important input to the design of such a system. This voltage window is most easily characterized by the center voltage in the window and the plus and minus percentage of movement, or tracking range, from the center voltage.

The hourly computer simulations were used to develop data on the optimum center voltage and the fraction of the available energy that is obtained as a function of the tracking range. The optimum center voltage turns out to be nominally the same as the optimum fixed voltage presented in Table 1. Fig. 5 illustrates the percentage loss in annual available energy for five representative sites as a function of the tracking range half width (stated as a percentage of the optimum center voltage).

As can be seen from these data, a ±5% tracking range achieves most of the available energy, and a ±12% tracking range is the

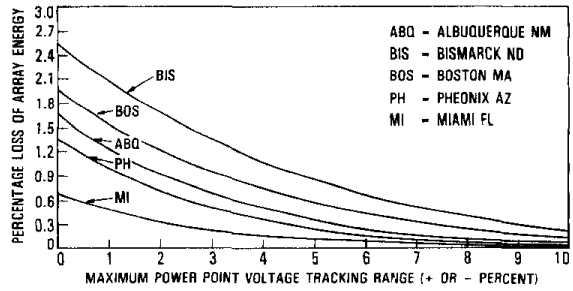

Fig. 5. Percentage Loss in Array Annual Available Energy vs PCS Voltage Tracking Range Half Width, Expressed as a Percentage of Optimum Center Voltage

maximum needed at any site. Fill factor is found to have a minor effect on these results.

An additional consideration in the selection of continuous tracking as a strategy, and tracking range as a parameter, is the opportunity to accommodate not only the seasonal weather variations, but also the site and fill-factor dependencies. The latter requires a tracking range that reflects the changing center voltage as well as the tracking range shown. From an analysis of the data it appears that a ±18% tracking width together with a center voltage around 0.92 will accommodate all of the 26 sites studied.

Another consideration in the design of voltage tracking systems is the degree to which the control algorithm leads to local searching or oscillation about the maximum power point. Depending on the amplitude of oscillation, sufficient energy can be lost to negate the advantages of continuous tracking.

4. EXTREME VALUE ANALYSIS

Another important PCS design issue is the maximum power, current and voltage that the PCS must withstand. Three key considerations are evident:

(1) The amount of energy that is lost during times when the array output exceeds PCS operating limits and energy is rejected.

(2) The protection strategy to be used when the maximum limits are exceeded.

(3) The absolute maximum levels expected if survival limits are a consideration.

4.1 Current and Power Limits

A key consideration in the selection of current and power limits is the cost of accepting higher levels compared with the energy lost, or down-time suffered when over-limit conditions are encountered. At least three

basic protection strategies exist. One involves PCS shutdown, with manual reset, when ratings are exceeded. This operating strategy requires that operating limits be set near the maximum values foreseeable in order to eliminate nuisance tripping. A second strategy involves total rejection of power during over-limit conditions, with automatic recovery when acceptable levels return. The third strategy involves rejection of only enough power to bring the current or power within limits. This could be accomplished by shunting some of the array current around the PCS, or by moving away from the maximum power point to a location on the I-V curve with acceptable power and current levels.

To assess the above options, the energy loss was calculated for the last two strategies as a function of the PCS current and power levels. Table 3 summarizes the current limits that would result in obtaining 99% and 99.9% of the available annual energy for 12 representative sites. In each case the limits are normalized to the array current at maximum power at SOC. It can be seen that for the same energy performance, a PCS using a total-rejection strategy must accommodate levels about 15% higher than one using a partial-rejection strategy.

TABLE 3. EFFECT OF PARTIAL AND TOTAL REJECTION STRATEGIES ON POWER AND CURRENT LIMITS VS FRACTION OF AVAILABLE ENERGY OBTAINED

SITE	PC CURRENT LIMIT ARRAY I_{mp} at SOC TO GAIN INDICATED % OF ENERGY OBTAINED WITH NO LIMIT				VOLTAGE EXCURSION FOR 99% LIMIT (%)
	99%		99.9%		
	(P)	(T)	(P)	(T)	
ALBUQUERQUE	1.06	1.19	1.17	1.20	11.5
BISMARCK	0.95	1.07	1.05	1.10	15.5
BOSTON	0.89	1.04	1.01	1.09	13.4
BROWNSVILLE	0.92	1.04	1.03	1.05	6.5
CARIBOU	0.94	1.09	1.08	1.10	15.0
CHARLESTON	0.90	1.04	1.01	1.08	9.5
FORT WORTH	0.94	1.05	1.04	1.10	15.1
FRESNO	0.98	1.05	1.04	1.05	10.6
MIAMI	0.86	1.02	0.97	1.05	9.7
OMAHA	0.95	1.09	1.08	1.26	12.5
PHOENIX	1.00	1.06	1.05	1.16	9.8
SEATTLE	0.88	0.95	0.95	0.96	12.4

(P) = PARTIAL (T) = TOTAL

For the partial-rejection strategy it is also useful to know the maximum voltage excursion away from the PCS center voltage that would be required to bring the operating levels within the limits. This was determined for a PCS sized to obtain 99.9% of the available energy, and is included in the last column of Table 3. The complete results for the 26 sites show that the maximum excursion ranges from 5% to 17% of the center voltage, and exceeds the tracking-range requirements presented in Fig. 5, which assume no current or power limits. Fill factor was found to have only a small effect on maximum current and power limits.

4.2 Voltage Limits

Voltage limits must also be considered by the PCS design, particularly during startup when the array may be at its maximum open-circuit voltage (V_{oc}). Worst-case V_{oc}s generally are associated with low temperatures and high irradiance levels, such as might be encountered during a bright, cold winter day with snow on the ground. Three approaches were used to estimate likely maximum V_{oc}s:

(1) The hourly combination of incident irradiance and calculated cell temperature (based on incident irradiance and ambient air temperature) that led to the maximum V_{oc}s was noted. This voltage represents the worst-case thermal-equilibrium condition existing on the SOLMET TMY tape. Because this condition does not reflect the easily foreseeable case where the sun suddenly appears from behind an obstruction and shines on a cold array, it is considered a lower-bound estimate of the maximum V_{oc}.

(2) The lowest ambient temperature as recorded in the TMY data tape was assumed as the solar cell temperature. This cell temperature was then combined with a 100 mW/cm^2 irradiance level to determine the array open-circuit voltage in these conditions. Since the simultaneous occurrence of such conditions is unlikely, this determination of open-circuit voltage can be viewed as an upper limit for the selected TMY year.

(3) The lowest ambient temperature as recorded in a weather atlas (Ref. 3) was assumed in place of the TMY lowest temperature in (2) above. This condition is considered to yield a true upperbound value because of the inclusion of long-term weather extremes.

Table 4 summarizes the results from the three estimation techniques. Because the upper-bound estimates are only about 12% higher than the lower-bound estimates, they serve as a useful basis for estimating the worst-case voltages for any site without an excessive penalty for conservatism.

Although accommodating the maximum open-circuit voltage will be a requirement for most PCS designs, the maximum voltage withstand could be limited to the non-operating state. In this case PCS startup would not

TABLE 4. MAXIMUM OPEN-CIRCUIT VOLTAGE FOR 12 SITES (NOCT = 50°C)

SITE	MAXIMUM OPEN CIRCUIT VOLTAGE V_{mp} at SOC		
	LOWER BOUND, TMY*	UPPER BOUND, TMY	UPPER BOUND, ATLAS
ALBUQUERQUE NM	1.49	1.69	1.74
BISMARCK ND	1.57	1.79	1.83
BOSTON MA	1.52	1.69	1.69
BROWNSVILLE TX	1.43	1.57	1.57
CARIBOU ME	1.57	1.79	1.82
CHARLESTON SC	1.46	1.64	1.65
FORT WORTH TX	1.46	1.66	1.67
FRESNO CA	1.44	1.61	1.61
MIAMI FL	1.40	1.56	1.56
OMAHA NB	1.58	1.75	1.75
PHOENIX AZ	1.43	1.61	1.61
SEATTLE WA	1.49	1.64	1.64

*START-UP VOLTAGE FOR 99.9% OF AVAILABLE ANNUAL ENERGY

occur unless the array V_{oc} were below some allowable start-up limit. Examination of the detailed simulation results indicates that the lower-bound estimates in Table 4 are a good selection for a startup-voltage limit with minimal energy loss. With a PCS startup-voltage limit at or above these values, less than 0.1% energy loss is suffered; below these values the energy loss increases rapidly.

5. ARRAY POWER DISTRIBUTION

Because PCS efficiency typically varies with output power level, the calculation of average efficiency, or total annual energy losses, requires data on the fraction of annual energy input to the PCS as a function of power level.

The hourly simulation results for the 26 sites were also used to construct plots defining the operating time, and thus the annual energy generated, at various relative power levels.

Table 5 tabulates the fraction of annual energy generated within each of six power intervals for each of 12 sites. The fractions serve as useful weighting factors for the determination of an average power-conditioner efficiency, which is defined as annual energy input to the PCS divided by annual energy output to the load. Ref. 2 contains more detailed data for 26 sites and a complete design example.

6. CONCLUDING REMARKS

The information included in the above figures and tables should provide a useful data base

TABLE 5. FRACTION OF ANNUAL ARRAY ENERGY AVAILABLE IN VARIOUS RELATIVE POWER INTERVALS

SITE	ARRAY RELATIVE POWER INTERVAL					
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2
ALBUQUERQUE NM	0.0343	0.0782	0.1040	0.2133	0.3693	0.2010
BISMARCK ND	0.0750	0.1363	0.1442	0.2435	0.3277	0.0739
BOSTON MA	0.0907	0.1383	0.1965	0.2840	0.2741	0.0163
BROWNSVILLE TX	0.0572	0.1393	0.2025	0.3967	0.1905	0.0138
CARIBOU ME	0.0779	0.1734	0.1754	0.2511	0.2542	0.0689
CHARLESTON SC	0.0541	0.1512	0.1996	0.3749	0.2043	0.0158
FORT WORTH TX	0.0590	0.1185	0.1642	0.3184	0.2995	0.0403
FRESNO CA	0.0446	0.0990	0.1213	0.2721	0.4098	0.0533
MIAMI FL	0.0508	0.1554	0.2382	0.4448	0.1073	0.0035
OMAHA NB	0.0682	0.1282	0.1426	0.2723	0.3119	0.0767
PHOENIX AZ	0.0339	0.0879	0.1275	0.3091	0.3821	0.0596
SEATTLE WA	0.1302	0.1603	0.1847	0.2524	0.2692	0.0032
AVERAGE	0.0647	0.1305	0.1667	0.3027	0.2833	0.0522
CUMULATIVE VALUE OF AVERAGES	0.0647	0.1952	0.3619	0.6646	0.9479	1.0000

for designing array loading systems that effectively use the output from a photovoltaic array. In addition the summary of site-to-site and fill-factor influences should serve to identify capabilities needed in generic PCSs designed to function with a variety of array types, sizes and site locations.

In selecting various design parameters such as voltage-tracking strategy and current and voltage limits, it should be kept in mind that a 1% loss in available energy is comparable to a 1% increase in total system cost. For a present-day (1982) system costing $25/watt this implies that approximately $0.25 per watt can be justified to achieve a 1% performance improvement.

7. REFERENCES

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.