

Chapter 5. A NEW DIRECT-COUPLED PERFORMANCE MODEL

Section 1.4 of Chapter 1 outlined a proposed method by which the long-term performance of direct-coupled PV systems without battery storage could be estimated. Chapters 2, 3, and 4 detail the key components of such a method. This chapter addresses two subjects: the design of a computer-based model using the proposed method, and the design of a variety of simulations to evaluate the model.

5.1 The DCPVSIMP program

This section describes a computer program which models the long-term performance of direct-coupled PV systems without battery storage. The structure, but not the detailed code, of this FORTRAN program, called DCPVSIMP (for Direct-Coupled PV model, Simplified version) is presented here. The code is listed in Appendix c.

5.1.1 Program Uses and Limitations

The logic and structure of the DCPVSIMP program is best understood by first identifying its intended uses and limitations. The program has been designed to produce monthly and annual summaries of DC electrical output from systems of PV cells, modules or arrays of any desired series/parallel arrangement, where the system is directly connected to an electrical load. The maximum power-tracked electrical output is also calculated, to give an indication of the fraction of PV system capacity utilized by the direct-coupled load. The program also calculates monthly and annual estimates of the volume of water p for pumping applications.

The type of electrical loads which can be modeled fall into three general

categories: Fixed voltage, resistive, or motor loads. Any positive value may be chosen for the fixed voltage load, or any positive integer for the resistive load (The chosen value is assumed constant for the year. although the program could be easily modified to adjust the value by month). Given a set of load I-V pairs, the program can model any variety of DC motors, or any arbitrary electrical load. Currently, the program contains data on six motor/mechanical load combinations rated from 40 W to 5000 W, including centrifugal fans, centrifugal water pumps, and positive displacement water pumps connected to either series, permanent magnet, or shunt DC motors.

Any type of cell, module, or array can be modeled, as long as the required data listed in Table 6 of Chapter 2 are available. The program contains data on nine PV unit types - either modules or arrays - ranging from 30 W to 4500 W.

Given the latitude and monthly average values for the clearness index and ambient temperature, any location can be modeled. The program is presently limited to northern hemisphere locations, but with minor modifications, it could be made applicable to southern hemisphere locations as well. Data for six U.S. locations are included in the present version.

The number of "typical days" per month, which directly affects the number of computations required, may be specified by the user as any positive integer, although 30 "typical days" per month is a practical upper limit, because the number of computations required for a 30 "typical day" run is about the same as for a detailed simulation with

hourly data.

The program is currently limited to fixed tilt flat plate collectors oriented south. Any tilt angle may be specified. The program could be readily enhanced to include tracking collectors, low level concentrating collectors, and collectors oriented other than south.

Other limitations of the program are:

1. It is not applicable to systems with battery energy storage.
2. The effects of non-uniform illumination (shading) and mismatch due to non-identical PV system components are not considered.
3. The effects of long-term performance degradation or individual component failures are not considered.
4. The effect of varying incidence angle on absorbed radiation is neglected.

5.1.2 Defining a Case

To define a unique case for an annual performance estimate, the user is prompted to make selections for each of the following variables:

1. Location
2. Number of segments, or "typical days"
3. PV unit type - The program will then suggest a value for the series resistance, which may be kept or overridden by a user-specified value.
4. Collector tilt angle

5. Number of units in each series string

6. Number of parallel strings

7. Load type - If a resistive load is chosen, the resistance must be specified.

Multiple annual runs are possible, if a range of resistances and an increment between each is specified. If a fixed voltage load is chosen, the voltage must be specified. If a motor load is specified a motor/mechanical load type must be selected.

5.1.3 Program Structure

A flowchart of the DCPVSIMP program is shown in Figure 53. It consists of a once-through initialization sequence where several variables are selected to define the case, constants are initialized, and reference values for the array I-V equation parameters are calculated (using methods described in Section 2.4.5). This section is followed by two main calculation sections, the first of which calculates weather-dependent variables, and the second which solves for the operating point and performs PV power calculations. In both sections, the calculation sequence is repeated for each hour of each "typical day," for each month. The last section aggregates hourly results (e.g., direct-coupled kWh, maximum power-tracked kWh, pumped water volume, irradiance, ambient temperature) on monthly and annual bases and writes the results to an output file.

The first of the main sections starts by reading the monthly-average clearness index and ambient temperature from an external file and then, using all but the last step of the method detailed in Chapter 4, calculates the plane of array irradiance and ambient temperature for each hour (both quantities are assumed to be constant over an hour).

The second of the two main sections performs a series of calculations, beginning with the cell temperature, which is computed using the last step of the method detailed in Chapter 4. Then, the array I-V equation parameters are updated from their reference condition values using equations given in Section 2.3.1, and the maximum power-tracked output is calculated using equations given in Appendix B. Lastly, the power output of the direct-coupled system is found by solving for the operating point, or intersection of the load and any I-V expressions, using a procedure given in Appendix B.

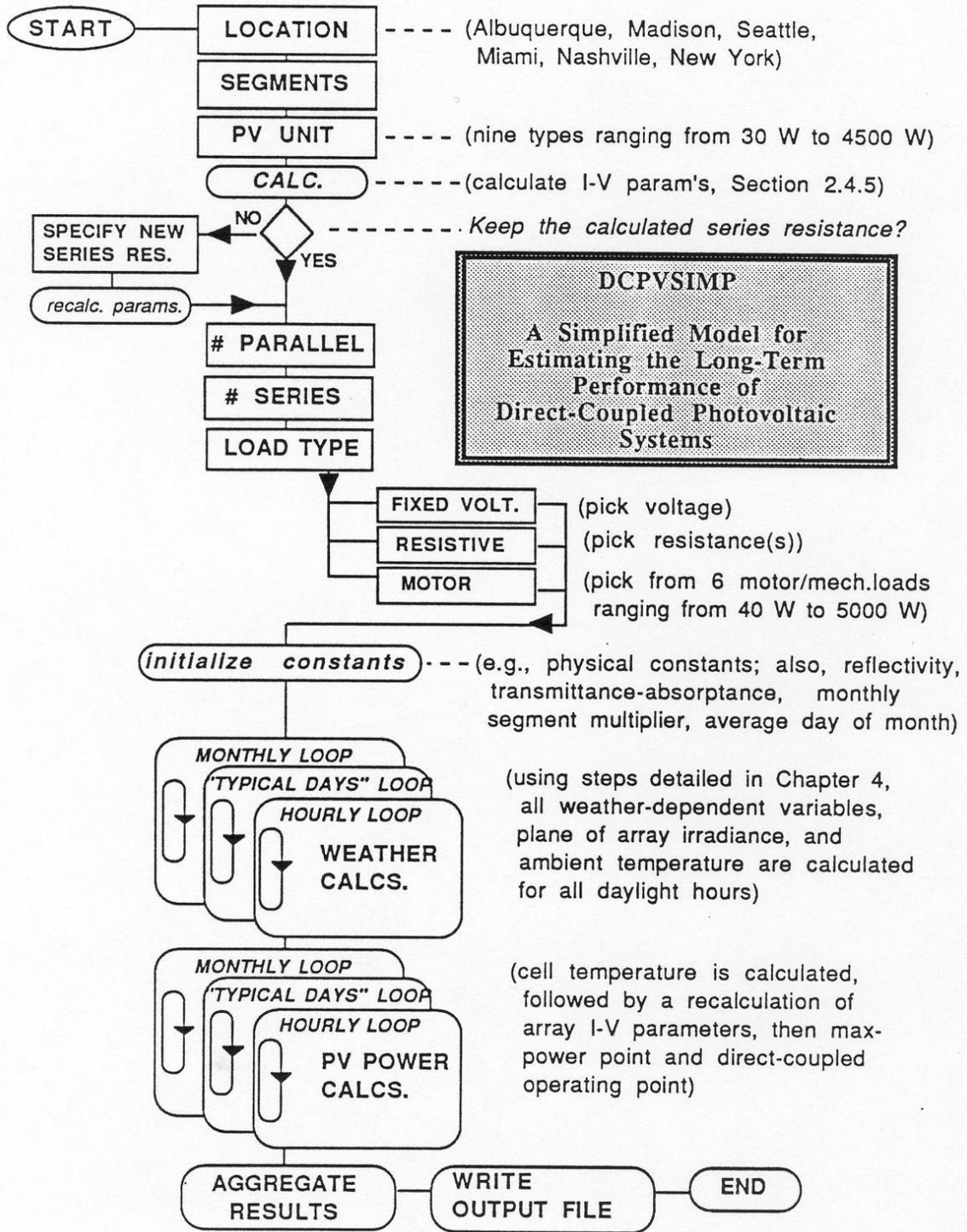


Figure 53. DCPVSIMP Model Flowchart

5.2 The DCPVDET program

As a measure of comparison for the results obtained using the simplified model, a reference program was written which performs identical calculations, except that TMY data are used as hourly weather inputs. This program is titled DCPVDET (for Direct-Coupled PV model, Detailed version). It is used in a side-by-side evaluation of the simplified model over a wide range of cases. The design of these cases, or simulations, is discussed in the following section, and the results from them are discussed in Chapter 6.

5.3 Simulation Design

There are several ways to evaluate the simplified direct-coupled performance model. Lacking actual long-term test data, the best alternative is to compare the predicted performance from this model to that of an alternative model. For maximum power-tracked systems, several models are available, such as PV i-Chart PVFORM [12], or TRNSYS [13] (MIT and ASU/Sandia versions of TRNSYS exist). In Chapter 6, predicted maximum power-tracked results from the DCPVSIMP and DCPVDET programs are compared to PV f-Chart and PVFORM for several of the cases described in this section.

Except for the DCPVDET model, no previous models are capable of comparing the predicted performance for any type of direct-coupled load to that predicted by the DCPVSIMP model. The TRNSYS model is capable of simulating fixed voltage direct-coupled loads, but both versions have been ruled out for comparison to the new model. The MIT version of TRNSYS uses a different I-V curve model which was evaluated in Chapter 2 and found to be inferior to the UP I-V curve model. The ASU/Sandia version,

which uses the SOLCEL-II I-V model [13], requires additional experimentally derived parameters not ordinarily available from manufacturers, and only contains data on one type of PV cell. Therefore, the DCPVDET model has been chosen as a measure for comparison for the DCPVSIMP model.

As outlined in Section 5.1.2, seven variables need to be selected in order to define a single case for an annual performance estimate using the DCPVSIMP model. Six of these are needed to define a case for the DCPVDET model. The only variable which is omitted is the number of "typical days," which is not applicable, since hourly TMY data are used.

To provide a statistical framework for evaluating the DCPVSIMP model, 3264 cases have been defined which cover a wide range of possible values for each variable. They are designed to yield information on the expected monthly and annual performance of a range of system configurations, loads, and locations. Cross-comparisons are possible which isolate the effect of any variable, such as the number of "typical days;" location, PV unit type, number of series and parallel strings, load type, or motor type. For simplicity, the only tilt angle considered is an angle equal to the latitude for each location.

The 3264 DCPVSIMP cases are the product of 816 individual cases that are replicated 4 times, each time with a different number of "typical day" segments (either 3, 5, 10, or 20 segments). An additional 816 cases are needed using the DCPVDET model, so that the results of any individual case using the DCPVSIMP model may be compared

to a those of a similar case using the DCPVDET model. The 816 cases defined for each choice of "typical days" are, in turn, the product of 272 cases replicated 3 times with different choices of location (either Albuquerque, Madison, or Seattle). The overall breakdown is: $(272 \text{ cases}) \times (3 \text{ locations}) \times (4 \text{ DCPVSIMP versions} + 1 \text{ DCPVDET version}) = 4080 \text{ cases}$.

The 272 cases defined for each location and each choice of "typical days" are based on the following combination of loads, PV units, and number of units in parallel and in series:

Resistive loads make up 54 of the 272 cases. Three PV unit types are used (either a 30 W Solarex module, 500 W ARCO array, or 4500 W Tri-Solar array), and simulations are run for 18 resistances for each unit ($3 \times 18 = 54$ cases). A different set of 18 resistances are chosen for each unit. These are shown in Table 10. The various resistances for each unit are chosen so that the optimum annual resistance is near the median of the 18 values. The lowest value is about 15% of the optimum and the highest is about twice the optimum resistance. Only 1 series and 1 parallel unit are used for these runs.

For fixed voltage loads, the same three PV unit types are used as for the resistive load cases. Simulations are run for 11 fixed voltages for each unit. for a total of 33 cases. As with the resistive load cases, a range of voltages are chosen so that the optimum annual fixed voltage lies near the median of the range. These are shown in Table 11. The

lowest voltage is about half the optimum voltage and the highest is about 30% greater than the optimum. Only 1 series and 1 parallel unit are used for these runs.

The remaining 185 cases (of the original 272) are divided among various motor loads. These are summarized in Table 12. 16 cases are run with a 5000 W series motor/centrifugal water pump load, using 2 series and 8 parallel multiples of the 500 W ARCO array. Another 16 cases are run with a 5000 W permanent magnet motor/centrifugal water pump load and the same series/parallel combinations. 49 cases are run with a nominal 1000 W series motor/fan load, using 7 series and 7 parallel multiples of the 30 W Solarex module. Another 49 cases are run using a comparably rated permanent magnet motor, and another 49 cases are run using a comparably rated shunt motor, with all other factors being the same. The last 6 cases are run using 3 parallel and 2 series multiples of the Solarex module coupled to a 40 W permanent magnet motor/positive displacement water pump load.

Table 10.54 Resistive Load Cases

Load resistance, ohms, by PV unit type			
Case	30 W Solarex mod.	500 W ARCO array	4500 W Tri-Solar array
1	3	23	1
2	5	46	2
3	8	70	3
4	10	89	4
5	11	97	5
6	12	106	6
7	13	114	7
8	14	122	8
9	15	131	9
10	16	139	10
11	17	147	11
12	18	156	12
13	19	164	13
14	20	172	14
15	21	181	15
16	24	209	16
17	32	278	20
18	48	417	30

Table 11.33 Fixed Voltage Load Cases

Fixed voltage, volts, by PV unit type			
Case	30 W Solarex mod.	500 W ARCO array	4500 W Tri-Solar array
1	9	105	90
2	13	157	134
3	15	178	152
4	16	188	161
5	17	199	170
6	17.8	209.4	179.3
7	18.3	216	185
8	18.9	222	190
9	19.6	230	197
10	20.5	241	206
11	23.1	272	233

Table 12.185 Motor Load Cases

Motor/Load Type	PV unit type	# series	# parallel	# cases
Perm.Mag./Cent.Pump	500 W ARCO	1,2	1,3,5,7, 9,11,13,15	16
Series/Cent.Pump	500 W ARCO	1,2	1,3,5,7 9,11,13,15	16
Series/Cent.Fan	30 W Solarex	1,3,5,7, 9,11,13	1,3,5,7, 9,11,13	49
Perm.Mag./Cent.Fan	30 W Solarex	1,3,5,7, 9,11,13	1,3,5,7, 9,11,13	49
Shunt/Cent.Fan	30 W Solarex	1,3,5,7, 9,11,13	1,3,5,7, 9,11,13	49
Perm.Mag./Pos.Displ. Pump	30 W Solarex	1,2	1,2,3	6
TOTAL =>				185

A consequence of this type of experimental design is that it permits a variety of independent comparisons between each version of the simplified model and the reference detailed model. The most important overall result is a calculation of the average percentage difference in predicted direct-coupled output, over 816 cases, between the simplified model and the reference detailed model. This calculation is done for each

version of the simplified model, and is repeated for three periods: January (a representative poor month), July (a good month), and annual. The intent of such a comparison is to determine how important the number of "typical days" may be for predicting long-term (monthly and annual) performance. This, and additional results which show the effect of other factors, will be presented in Chapter 6.