

# Modeling and Simulation of Solar PV Arrays under Changing Illumination Conditions

Dzung D Nguyen and Brad Lehman  
 Department of ECE, Northeastern University  
 Email: [nguyen.dun@neu.edu](mailto:nguyen.dun@neu.edu)

**Abstract-** This paper proposes a modeling and computing algorithm to simulate and analyze the effect of non-uniform changing shadows (a passing cloud) on the output power of solar PV arrays. Each solar array is composed of a matrix of individual solar cells or solar modules interconnected in series and parallel. Bypass switches and diodes are also modeled. The model is able to determine the power loss in each solar cell and the hot spots of a shaded solar PV array as well as the PV output power. The model is also able to simulate and compute the output power of solar PV arrays for any configuration, with or without bypass diode.

## NOMENCLATURE

$I_M$	output current of solar module
$I_C$	output current of solar cell
$V_M$	output voltage of solar module
$V_C$	output voltage of solar cell
$I_{SCM}$	short-circuit current of solar module
$I_{SC}$	short-circuit current of solar cell
$R_{SM}$	series resistance of solar module
$R_S$	series resistance of solar cell
$R_{SHM}$	shunt resistance of solar module
$R_{SH}$	shunt resistance of solar cell
$a, a_1$	ideality factor of bypass diode
$k$	Boltzman's constant.
$T$	cell operating temperature
$q$	electron charge
$s$	number of solar cells per column of a module
$p$	number of solar cells per row of a module
$I_0$	saturation current of the diode
$I_{OBP}$	saturation current of the bypass diode
$A_{i,j}$	vertical element ( $i, j$ running position index)
$B_{i,j}$	horizontal element ( $i, j$ running position index)
$IA_{i,j}$	current at element $A_{i,j}$
$IB_{i,j}$	current at element $B_{i,j}$
$V$	total output voltage
$I$	total output current
$R$	load resistance
$VA_{i,j}$	voltage at element $A_{i,j}$
$VB_{i,j}$	voltage at element $B_{i,j}$
$m$	number of vertical elements of a column
$n$	number of horizontal elements of a row
$R_{ON}$	resistance of turned <i>ON</i> switches
$R_{OFF}$	resistance of turned <i>OFF</i> switches
$t_p, t_1, \dots, t_{10}$	instant of time
$v$	speed of a moving cloud
$R_{i,j}$	distance between solar cell and the center of a cloud

## I. INTRODUCTION

The performance of a solar PV array is strongly dependent on operating conditions and field factors, such as the sun's geometric location, its irradiation levels of the sun and the ambient temperature. Each individual array is composed of a matrix of solar cells interconnected in series and parallel. Consequently, the performance of the array depends on the behavior of each individual solar cell. While the performance specifications of solar cell modules are available, the data provided for these arrays does not accurately reflect the amount of electric power that may be generated from the solar panel at time of use. To be specific, performance specifications do not take into account the influence of shade or other changes for solar conditions.

For example, a cloud passing over a portion of solar cells, or a sub-module will reduce the total output power of solar PV arrays. Under certain cloud conditions, the changes can be dramatic and fast. A method is required to assess the cost of such fluctuations and their effect on other systems to which a solar array may be connected, e.g. a utility [1].

A method that has been proposed by various authors measures changes in solar insolation over a one minute time interval [1], [2]. With this method, solar insolation values may be measured in the horizontal plane and subsequently used to calculate insolation levels for any desired angle [3].

There have been several attempts to predict the solar PV array output power. An estimation method used in [3] proposes that the power output of a PV system is proportional to the insolation levels measured for the surface of a solar cell at any angular position. However, the output power of a solar array is not only dependent on changes in irradiance values, but also depends on factors such as the interconnection of the individual solar cells, the parameters of solar cells, and the use of bypass diodes [4], [5].

A shadowed solar cell acts like a load because it dissipates input current. In the presence of shadows, where there is no exposure to sunlight, a solar cell will heat up and develop what is called a hot spot. To reduce the overall effect of shadows, bypass diodes are connected across shadowed cells to pass the full amount of current while preventing damage to the solar cell [5]. Thus, predicting the electrical characteristics of a solar PV array when experiencing passing clouds, is rather complex.

References [4], [6] show mathematical models that have been used to accurately model the electrical characteristic of solar PV arrays. Reference [4] considers the effect of non-uniform illumination on various configurations of solar PV arrays without a bypass diode, and requires different algorithms for different configurations.

This paper proposes a modeling and computing algorithm based on [6], which simulates and analyzes the effect of non-uniform changing shadows (i.e. a passing cloud) on the output power of solar PV arrays. The model is able to determine the power losses in each solar cell and the collective hot spots of an array. The following procedure is proposed for simulating a solar PV array under a passing cloud in MATLAB.

*Step 1:* Create a solar array in the matrix from (m x n). This model includes the behavior of the bypass diode and switches. A graphical interface in MATLAB has been created to perform this Step 1 (see Fig. 1).

*Step 2:* Model a passing cloud by specifying insolation conditions expressed according to the Standard Testing Conditions (STC: irradiance  $G = 1000 \text{ W/m}^2$ , temperature  $T=25^\circ\text{C}$ , spectrum  $E(\lambda) = \text{AM1.5}$ ).

Determine the shadow conditions, which are usually characterized by open-circuit voltages, short-circuit currents, and the parameters of the solar cells. These data can be obtained by measurements or from the manufacture. A three dimensional MATLAB plot images the irradiance on the solar panel (see Fig. 2).

*Step 3:* Use the numerical methods in [6] to determine the total current, the sub-voltages and the sub-currents for a given

total voltage for each shadow case. These calculations are performed in MATLAB.

*Step 4:* Display the resulting influence of the passing clouds on the output power of solar PV array.

## II. MODELING AND SIMULATION OF SOLAR PV ARRAY UNDER A PASSING CLOUD

*Step 1:* The solar PV array is modeled as a matrix with dimension (m x n): m represents the number of solar cells connected in a series string, while n represents the number of strings connected in parallel. Fig. 1(a) shows a solar array: all the vertical components are solar cells or modules and all horizontal components are controlled switches.

*Step 2:* Model a passing cloud. The shadow of a passing cloud will reduce current, resulting in non-uniform irradiance to solar PV array. The change of irradiance will change the short-circuit currents and open-circuit voltages of each cell. In this case we assume that the parameters and temperature of the solar cells are unchanged. The user specifies the ratio of the irradiance in each solar cell at each instant of time ( $t_1 \dots t_{10}$ ) according to irradiance standards (STC).

To simulate a moving cloud, we must first determine the distance,  $R_{i,j}$ , between the solar cell with index  $i, j$  at instant of time  $t_p$  and the center of a cloud. This is found by solving the right side of (1).

$$R_{i,j} = \sqrt{(i - t_p * v)^2 + (j - t_p * v)^2} \quad (1)$$

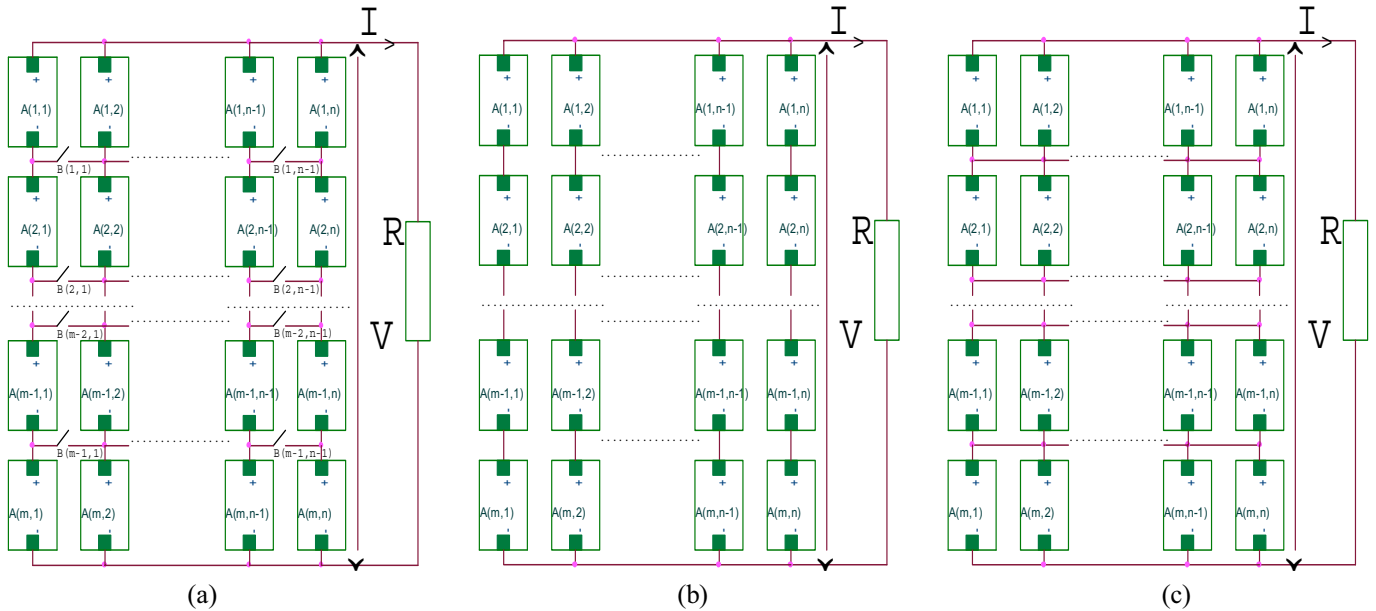


Figure 1(a). Solar PV array from sub-modules, controlled switches, (b) Series-parallel interconnection, (c) Total-cross-tied interconnection.

Realizable values for the ratio of the irradiance in each solar cell will range from 0 to 1, and can be specified using the sine function in the following equation:

$$\frac{I_{SCi,j}}{I_{SC0}} = 0.5 + \frac{\sin(R_{i,j})}{1 + R_{i,j}} \quad (2)$$

The irradiance is approximately proportional to the short-circuit current, so that the effect of a passing cloud to a solar array may be modeled as the change of short circuit current through all elements of  $m \times n$  matrix. Fig. 2 illustrates the graphical output of the MATLAB program. The resulting irradiation on each individual solar cell (10x10 cells in this example) represents a passing cloud.

Step 3: A. Inputting the irradiance data ( $I_{SCi,j}, V_{OCi,j}$ ) from step 2, the numerical method of [6] (in MATLAB) can be used to determine the total current, sub-voltages and sub-currents for each cell. In this method, Kirchhoff's laws are applied to provide a system of equations relating all currents and voltages in the network. Each element has to be described by the mathematical relationship between current and voltage. The Newton-Raphson method is used to calculate the solution for the systems of equations.

The controlled switches shown in Fig. 1(a) may be relays or transistors; their switching action is described by the following equation:

$$V_{Bi,j} = I_{Bi,j} * R_{Bi,j} \quad (3)$$

In the above equation,  $R_{Bi,j} = R_{ON}$  if the relays are turned ON,  $R_{Bi,j} = R_{OFF} = 10^{20} \Omega$  if the relays are turned OFF.

Equation (3) has the form:

$$f(I_{Bi,j}, V_{Bi,j}) = 0$$

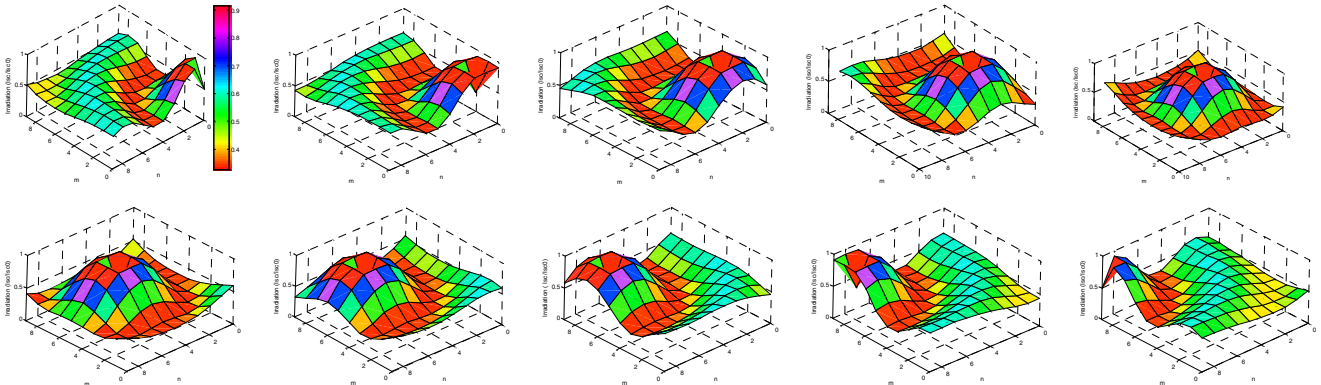


Figure 2. The non-uniform and changed irradiance is the effect of a passing cloud. The irradiance of each instant of time ( $t_1 \dots t_{10}$ )

### B. Solar array with great number of solar cells

When a solar panel contains a large number of solar cells, computational time may be reduced by dividing the solar panel into modules. Assume that each module is uniformly illuminated. Each vertical element in Fig. 1(a) is a solar module, made up of  $s \times p$  solar cells and protected by bypass diodes as shown in Fig. 3. Assume that all solar cells are illuminated by the same irradiance. In this case, the equation for the vertical components will be the following:

$$f(I_M, V_M) = I_{SCM} - pI_0 \left[ \exp\left(\frac{q}{sakt}(V_M + I_M R_{SM})\right) - 1 \right] - \left( \frac{V_M + I_M R_{SM}}{R_{SHM}} \right) - I_M + I_{OBP} \left[ \exp\left(\frac{-qV_M}{a_1 kT}\right) - 1 \right] = 0 \quad (4)$$

Where,

$$I_M = pI_C, V_M = sV_C, I_{SCM} = pI_{SC}$$

$$R_{SM} = \frac{sR_S}{p}, R_{SHM} = \frac{sR_{SH}}{p}$$

The last component in (4) is the equation for the bypass diode. In this case, the bypass diode is connected in parallel to the whole module of the solar array.

The relationship between the current and voltage of the solar panel has the following form:

$$f(I_{Ai,j}, V_{Ai,j}) = 0$$

From (3) and (4) we can define  $\frac{dI(V)}{dV}$  for each element of the solar PV array.

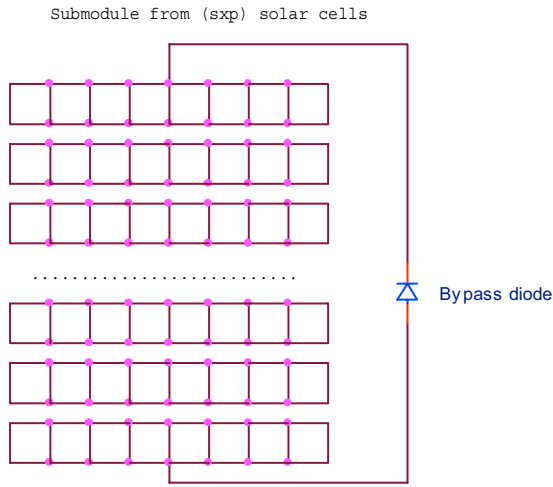


Figure 3. The sub-module of solar PV array

*Step 4:* Shows the influence of a passing cloud on the output power. Based on this curve, we can predict the maximum, minimum and average electrical power generated from a solar PV array for non-uniform and variable irradiance.

Fig. 4 shows the output power of a solar PV array for shadow conditions simulated by the linear approximation method and the numerical method.

### III. SOLAR ARRAY WITH AND WITHOUT BY PASS DIODE

Using the above simulation methods, we can compare the simulated output powers of the solar PV array with and without bypass diode.

i) With bypass diode: Assume that we have a solar module that is composed of solar cells, where each one is protected by a bypass diode. When current goes through a bypass diode, the solar cells that are in parallel (i.e. in the same row) will be shorted. The remaining solar cells will operate normally.

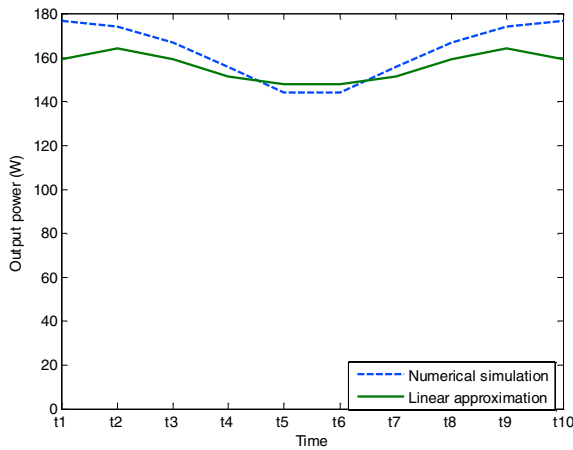


Figure 4. Output power of solar PV array simulation is based on two different methods

ii) Without bypass diode: In this case, the output current of a solar module will be limited by the most shadowed row.

For conditions of shadow cover, using a bypass diode causes different voltage levels to develop in a solar array. Alternatively, without the use of a bypass diode, different current levels develop in a solar array.

Assume that illumination conditions are the same. Although the difference is very small, Fig. 5 shows that the average power of a solar array with bypass diode is higher than the average power of a solar array without bypass diode.

### IV. SOLAR PV ARRAYS OF DIFERENT CONFIGURATIONS

Fig. 1(b), 1(c) shows the following two common solar PV array configurations:

i) Simple series-parallel (SP) array, when all the controlled switches are OFF and modeled as insulation resistance,

$$R_{Bi,j} = R_{OFF} = 10^{20} \Omega$$

ii) Total-cross-tied (TCT) array, when all the controlled switches are ON and modeled as conductance,

$$R_{Bi,j} = R_{ON}$$

In general, by combining different ON/OFF switching matrices, different configuration and simulation results of the solar PV array may be obtained.

In Fig. 6, the output power of two configurations is shown. We can see that for the same illumination condition the total-cross-tied interconnection array gives more output power than the series-parallel interconnection array.

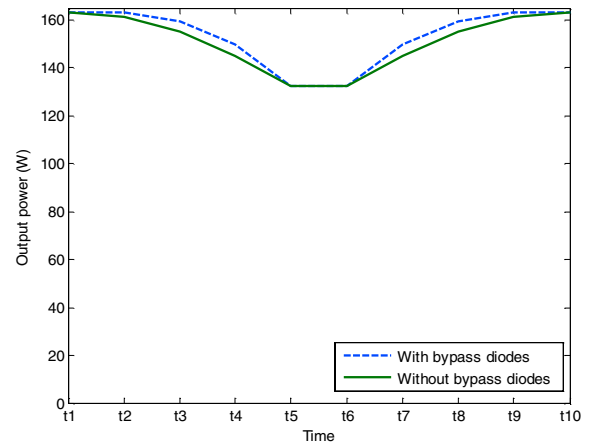


Figure 5. Output power of solar PV arrays with and without bypass diode

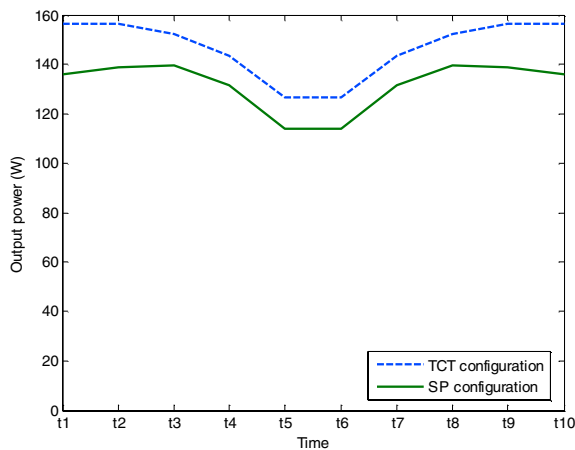


Figure 6. Output power of solar PV array depends on interconnection

## VI. CONCLUSION

The modeling and computing algorithm used to simulate and analyze the effect of non-uniform changing shadows (a passing cloud) on the output power of solar PV arrays is discussed. The software implementation in MATLAB is shown to converge.

The model is able to determine the power losses in each solar cell and the hot spots of a shaded solar PV array as well as the PV output power.

The model is flexible enough to simulate solar PV arrays with various configurations, with or without bypass diode.

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