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켐벨 라이언*, 김학만**, 이종수*, 신명철*
* 성균관대학교
** 한국전기연구원

A Photovoltaic Device Model for Grid-connected PV System Simulation

Ryan Campbell*, Hak-man Kim**, Jong-su Lee*, Myong-chul Shin*
* Sungkyunkwan University
** Korea Electrotechnology Research Institute (KERI)

Abstract - The recent interest in distributed generation (DG) due to the opening of the electricity market and the need for alternatives to conventional fossil fuel-based electricity generation has created renewed interest in grid-connected photovoltaic (PV) systems. Many studies are being performed at the power system level to examine the impacts of grid-connected PV systems and several models for PV arrays have been proposed in the literature. However, the complexity of these models and difficulties of implementing them in various software programs can be deterrents to their use. This paper proposes a robust and flexible PV device model suitable for dynamic and transient studies where the PV array's non-linear DC characteristics are important. The model's implementation in software is straightforward and it can even be constructed using standard software library components, as demonstrated using PSCAD/EMTDC.

1. INTRODUCTION

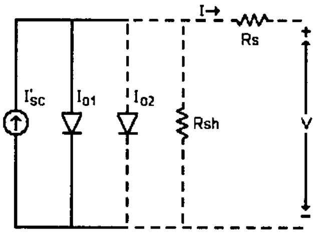
The opening of the electricity market and the need for alternatives to conventional fossil fuel based electricity generation has caused renewed interest in distributed generation (DG), such as grid-connected photovoltaic (PV) systems. Many studies are being performed at the power system level to examine the impacts of grid-connected PV systems, but it is not uncommon to find that the PV array models used are oversimplified. The output of a PV array is highly non-linear, and to simplify the array to a constant voltage source is usually not appropriate. Several models for PV arrays have been proposed in the literature [1]-[4]. However, in some cases, the models are not fully explained and in all cases, their complexity, when coupled with the difficulties of implementing them in various software programs, can be a deterrent to their use. Furthermore, the level of detail in these models may not be necessary for system level studies, and it is helpful to have a flexible model that can be based either on theory or on measured module/array I-V characteristics. In regards to the latter, PV module manufacturers often provide measured data for their products, either on their Websites or upon request, and there also exists a useful empirical model with a database of well over one-hundred commercially available PV modules and several installed arrays [5].

This paper proposes a PV device model suitable for use with power electronic inverters in dynamic and transient power system studies, and reflects the PV array's non-linear DC characteristics. The model is robust, flexible, and its implementation in software is straightforward; it can even be constructed using standard software library components as is demonstrated in this paper using PSCAD/EMTDC.

2. PV Model Development

2.1 Theory

The ideal solar cell can be modeled as a current source anti-parallel with a diode, as shown connected by the solid lines in Fig. 1. The DC current, I'sc, generated when the cell is exposed to light, varies linearly with solar irradiance. Refinement of the PV cell model includes the effects of series and shunt resistance, as shown connected by the dashed lines. A second diode can also be included [6], [7], [1], as it provides an even more accurate I-V curve that accounts for the difference in current flow at low current values due to charge recombination in the semiconductor's depletion region. Since a PV module is composed primarily of series-connected cells, and a PV array is composed of series- and parallel-connected modules, the single cell circuit can theoretically be scaled up to represent any series/parallel combination.



<Figure 1> PV Cell Equivalent Circuit Model

The equation for the single-diode model including series and shunt resistances is given by equation 1 (adapted from [6]):

$$I = I'_{sc} - I_{o1}\left(e^{\frac{q(V+IRs)}{kT}} - 1\right) - \frac{(V+IRs)}{Rsh} \qquad (1)$$

where

I'sc is the light-generated current (short-circuit value assuming no series/shunt resistance)

Io1 is the dark saturation current

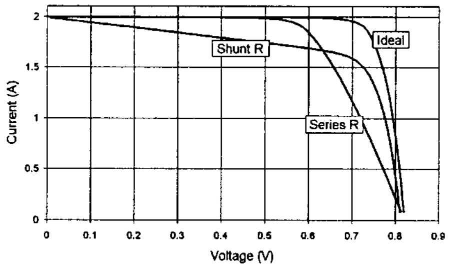
q is the charge of an electron (coul)

k is the Boltzman constant (j/K)

T is the cell temperature (K) (assumed constant in this paper, given the short time-frames of interest in transient and dynamic power system analyses)

I, V, Rs, Rsh are cell current (A), voltage (V), series and shunt resistance (Ohms) as indicated in Fig. 1.

Figure 2 illustrates the I-V characteristics of the single diode model, showing the ideal curve and illustrating the effects of series and shunt resistances.

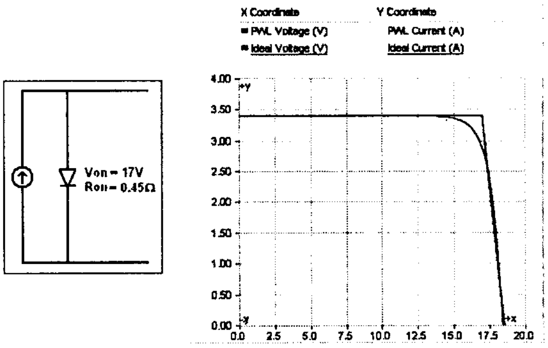


<Figure 2> I-V Characteristic Curves

2.2 Piece-wise Linear Model

Coding a custom component for the array is certainly possible and many researchers do this (though they do not often reveal their code); however, mathematical and software integration complexities with modeling at the small time-steps needed for simulation with power electronic converters can make this a difficult task, and the result is usually not as robust or reliable as may be desired. Furthermore, completely modeling the continuous non-linear curve may result in slow simulations.

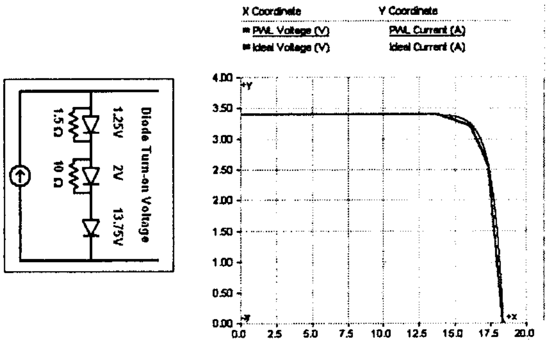
To overcome these problems, this paper presents a PV array model based on the single-diode model described above, and implemented directly as an electrical circuit in a way that avoids the mathematical complexities of solving the implicit and non-linear Equation 1. It is challenging to obtain a good fit to the non-linear curve of Fig. 2 with power system simulation programs using standard software library components due to the simplification of diode representation: in most circuit simulators that utilize the trapezoidal integration solution method, diodes are modeled piece-wise linear (PWL) as voltage controlled resistors with two states: on and off resulting in low and high resistance values, respectively. Using a PWL diode, the circuit model for the non-linear response is shown in Fig. 3 along with the resulting two-segment I-V curve. Since many software programs provide a parameter for the diode's turn-on voltage, an entire array (or module) can be modeled with this simple circuit by setting the diode voltage near the array (or module) voltage and adjusting the current source to the desired current.



<Figure 3> Two Segment PWL Circuit & I-V Curve

While this may be sufficient for some studies, it is not a very good match to the ideal curve and will clearly over-estimate the maximum power point (MPP) of the PV array, which is located at the knee of the curve. It will also be problematic for MPP tracking controls, since the slope of the curve changes so abruptly - in reality, the MPP is not nearly so sharp so it is far easier for the power electronics to control the operating point. Some improvement could be made in these respects by aligning the MPP's, but this would require exaggerated series and shunt resistances, which would reduce the overall curve fitting accuracy.

A much better fit to the non-linear curve can be achieved using three series diodes and two low valued bypass resistors, as shown in Fig. 4. In fact, the curve can be fit to any degree of desired accuracy in this way by simply adding more bypass resistor and diode pairs. Methods for determining the appropriate values for the resistors and diode voltages will be discussed in the next section.



<Figure 4> Four Segment PWL Circuit & I-V Curve

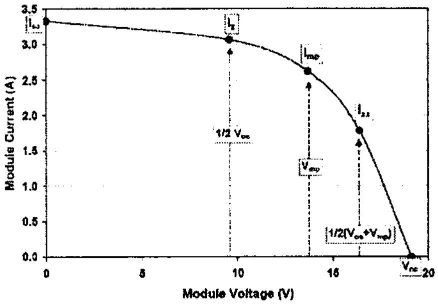
A PV device's operating point depends on the resistance of the load, and I-V curves such as those above can be generated using a variable resistor that sweeps from zero to infinite resistance. With this in mind, operation of the circuit in Fig. 4 can be explained as follows:

1) When the load resistance is small, all diodes are off, and the bypass resistors provide a path for voltage to build up across the bottom diode, resulting in the first segment of the curve in the constant current region.
2) As the load resistance increases, voltage builds up across the bottom diode until its turn-on voltage is reached, at which point more current is drawn through the branch (though limited by the bypass resistors) resulting in the second PWL segment.
3) If the value of the middle resistor is greater than that of the top resistor, then the middle diode will turn on next, resulting in operation in the third PWL segment.
4) Finally, the top diode switches on and the device operates in the (nearly) constant voltage region of the PWL curve.

2.3 Calculation of Model Parameters

In this section, methods for calculating the values of the bypass resistors and diode turn-on voltages are discussed. As mentioned earlier, I-V data is usually available for commercial PV modules. Depending on the data quality, an appropriate PWL-type curve fitting technique, such as the MDL method of [8] (see also [9]) can be used to fit the data. Low quality data sets may benefit from pre-fitting using a traditional PV method (e.g., [10]).

Another option is the Sandia National Laboratories model and empirical database of real module and array data [5]. The Sandia model can be used to generate the vertices of the PWL curve based on the five key points of the I-V curve shown in Fig. 5 (from [5]).



<Figure 5> PWL Vertex Determination Using Sandia Model [5]

Finally, if the above mentioned techniques prove more time-consuming and rigorous than is necessary for the study, the values of bypass resistors and diode turn-on voltages can easily be selected iteratively by trial-and-error to fit any reference curve (such as the ideal curve of Fig. 2).

3. CONCLUSION

This paper proposed a PV device model suitable for use with power electronic converters in dynamic and transient power system studies. The model accounts for the important non-linear DC response of PV devices, and is very robust and flexible. Furthermore, the model's implementation in software is straightforward: it can be constructed using standard software library components as demonstrated in this paper using PSCAD/EMTDC.

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