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Letter

Improving the Efficiency of Organic Thin Film Photovoltaic Cells

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ABSTRACT

Organic photovoltaic (OPV) cells are advanced, newly emerging technologies that are lightweight, mechanically flexible devices with high-throughput processes from low cost material in a variety of colors. Rathnayake et al. of Western Kentucky University have developed a nanostructure-based OPV cell. Presented in this work is a model and simulation of a generalized PV powered system that can predict the performance of solar arrays in various environmental conditions. The simulation has been carried out in Matlab/Simulink, and upon entering the cell's parameters, it provides key electrical characteristics such as the cell's I-V curve and efficiency information. The total system that is simulated consists of three elements: a universal two-cell solar array that can account for partial shading and manufacturing variation, a current-controlled power converter, and an energy storage device with charging and discharging capabilities.

KEYWORDS Photovoltaic, Organic cell, Nanostructure, Power converters, Energy storage.

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INTRODUCTION

A great deal of research and effort has been placed in solar energy harvesting using photovoltaic (PV) devices and systems. This has been mainly due to increasing demand for energy, price instability of fossil fuels, global warming, and environmental concern. Furthermore, among various sources of renewable energies, solar cells have a set of unique features of quiet operation, high power density per unit of weight, and mobility. Photovoltaic arrays also have short lead times to design, install, and startup, as well as long expected life with low maintenance. Another key feature of PV cells is their inherent modularity, which decouples the plant economy from its size, facilitating their applications over a wide range of power levels. Most solar energy production and control research has been focused on silicon-based PV technology, and, coupled with reduced material costs,[1] has allowed this technology to retain approximately 89% of the PV market share.[2] Also, there has been substantial investment in several thin-film PV technologies, with capital investments reaching nearly $300 million in Q4 2011 to Q1 2012 combined.[3] However, there has been less research in organic photovoltaic (OPV) technology. Much OPV research has been dedicated to material synthesis,[4, 5] morphology control,[6, 7] and low-level cell modeling.[8]

Unlike the broad spectrum outside the atmosphere, the solar radiation wavelengths that reach the Earth vary from approximately 300 nanometers to 400 nanometers.[1] Because of this, the PV industry, the American Society for Testing and Materials (ASTM), and the American government research and development laboratories have defined two spectral distributions for the sun. The spectrum for outer space is represented by the Air Mass (AM) 0 spectrum. The AM 1.5 G spectrums describe terrestrial solar radiation at a standard direct normal and a standard total spectral irradiance. The distributions are shown in Fig. 1.[2]

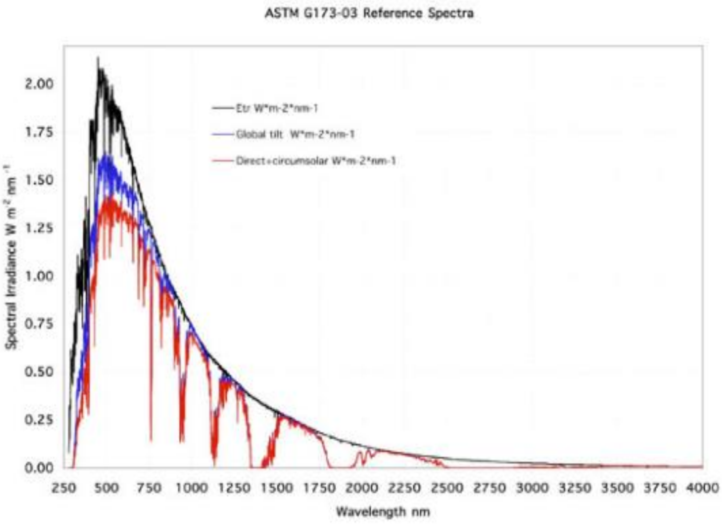

Fig. 1: AM 0 and AM 1.5 G spectrums.[2]

Three parameters that are very important in classifying the PV characteristics of a solar cell are the short circuit current (Isc), the open circuit voltage (Voc), and the maximum power point (Imp, Vmp). The short circuit current is the maximum current that can be delivered by the PV cell. The open circuit voltage is the maximum voltage that can be delivered by the PV cell. The maximum power point of the current voltage curve (IV curve) is the operating point at which the PV cell is delivering its maximum power. The values for Impand Vmp are typically less than Isc and Voc. Another important parameter is Fill Factor (FF). The fill factor is a ratio of the maximum area that the maximum power point of the IV curve can fill in the square that is defined by Voc and Isc. This concept is illustrated in Fig. 2.

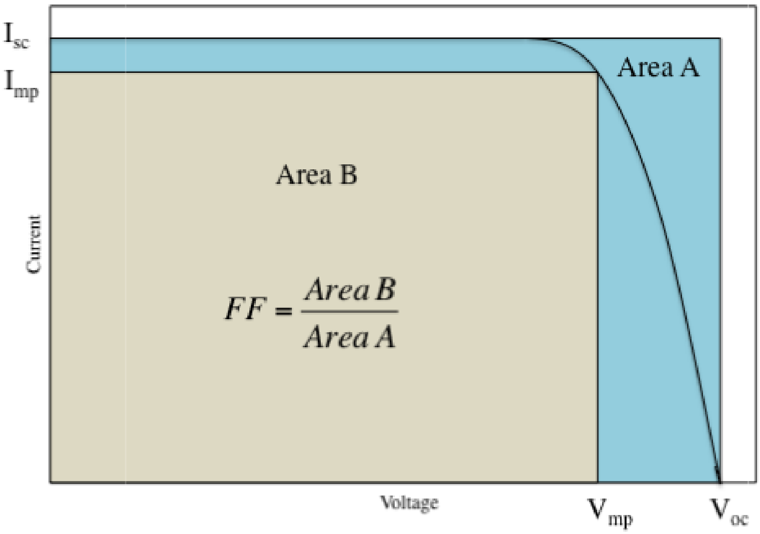

Fig. 2: Fill-factor diagram.[4]

There has been less research on predicting the electrical performance of OPV technology, at the system level in various operating points and environmental conditions. This research fills this gap. Currently, inorganic photovoltaic technologies dominate the solar energy market. The majority of PV cells and arrays are made from crystalline silicon technology, but inorganic thin film materials are quickly gaining solar market share and may surpass crystalline silicon-based PV technology.[6] Five popular inorganic photovoltaic technologies include mono-crystalline silicon, poly-crystalline silicon, gallium arsenide (GaAs), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS).

ORGANIC PHOTOVOLTAIC TECHNOLOGY

The simplest organic photovoltaic cell is the single layer OPV (Fig. 3). The cell is made up of three components: an anode (made of materials such as indium tin oxide (ITO) coated glass), the organic electronic material, and a cathode layer of aluminum, magnesium, or calcium. They are typically arranged by having the high work function anode on top, followed by the organic electronic material in the middle, and the low work function cathode on bottom.

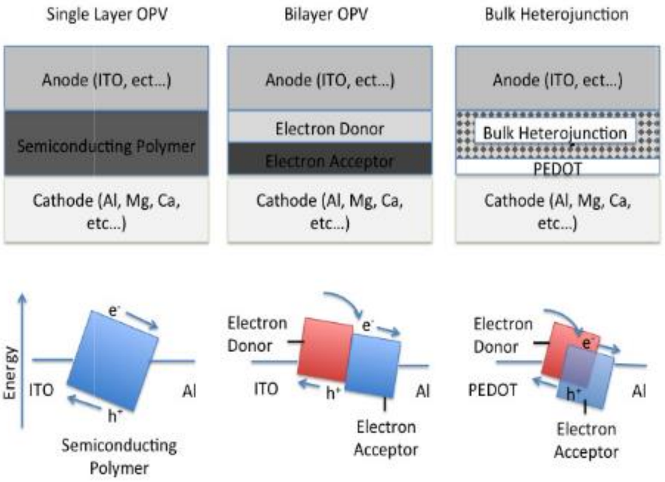

Fig. 3: Typical OPV cell architectures.

SOLAR CELL MODEL

To develop an electrical equivalent circuit of an ideal solar cell, one must take into account two factors. First, a solar cell acts as a diode while not illuminated. Second, while illuminated, a solar cell acts as a current source over a wide range of its operating conditions. To account for these two factors, an ideal model shown in Fig. 4 has been developed. This ideal model consists of a current source in parallel with a diode.

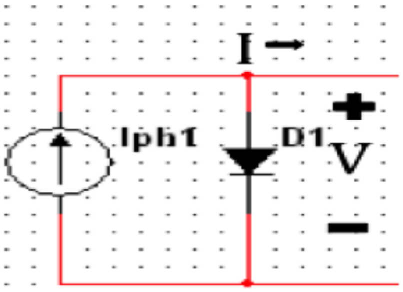

Fig. 4: Ideal solar cell model.

To mathematically describe the current-voltage (I-V) characteristics of the ideal model, eq. (1) can be used.

$$I = I_{ph} - I_s\left(e^{\left(\frac{qv}{AkT_c}\right)} - 1\right) \qquad (1)$$

In eq. (1), Iph is current generated by incident light, Is is the reverse saturation current of the diode, V is the load voltage, q is the electron charge, k is the Boltzmann constant, Tc is the working temperature of the cell, and A is the diode ideality constant.

Unfortunately, the ideal model does not represent the I-V characteristics of real-world photovoltaic systems. In fact, real photovoltaic cells show a voltage drop proportional to the current that can be modeled by an internal series resistors, RS. It also demonstrates an internal current loss or leakage that can be modeled by a shunt resistor, RSh. As a result, in this work, we consider the standard single-diode model as depicted in Fig. 5.

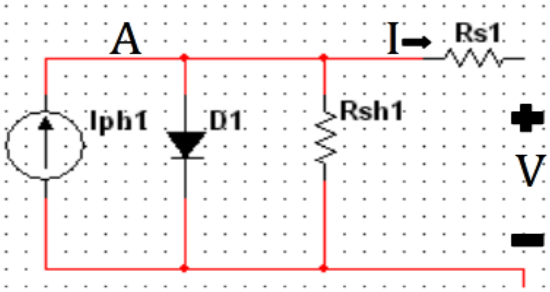

Fig. 5: Single-diode solar cell model.[9]

SIMULATION RESULTS

The electrical output of a single cell device under nominal testing condition simulated by Matlab/Simulink can be seen in Fig. 6. Nominal cell characteristics include a working temperature of 25°C, an irradiation of 1 kW/m^2, a large shunt resistance, a small series resistance, and a diode ideality factor of approximately 1. Altering these five parameters can greatly affect the profile of the IV curve.

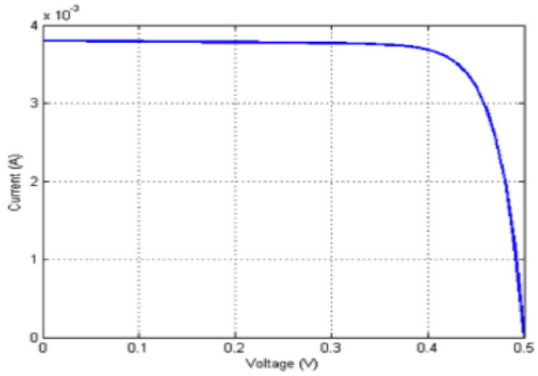

Fig. 6: Solar cell IV curve at nominal conditions.

The shunt resistance values were 100, 200, 400, 600, and 1000 ohms. As the resistance of the shunt resistor decreases, the current source section of the IV curve slants more downward, reducing the current value of the maximum power point. This parameter modification does not greatly influence the angle of the voltage source section of the IV curve (Fig. 7). It should also be noted that the open-circuit voltage is reduced for low values of Rsh.

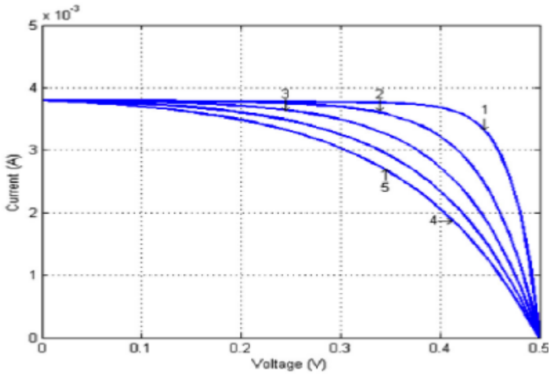

Fig. 7: Varying diode ideality factor for single cell solar model.

The third parameter that greatly influences the profile of the IV curve is the diode ideality factor, A. The parameter A is dependent on the specific characteristics of the PV technology.[9] Fig. 7 shows how the shape of cell's IV curve is changed when the diode ideality factor varies from 1 to 5 in increments of one. One can see that A changes both the current source and voltage source sections of the I-V curve. As A is increased, the I-V curve becomes more gradually sloped, decreasing the maximum power output of the cell. A graph showing how varying the input irradiation of a cell influences its electrical output is shown below in Fig. 8.

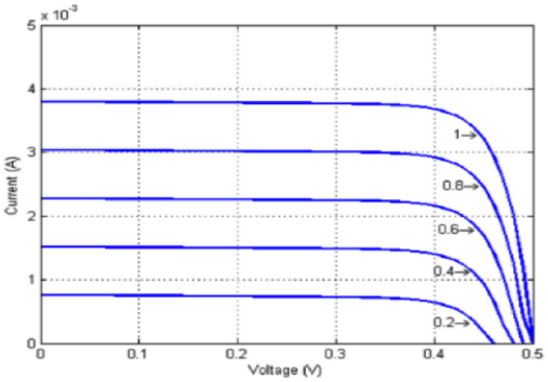

Fig. 8: Varying irradiation for single cell solar model.

CONCLUSION

A generalized OPV power system has been mathematically modeled and simulated within a Matlab/Simulink environment. The output of the solar cell model has been verified by the work of Tsai group et al.; the output of the buck converter was verified by the work of the Colorado Power Electronics Center; and the lithium-ion battery model was validated by the work of Erdinc et al. The proposed model takes irradiation, temperature, specific solar technology parameters, converter component values, and battery state of charge information as input parameters. Model outputs include the solar panel current and voltage, the buck converter output voltage, output current, inductor current, duty cycle, and the lithium-ion battery output voltage, impedance, and state of charge. Complete system model output is stable except for low SOC (less than 0.1) and low ISC (less than 0.1) values. This work will serve as a springboard into numerous expansions in solar cell research. The most immediate opportunity lies in the development of a variable solar array model. This model will have increased capabilities to automatically construct the appropriate electrical governing equations for any modular sized solar array. This powerful tool would greatly accelerate research in scaling the size of the WKU OPV cell to the module level. This simulation model would still be able to account for partial shading and manufacturing variation, thus allowing evaluation of arrays that have the capacity to power moderately sized electronics.

DISCLOSURE STATEMENT

The author(s) did not report any potential conflict of interest.

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