International Journal of Scientific Research and Engineering Development-– Volume 9 Issue 2, Mar-Apr 2026
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

To Build Mathematical Models for Different Photovoltaic Systems

Aasif Amir Najar, Dr. Abha Tenguria
Research Scholar, Department of Mathematics, Barkatullah University, Bhopal, M.P.
Professor & Head, Department of Mathematics, Govt. M.L.B. Girls P.G. College, Bhopal, M.P.

Abstract:
Research and technical advancement in the field of renewable energy sources are both required to take into consideration the rise in energy consumption and environmental issues in the entire planet. The greatest options for low-power appliances, water pumping, and communication systems in rural areas are standalone solar systems. A PV generator, energy storage devices, AC or DC consumers, and power conditioning components make up such systems. A PV generating system's basic power conversion unit is represented by a PV module.
In order to simulate maximum power point tracking for standalone PV systems, it is important to represent the nonlinear output characteristic of a PV module that depends on the temperature of the cell and the intensity of the irradiance. The I-V and P-V properties of a typical solar module are examined using a one-diode equivalent circuit.

Keywords: **Solar Photovoltaic, Modeling, Maximum Power Point Tracking (MPPT), Voltage and Current.**

Introduction:
The photovoltaic (PV) effect's energy can be regarded as the most vital and necessary sustainable resource among renewable energy sources because of the sustainability, availability, and pervasiveness of solar radiation. Solar energy is universally accessible and cost-free, regardless of how frequently the sun shines. Photovoltaic systems are now acknowledged as leading the way in the production of renewable electricity. When exposed to solar radiation, it can produce direct current electricity without causing pollution or harm to the environment. Since the PV system is a semiconductor, it is silent, static, devoid of moving parts, and requires little upkeep and operation. The core power conversion component of a PV generating system is a PV module. A PV module's output characteristics are determined by its output voltage, cell temperature, and solar insolation. The design and simulation of maximum power point tracking (MPPT) for PV system applications need modeling of the PV module due to its nonlinear properties. To help researchers better understand how the PV module operates, mathematical modeling is constantly being updated. Alternative energy sources are becoming more and more popular as fossil fuel supplies are running low and the effects of global warming are becoming more apparent. Solar energy is the alternative energy source that receives the most attention. Solar energy is used in two different types of technology: solar thermal and solar cell. By using the photovoltaic effect, a PV cell (solar cell) transforms sunlight into electrical energy. PV module energy provides numerous benefits, including little maintenance needs and zero environmental contamination. PV arrays are now utilized in a wide range of applications, including satellite power systems, grid-connected PV systems, solar hybrid cars, battery chargers, and solar-powered water pumping systems. A PV module is the basic power conversion component of a PV. generator setup. The solar insulation and cell temperature have an impact on the PV module's output characteristics. Due to the nonlinear features of PV modules, it is essential to simulate it for maximum power point tracking (MPPT) applications in PV system design and simulation. Usually, a PV module is made up of several PV cells connected in series. Examining the physics of p-n junctions is the standard method for

modeling a PV cell. It is possible to mimic the non-linear voltage-current (V-I) characteristic of a PV cell using resistors, diodes, and current sources. To mimic PV characteristics, single-diode and double-diode models are frequently employed. The PV properties are accurately and fairly replicated by the single-diode model [22][23].

Mechanism:

The basic physical mechanism that allows solar cells to transform sunlight into electrical energy is known as the photovoltaic effect. When light photons hit a suitable semiconductor material, like silicon, they transfer their energy to the electrons in the material, releasing them from their atomic bonds and forming electron-hole pairs that produce an electric current. [29], [30], [31]

The semiconductor material first absorbs photons from sunshine, which excites the electrons and raises them to a higher energy state known as the conduction band.Positively charged holes remain in the valence band as a result. These split electrons and holes move in opposite directions due to the difference in energy levels and the existence of an internal electric field at the semiconductor's p-n junction, producing an electrical current flow [30][32][33][29].

In specifics, the mechanism includes:

1.Photon absorption: In a semiconductor, photons impart their energy to electrons.
2.Excitation of electrons: Electrons acquire sufficient energy to transition from the valence band to the conduction band.
3.Charge carrier separation: Electrons are driven to the n-side and holes to the p-side by an electric field at the p-n junction.
4.Current flow: Electrons produce electricity by passing via an external circuit [33][29].

Architecture:

A solar photovoltaic (PV) panel's architecture is made up of several layers and parts that are intended to effectively convert sunlight into electricity while offering protection and mechanical support.

The following essential layers and parts make up a typical solar PV panel:

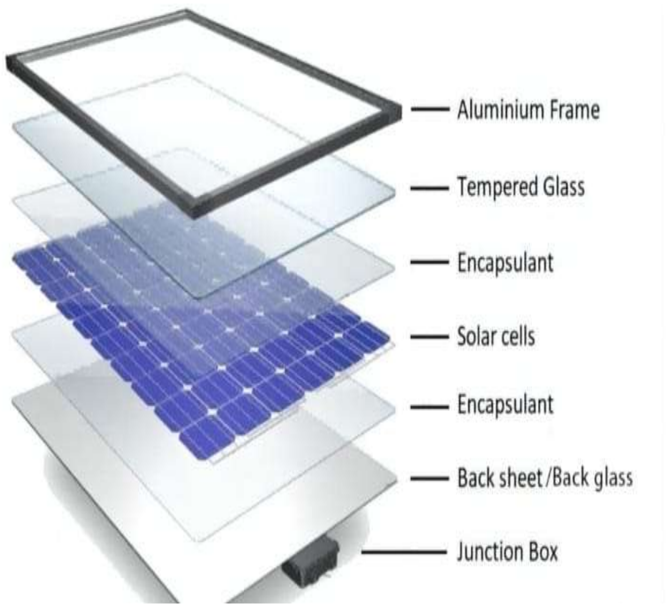

Fig.18 Cross Section of a solar panel

Semiconductor Layers: The p-type (positively charged) and n-type (negatively charged) layers that create a p-n junction make up the core of a photovoltaic cell, which is typically made of silicon. The electric field produced by this connection is essential for the photovoltaic effect [35].

Anti-Reflective Coating: applied to the upper surface to improve light absorption and reduce reflection.

Metal Contacts: A solid metal layer on the back works as the rear electrical contact for current collection, while a thin metal grid on the front surface lets light through while gathering electrons [35].

Encapsulant Layers: Usually made of ethylene-vinyl acetate (EVA), these layers envelop the solar cells and shield them from moisture and mechanical stress, guaranteeing their lifespan.

Glass Cover: The top's tempered glass lets sunlight through while shielding the cells from environmental harm.

Back Sheet: An insulating and mechanically protective polymer layer on the rear of the panel.

Frame: Typically made of aluminum, frames offer structural stability and make it easier to attach the panel on support structures [36].

Junction Box: Connected to the rear, it has electrical connections and bypass diodes that control current flow and safeguard cells.

In order to create modules and panels with the desired voltage and current outputs, cells are electrically connected in series and parallel [37].

```
        |---[Rs]---(+)----|----+----|---(+Vout)
Iph ----|                [D]   |   [Rp]
        |---+----(-)---------|---(-Vout)
```

Fig.19.Circuit diagram for mathematical modeling of a Solar PV Cell

MODELING OF PHOTOVOLTAIC SYSTEM

Modeling of PV Module:

The internal losses of the current are not included by the model. The light-generated current source is linked in anti-parallel to a diode (Fig. 1a). The Kirchhoff's law is used to determine output current I:

$I=Iph-Id$ (1)

(Iph) is the photocurrent,

(Id) is the diode current which is proportional to the saturation current and is given by the equation.

$$Id = I0\left[exp\frac{V}{A.N_S.Vt} - 1\right] \text{ and } \quad 2$$

$$VT = K.TC/q \quad 3$$

(Id) is the reverse saturation or leakage current of the diode (A),

VTc = 26 mV at 300 K for silisium cell,

Tc is the actual cell temperature (K),

K=Boltzmann constant 1.381 10-23J/K,

q is electron charge (1.602 10-19 C).

VT is called the thermal voltage because of its exclusive dependence of temperature.

Ns: is the quantity of PV cells that are linked together in series. The ideal factor is denoted by A. It can be selected from Table 1 and is dependent on PV cell technology. It must be emphasized that A is a constant that is dependent on the technology of PV cells. Because they are inversely proportional to cell temperature, all of the factors used to divide V in equation (2) under the exponential function change depending on the circumstances. This term, which is designed by "a" and is referred to as the thermal voltage (V), the ideal factor, is determined in Table 1 based on the PV cell's technology and is thought to be constant. The following equation (1) displays the thermal voltage "a."

$$a = a = \frac{N_S.A.K.T_2}{q}\ NS.A.VT$$

Where ‘a’ is called ‘‘the modified ideality factor’’ and is considered as a parameter to determine, while A is the diode ideality.

Due to their influence on the PV cell's and PV module's efficiency, the series resistance RS and parallel resistance RP cannot be ignored. Equation (2) should like this when is RS taken into account:

$$Id = I0\left[exp\left(\frac{V+I.R_S}{a}\right) - 1\right] \quad (5)$$

Naturally, Fig. 1b is a simplified form that is simple to incorporate into simulators. However, the PV cell is best represented by Fig. 1c.

The following equation will yield current when Kirchhoff's law is applied:

$I=I$ph– Id-Ip (6)

Where IP, is the current leak in parallel resistor.

The output current of a module containing NS cells in series will be:

$$I = Ihp - I0\left[exp\left(\frac{V+I.R_S}{a}\right) - 1\right] - \frac{V+I.R_S.I}{R_S} \quad (7)$$

The parameters of this transcendental equation are difficult to find. However, the best fit to experimental values is provided by this model.

The Characteristic of Photovoltaic System

Figures 12, 13, and 14 illustrate the relationship between voltage and current, whereas Figures 14, 15, 16, and 17 illustrate the relationship between voltage and power.

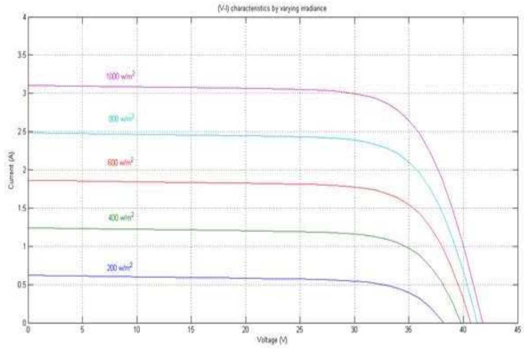

Fig. 12 (V-I) Characteristic by varying irradiance

The relationship between voltage and current when irradiance varies is depicted in the above figure. As the graph illustrates, the current increases as the irradiance changes, but the value of Vp is remains constant.

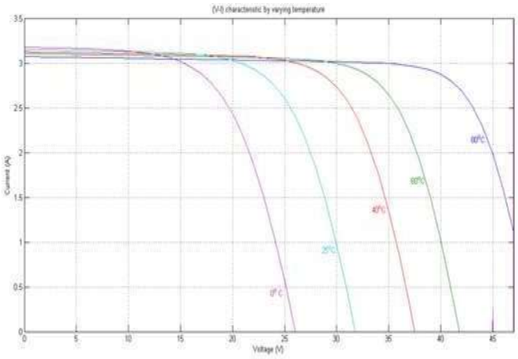

Fig.13.(V-I) Characteristics by varying Temperature

The relationship between voltage and current when temperature changes is depicted in the above figure. As can be seen in the graph, the current is roughly constant as the temperature rises, but the value of Vp is varies as well.

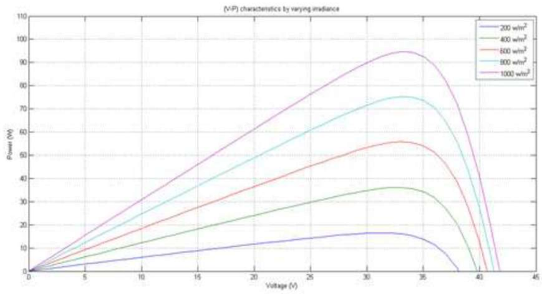

Fig.14 (V-P) Characteristics by Varying irradiance

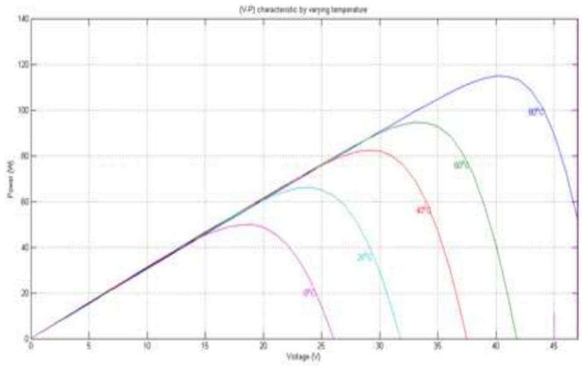

Fig.15 (v-p) Characteristic by varying temperature

The relationship between voltage and power when temperature changes is depicted in the above figure. As can be seen from the graph, power increases along with temperature, and the value of Vp is likewise increases. Then, by altering the resistance Rs, we exhibit the features. When these resistances (Rs) vary, the following figures illustrate the relationship between voltage and current (V-I) and voltage and power (V-P).As the graph illustrates, current and power drop as series resistance Rs rises. Furthermore, the power peak shifts to the right and the V-I characteristic takes on a more rectangular shape as Rs decreases. However, the manufacturer provides the value of Rs [27][28].

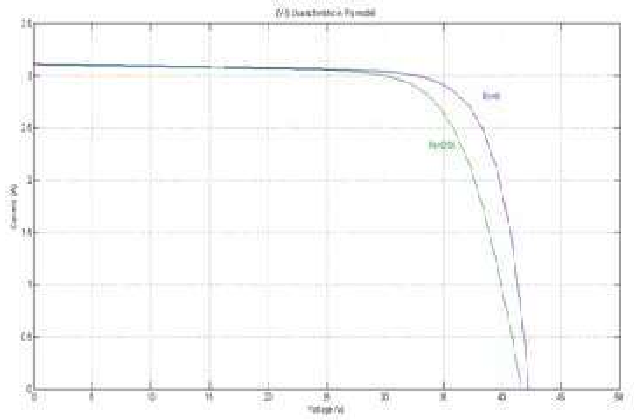

Fig.16 (V-I) Characteristic by varying Rs

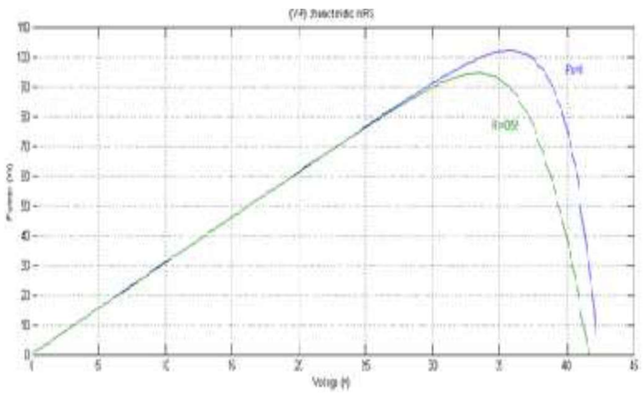

Fig.17 (V-P) Characteristic by varying Rs

CONCLUSION: The PV cell and module are thoroughly modeled and simulated in the work that is being presented. It is integrated in the MATLAB/Simulink environment, which is the most popular program by engineers and researchers. Initially, this concept was created using the principles of semiconductors and photovoltaic cell technology. Stated differently, the PV module characteristics have been chosen based on how they change with temperature and illumination. This implies that the I(V) and P(V) characteristics may be obtained for any kind of PV module by using this model to calculate all the required parameters under any new irradiation and temperature circumstances. This model may be thought of as a tool for researching all kinds of PV modules that are on the market, particularly how they behave in various weather conditions.

standard test conditions (STC) data. Even if RS is provided by a manufacturer, it is crucial to compute it since the calculated Maximum Power Point differs from the experimental one. A pair of (Rs, RP) is obtained for each iteration. However, only one combination meets the requirement that the modeled and experimental peak powers match. Thus, Rs is raised repeatedly until the condition is met. The suggested Rp model yielded (Rs = 0.45 Ω, Rp = 310.0248 Ω).

rather than (Rs = 0.55 Ω, and Rp not given). As a result, it may be calculated to simulate the PV module more accurately.
The suggested method offers a solar array model that is precise, dependable, and simple to adjust. Additionally, it is highly beneficial for examining the functioning of solar PV arrays from various physical characteristics (series, shunt resistance, ideality factor, etc.) and working conditions (changing temperature, irradiance, and particularly partial shadow impact).

References:

[22].Ganesan Pandima devi, Abdulhadi Abdullah Rashid Al-Abri,(2018),Mathematical Modeling of Solar PV Panels, International journal of Engineering Research and Technology,ISSN:2278-0181,Pp(1-6).
[23].Ranganath Muthu, Natarajan Pandiarajan,(2011) “Mathematical modeling of photovoltaic module with Simulink”, International Conference on Electrical Energy Systems (ICEES 2011), Pp(3-5).
[24]. P. Sudeepika, G.Md. Gayaz Khan,(2014),“Analysis Of Mathematical Model Of PV Cell Module in Matlab/Simulink Environment”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 3, Issue 3.
[25].J. Surya Kumari and Ch. SaiBabu,(2012), “Mathematical Modeling and Simulation of Photovoltaic Cell using Matlab-Simulink Environment” International Journal of Electrical and Computer Engineering (IJECE) Vol. 2, No. 1, ISSN: 2088-8708 _ 26,Pp. 26-34.

[26].S. Nema, R.K.Nema, and G.Agnihotri,(2010), "Matlab / simulink based study of photovoltaic cells / modules / array and their experimental verification," International Journal of Energy and Environment, Pp.487500, Volume1,Issue3,
[27].S. Chowdhury, S.P.Chowdhury, G.A.Taylor, and Y.H.Song, "Mathematical Modeling and Performance Evaluation of a Stand-Alone Polycrystalline PV Plant with MPPT Facility," IEEE Power and Energy
[28]s.Jay Patell, Gaurag Sharma,(2013), "Modeling and Simulation of solar photovoltaic module using MATLAB/SIMULINK",International Journal of Research in Engineering and Technology, DOI:10.15623/ijret.2013.0203003
[29].GauragShah,PhotovoltaicEffect,https://www.vedantu.com/physics/photovoltaic-effect

[30].Photovoltaiceffect,https://energyeducation.ca/encyclopedia/Photovoltaic_effect.
[31].Photovoltaic Effect, https://www.britannica.com/science/photovoltaic-effect
[32].How does solar power works, https://kpgroup.co/blog/how-does-solar-power-work/
[33].The Photovoltaic Effect,https://www.pveducation.org/pvcdrom/solar-cell-operation/the-photovoltaic-effect.
[34].How does Solar Power Works?,https://www.nationalgrid.com/stories/energy-explained/how-does-solar-power-work
[35].Solar N plus. (2024). PV cell construction and working. Retrieved from https://www.solarnplus.com/pv-cell-construction-and-working
[36].WiSolar. (2024). Exploring the layers of a solar panel structure. Retrieved from https://wisolar.co/layers-that-make-up-a-solar-panel
[37].Solar panel. (2005). In Wikipedia. Retrieved from https://en.wikipedia.org/wiki/Solar_panel

