Investigation into the Behavioral Characteristics of Photovoltaic Cells using Matlab/Simulink.

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Abstract: Renewable energy sources are significant given their economic benefits, reduced carbon emissions, and contributions to energy security and sustainability. Solar energy holds significant importance among renewable energy sources for several distinctive reasons. PV systems when connected to grid enhance the stability of the electrical grid by offering a decentralized energy source. This paper provides a survey of the latest developments in PV cell technologies, encompassing a broad spectrum of innovations ranging from materials and designs to manufacturing processes. Further, understanding the PV-IV characteristics is fundamental in assessing the performance and efficiency of PV cells. This paper investigates the attributes of the photovoltaic, with an emphasis on P-V characteristics, and evaluates its performance in different input conditions. Modeling of typical photovoltaic cell under standard test conditions (STC) as well as different irradiations and temperature levels is done. In this paper, a single diode modeling of a PV cell is presented and a step-by-step simulation of a solar PV module in Matlab/Simulink is carried out. Different parameters are explored, and their impact on solar cells is represented through the visualization of I-V (current-voltage) and P-V (power-voltage) curves. By scrutinizing the IV characteristics, the research aims to gain insights into the efficiency, reliability, and overall performance of PV cells.

Keywords : *Renewable energy sources; Open Circuit Voltage; Photo Current; Short Circuit Current, PV cell technology*

1. Introduction

Solar energy is of paramount importance for electricity generation due to its exceptional environmental, economic, and societal benefits. As a clean and renewable energy source, solar power plays a pivotal role in combating climate change by mitigating greenhouse gas emissions to a greater extent thereby reducing the environmental impressions created by the immense long term and continuous application of fossil fuel-based electricity production. Its abundance ensures a reliable, long-term energy supply, decreasing reliance on finite and polluting fossil fuels, thereby enhancing energy security.

Exhaustion of conventional resources and their adverse environmental impact has led the energy generation system to utilize natural resources to fulfill the energy demand. The renewable energy sector in India has established itself as a key contributor to the grid-connected power generation system. Solar photovoltaics have become a crucial component in addressing the nation's energy requirements, serving as an essential factor for accessing energy dividends.

Fig. 1 shows the source wise power installed capacity in India in respect of Renewable Energy Sources as on 31-05-2023. Solar power installed capacity stands at 67 GW in India [1].

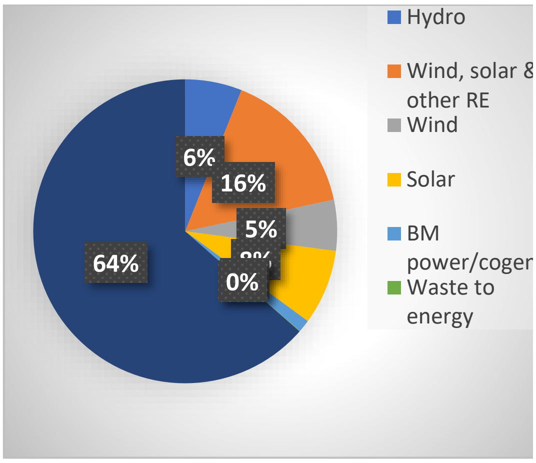

Fig 1. Installed capacity in respect of RES (MNRE) as on 31-5-2023

The exploration of technology and behavioral aspects within the realm of photovoltaic (PV) cells stands as a vital pursuit in the field of renewable energy. As pivotal components in the conversion of sunlight into electricity, PV cells exhibit a dynamic range of characteristics and responses that significantly influence their overall functionality. Authors in [2-5] have provided in-depth analysis of state of art in PV Cell Technology. The first, second, third and next generation technologies are assessed and compared across various parameters. The emerging/next generation technologies and the probable challenges are also discussed. Further, a comprehensive understanding of the behavioral intricacies inherent to PV cells is paramount for advancing the efficiency and effectiveness of solar energy utilization. This work delves into the multifaceted aspects of a PV cell's behavior, shedding light on the intricate mechanisms that govern its performance. The mathematical modeling of a solar cell is implemented in [6-8]. Effect of individual parameters is studied. M. G. Villalva et Al. in [9] adjusted the curve at three different points to find the best I-V equation.

Authors in [10-11] considered the effect of series and parallel resistances to evaluate the performance of PV Cell. An additional diode has also been considered in the circuit by several authors [12-13]. This additional diode takes the recombination effect in account. The two-diode model is known to be more accurate especially at low irradiance levels, but the computational time is high. For simplicity, the typical single diode model is used to study the characterization behavior of cell.

Solar Cell

A solar cell involves conversion of photon energy into electric current as apparent from the photovoltaic principle. When sun rays strike the solar cell, the semiconductor material absorbs the energy and emits electric currents. Basically, when the absorbed energy is greater than the band gap energy of the semiconductor material, the free electrons jump from valence band to the conduction band leading to creation of hole-electron pairs. The electrons tend to move in a particular direction which constitutes electric current which is drawn through an external circuit.

Silicon is the most commonly used semiconductor material solar cells. Monocrystalline and Polycrystalline Silicon are most commonly used commercially. Monocrystalline type offers high efficiency but higher costs are required. On the other hand, polycrystalline comes with low cost and low efficiency. Thin films made out of variety of materials currently provide a combination of low cost, and long lifetime. But they don’t promise an efficiency as that of silicon. Cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) is used in thin-film PV. Both materials can be deposited directly onto either the front or back of the module surface. Thin-film solar cells offers flexibility and lightweight, making them ideal for portable applications[14]. A third type of photovoltaic technology is named after the elements that compose them. III-V solar cells are mainly constructed from elements like gallium, and indium from Group-III, arsenic and antimony from Group V of the periodic table. This type of solar cells is more expensive to manufacture in comparison with other technologies. But they offer efficiency higher than other technologies. Table 1 shows the comparison of the commonly employed PV technologies.

Table1. Comparison of various PV Technologies.

Parameter	*Monocrystalline*	*Polycrystalline*	*Thin film*	*Multi-Junction*
Material	Silicon	Silicon	Variety of materials; common being CdTe and copper indium gallium diselenide(CIGS)	Stacks of multiple semiconductors
Appearance	Black	Bluish hue	Blue and black hues; depends on material; 350 times thinner	
Manufacturing	Cut from a single silicon wafer	Fusion of different silicon crystals	Portable, flexible and lightweight	III-V group elements of periodic table; difficult to manufacture
Cost	High	Low		High cost
Performance	High 14-18%	12-14%	5-6%	Record efficiency level as each layer absorbs a different part of spectrum
Temperature Tolerance	+5%	+/-5%	+/-3%	
Lifespan	25-30 yrs	20-25 yrs	15-20 yrs	

The crystalline and thin film silicon cells belong to first- and second-generation technologies. Third generation photovoltaic cells are made from organic materials, quantum dots, and hybrid organic-inorganic materials , also known as perovskites. PV Cells encompassing quantum dots and perovskite involves heterojunction structure [15] i.e. different layers of semiconductor material sandwiched together to form a solar cell. Each layer can generate electricity from different ranges of wavelengths of light, making the whole cell more efficient. These technologies may offer lower costs and greater ease of manufacturing among other benefits. The various aspects of next generation PV technologies are summarized in Table 2.

Table 2. Third generation PV Technologies

	Perovskite	*Organic*	*Quantum Dots*
Material	Heterojunction cells; layers of materials deposited onto substrate	Made of carbon rich compounds	Tiny particles of different semiconductors are deposited on a substrate
Characteristic		Can be tailored to enhance specific functions	Can be paired with other semiconductors to optimize the performance
Efficiency	High	Low	High
Cost	Low cost	Less expensive in bulk	Low cost
Lifespan	High	Short lifespan	Low

2. Modeling of PV Cell

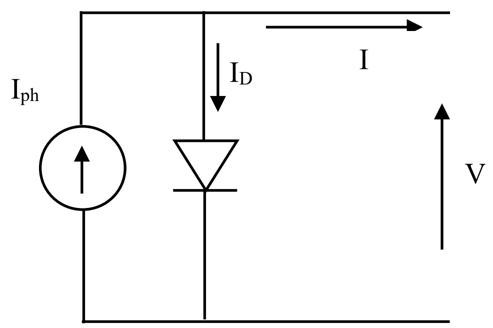

Fig. 2(a) Ideal Solar Cell

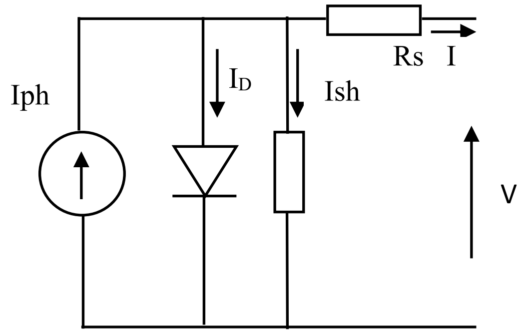

Fig. 2(b) Practical Solar Cell

Fig. 2(a) and 2(b) presents an ideal and practical solar cell respectively. Eq. (1) represents an ideal PV cell depicted in Fig. 2a.

$$I = I_{ph} - I_D \tag{1}$$

The current characteristic of a p–n junction diode is given by the Shockley equation [16] as:

$$I_D = I_s \left[\left(\frac{qV_{oc}}{N_s kAT_0} \right) - 1 \right]$$

By substituting the value of I_d in Eq. (1), the output current can be re-written as:

$$I = I_{ph} - I_s \left[\left(\frac{qV_{oc}}{N_s kAT_0} \right) - 1 \right]$$

Though, an ideal solar cell gives a very good estimate of photon current, there are some elements which are not taken accounted for in ideal case model for the purpose of simplification. Those elements do affect the output of a PV device to much extent in practical cases.

A practical circuit model of solar PV cell has been theorized in literature by introducing a resistance R_s in series and resistance R_{sh} in parallel with a diode in addition to the photon current as illustrated in Fig. 2b. The ohmic contact resistance is accounted for by the series resistance while the surface quality is represented in shunt resistance. Series resistance is very small while the shunt resistance is very large, hence they may be neglected to pursue an ideal case in order to keep the analysis simple. Practically, PV cells combine to form larger units known as PV modules. The modules combine to develop PV array, so it is not recommended to overlook these resistances.

The V-I characteristic equation of a practical solar cell, as illustrated in Fig. 3(b) is provided [10] as:

$$I_{ph} = [I_{sc} + K_s(T - 298)] * \frac{Z}{1000} \tag{2}$$

Where, I_{ph} and I_{sc} is the photo-current and the short circuit current. The K_s is coefficient of short-circuit current of cell and is estimated at STC conditions i.e. 25 °C and 1000 W/m^2; T is working temperature and Z is the actual solar irradiation.

The reverse saturation current I_{rs} is given by:

$$I_{rs} = \frac{I_{SC}}{[\exp\left(\frac{qVoc}{N_s kaT}\right) - 1]} \tag{3}$$

where, V_{oc} is the open circuit voltage, N_s is the number of cells connected in series and a is the ideality factor of the diode.

K is Boltzmann's constant and q is the charge of an electron.

The module saturation current I_0 varies with temperature in a manner as shown below:

$$I_0 = I_{rs} [\frac{T}{T_r}]^3 \exp\left[\frac{q * E_{g0}}{aK} \left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \tag{4}$$

Here, T_n: nominal temperature i.e. 298.15 K and E_{g0} is the band gap energy of the semiconductor.

Therefore,

$$I = N_P * I_{ph} - N_P * I_0 * [\exp\left(\frac{\frac{V}{N_S} + I * \frac{R_S}{N_P}}{n * V_t}\right) - 1] - I_{sh} \tag{5}$$

where

$$V_t = \frac{k * T}{q}$$

and

$$I_{sh} = \frac{V + I * R_S}{R_{sh}} \quad (6)$$

The standard model of PV Cell shown in fig 3 is designed using above equations in MATLAB/Simulink.

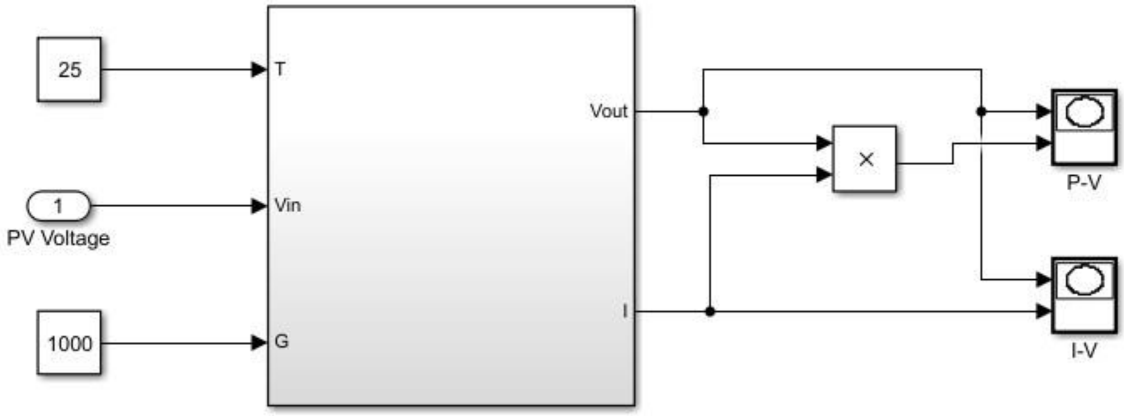

Fig.3 Matlab/Simulink Model of PV Cell.

The characteristic data for the PV cell under consideration is given in Table 3.

Table 3. Electrical data of PV cell.

Sr.No	**Parameter**	**Rating**
1	Power rating	200W
2	Voltage corresponding to maximum power (V_{mp})	26.4V
3	Current corresponding to maximum power(V_{mp})	7.5A
4	Open Circuit Voltage(V_{oc})	32.9V
5	Short Circuit Current(I_{sc})	8.2A
6	No. of cells in series(N_s)	54
7	No. of cells in parallel(N_p)	1

The blocks in MATLAB corresponding to PV sub system and each of the currents i.e. photo current, reverse saturation current, saturation current and shunt current are shown in Fig(4),Fig(5),Fig(6),Fig(7) and Fig(8) respectively.

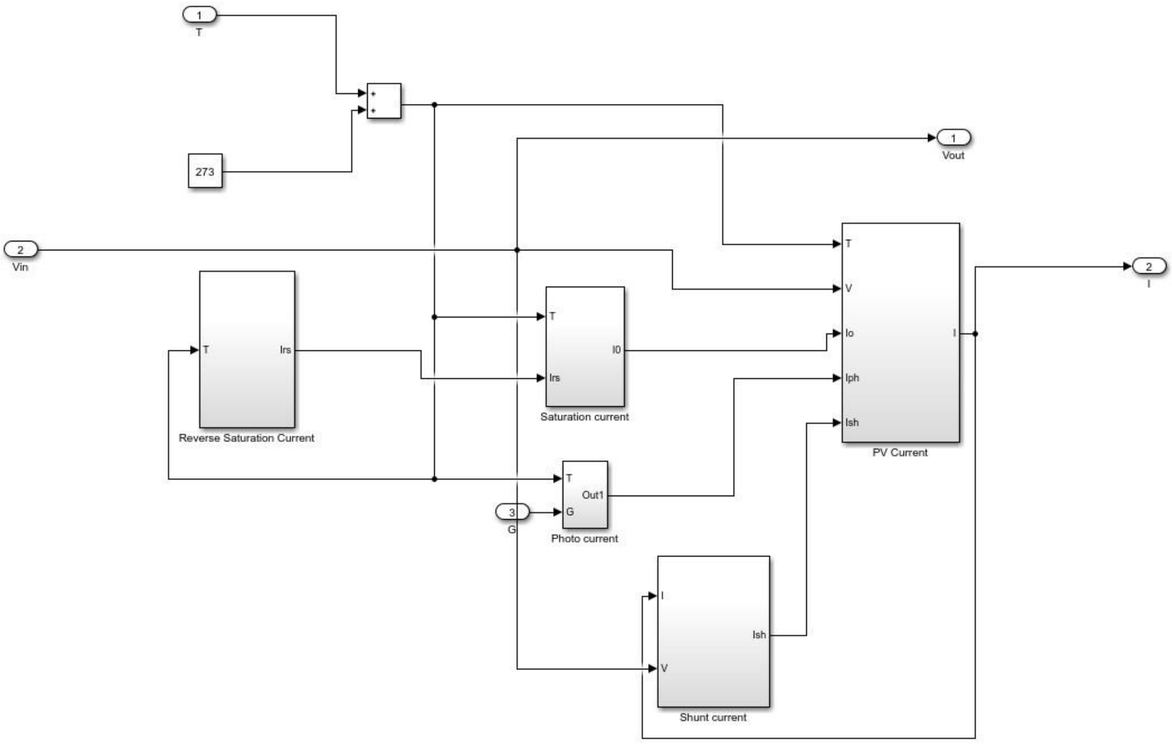

Fig.4 Description of PV Subsystem as expressed in Eqn.(5)

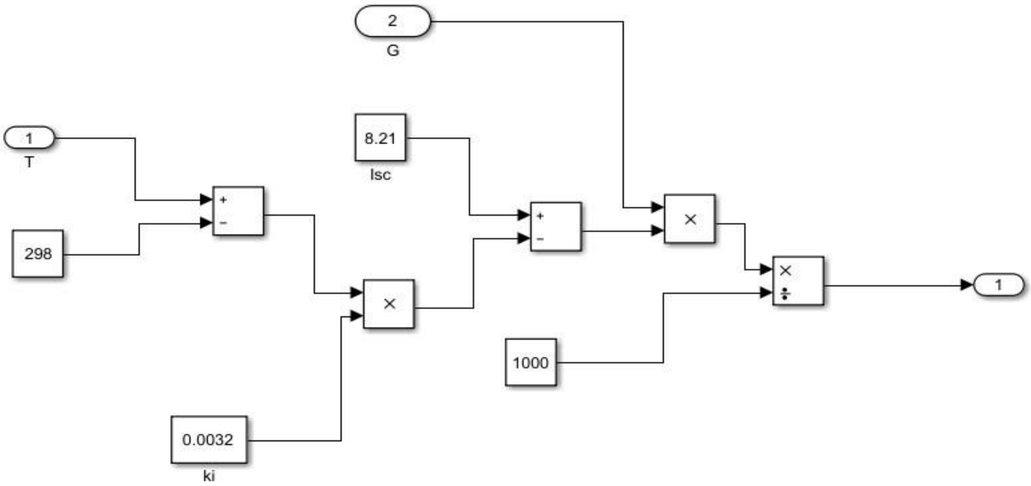

Fig.5 Modeling of Photo Current expressed in Eqn.(2)

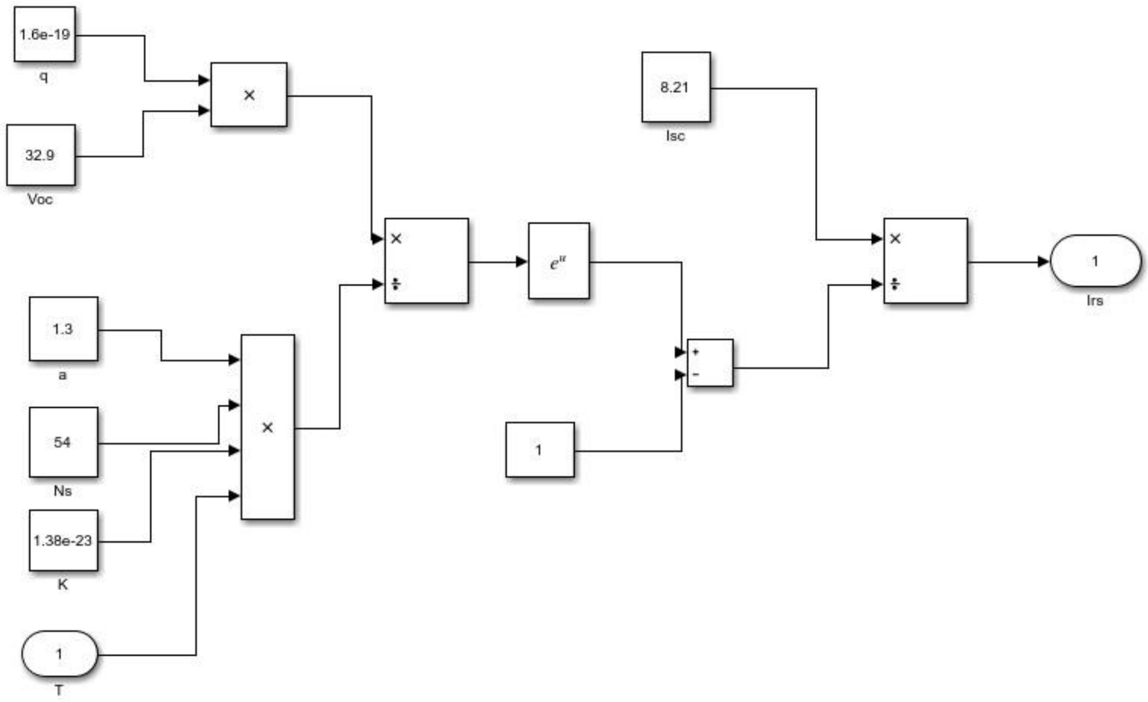

Fig.6 Modeling of PV Cell's Reverse Saturation Current expressed in Eqn.(3)

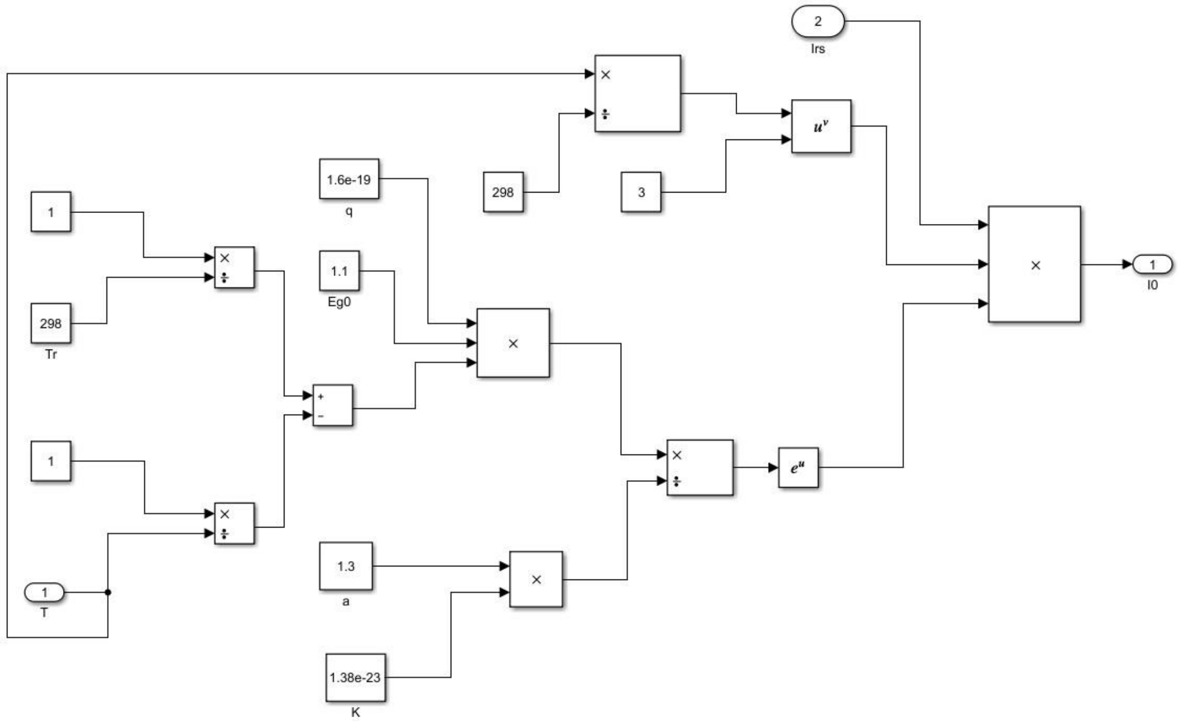

Fig.7 Modeling of PV Cell's Saturation Current expressed in Eqn.(4)

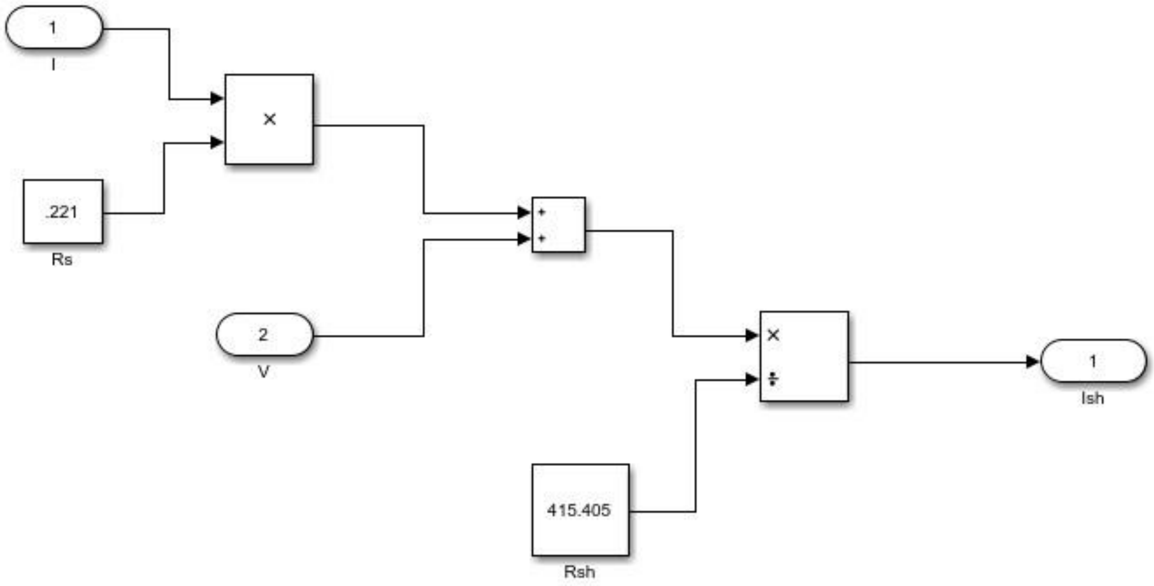

Fig.8 Modeling of PV Cell's Shunt Current expressed in Eqn.(6)

The different I-V and P-V curves are studied at STC and at variable input parameters of the solar cell. The dependence of (P-V) and (I-V) characteristic curves of PV cells on temperature and irradiance at standard test conditions of temperature 25° C and irradiance 1000 W/m^2 is shown in Fig 9(a) and 9(b). P–V and I–V characteristics at variable values of temperature and irradiation are depicted in Fig 4 and 5 respectively.

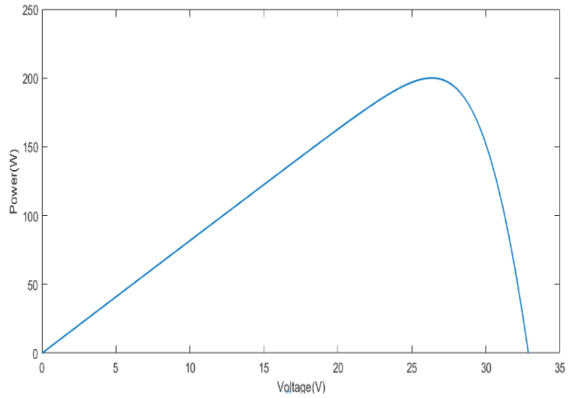

Fig 9(a). P-V characteristic of the solar cell at STC

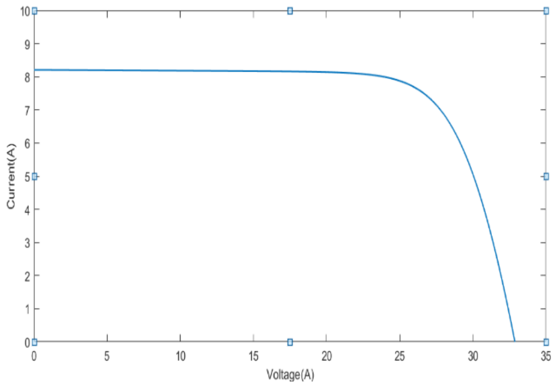

Fig 9(b). I-V characteristic of the solar cell at STC

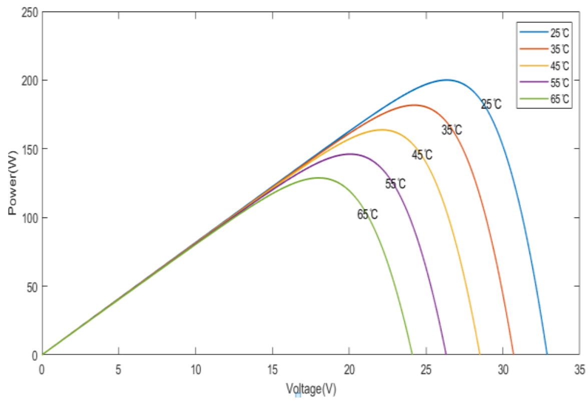

Fig 10(a)

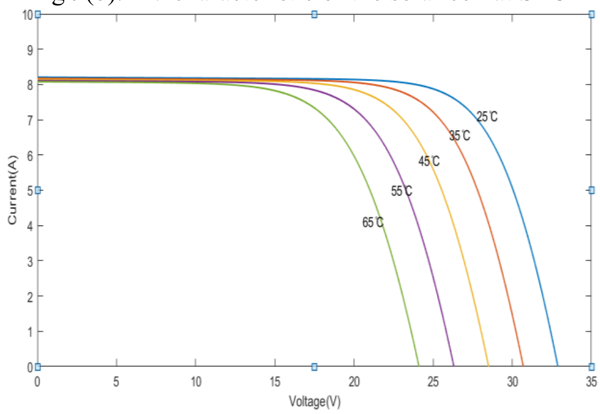

Fig 10(b)

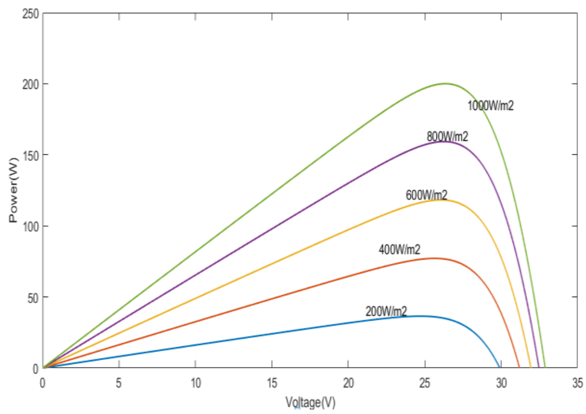

Fig 11(a)

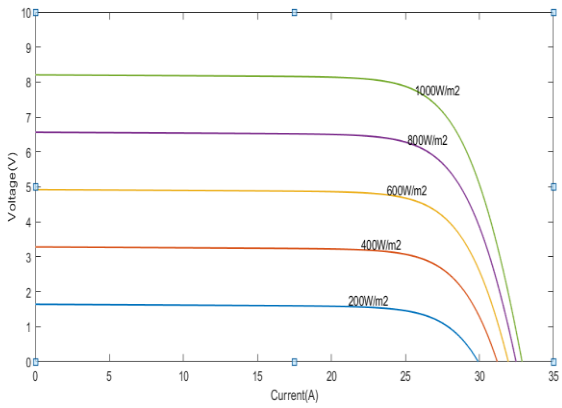

Fig 11(b)

Fig. 10(a) and 10(b). P-V and I-V characteristics of the solar cell at constant irradiance 1000W/m^2 and variable temperature values of 25℃,35℃,45℃,55℃ and 65℃.

Fig 11(a) and 11(b). P-V characteristics of the solar cell at constant temperature 25℃ and variable irradiance values of 200 W/ m^2,400W/m^2 ,600W/m^2 ,800W/m^2 and 1000W/m^2

Discussion

The PV array characteristics are interpreted as follow:

i) P–V and I–V characteristics are given in Fig. 10(a) and 10(b) for varying irradiation values and constant temperature value of 25˚C. The output voltage and current increases with the increase in irradiation resulting in increase in power output in this operating condition.

ii) P–V and I–V characteristics are obtained in Fig. 11(a) and 11(b) for varying temperature values and constant irradiation 1000W/m^2. With an increase in temperature, the output current slightly rises but the output voltage decreases which leads to net reduction in power output.

Conclusion

Through a nuanced examination of effect of various inputs and hence characteristics and responses, it becomes evident that the behavior of PV cells is a dynamic interplay of factors that significantly influence their performance. To understand the characterization of PV cell, a step-by-step modelling of single diode PV cell is carried out in Matlab/Simulink. Each equation is modelled and represented clearly through a Matlab block. The examination of the current-voltage (PV-IV) characteristics of the photovoltaic (PV) cell has yielded valuable insights into the behavior and functioning of the solar cell across diverse conditions. A thorough analysis of the PV-IV curves has outlined the intricate correlation between current and voltage, providing a nuanced comprehension of the cell's efficiency and limitations.

Through a systematic simulation, it has become apparent that the performance of the PV cell is significantly influenced by external factors such as irradiance and temperature. The study has demonstrated a direct correlation between incident light intensity and the resulting current, highlighting the sensitivity of the cell's performance to changes in light exposure. Moreover, the investigation emphasized the impact of temperature on the cell's efficiency, revealing that elevated temperatures contribute to a decline in overall performance.

Several factors influence the output power of solar cells, including shading effects, the types of PV materials used, temperature, radiation intensity, parasitic resistances, weather conditions, solar cell design, doping level, material properties, and quality. Proper optimization plays a crucial role in improving the overall performance of solar cells.

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