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Mathematical Analysis of Three-Diode Model with P&O MPPT using MATLAB/Simulink

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Abstract: **With the growing need for renewable energy resources, photovoltaic based energy generation has gained significant importance due to its high reliability owing to the abundant availability of sunlight and the direct conversion of light into electricity. But the overall efficiency of conversion is still low as compared to cost input in the system. Hence for designing highly efficient systems, successful simulation studies are required. The research paper insights the mathematical modeling of a three-diode model and its performance are analyzed in comparison with a single diode and two-diode model. The model's performance is also analyzed under different atmospheric conditions with MPPT.**

Keywords- Renewable energy, Photovoltaic (PV), Three-diode model, maximum power point tracking, boost converter, MATLAB

1. INTRODUCTION

Intending to lower the carbon emissions and reduce the dependency on non-renewable energy resources there has been significant technological development for utilizing renewable energy resources, such as Wind, Solar, Hydro, and many more. But for a long time, the focus has been on solar-based energy generation mainly due to high availability and easy conversion of light to electricity. PV energy conversion is static and does not require any rotating parts in the system for conversion. The system can be designed with basic semiconductor devices including diodes and transistors. But even with these benefits, the solar-based generation suffers from one major drawback, i.e., low efficiency in comparison to high cost for setting up the system. Hence various models have been presented for solar cell modeling including single diode, two-diode, and three-diode model. The paper covers the performance analysis of all three models for varying atmospheric conditions. There is non-linearity in the I-V and P-V characteristics during the operation, due to varying atmospheric conditions [1]. To maximize the output from the PV module it is operated at the maximum power point, yielding maximum output concerning atmospheric conditions. The most used method for maximum power point tracking is the Perturb-and-Observe method due to its high efficiency and easy employability. The MPPT is used to control the duty cycle for the switching element of the boost converter under varying conditions. The main reason for using the boost converter is to avoid using transformers, to reduce the overall power loss of the circuit and limitation of switching frequency associated with it [2].

2. PV MODULE

A photovoltaic cell is a P-N junction diode that is responsible for generating electricity when exposed to sunlight. This generation is mainly due to the recombination of electron-hole pairs, which are generated due to the photovoltaic effect. In the photovoltaic effect, electron-hole pairs are generated when incident photons have energy higher than the band-gap energy of the material. This generation and recombination are responsible for electricity generation in the device [3]. In general, a PV module is modeled based on different series and parallel combinations of solar cells concerning the power requirement. With a series connection, the voltage profile of the module is improved and with parallel the current profile. The output from the PV module is dependent on operating temperature, irradiance, angle of irradiance, and resistance (series and parallel).

2.1 Single Diode Model

In this model, a single diode is connected in parallel with a current source, a parallel resistance, and a series resistance. The output current equation is:

$$I = I_{PV} - I_d - I_{sh}$$

where,

$$I_{PV} = [I_{sc} + k_i(\Delta T)] * (G/1000)$$

$$I_d = I_o[\exp(\frac{V + IR_s}{\alpha V_T})]$$

$$I_{sh} = \frac{V + IR_s}{R_P}$$

Where I_{PV} is the photon current generated due to incident light, I_o is the reverse saturation current of the diode, V_T is the thermal voltage of diode and α is the diode ideality factor. The other parameters R_s (series resistance) and R_P (parallel resistance) are adjusted as per the requirement. The single diode equivalent model is given in Figure1a.

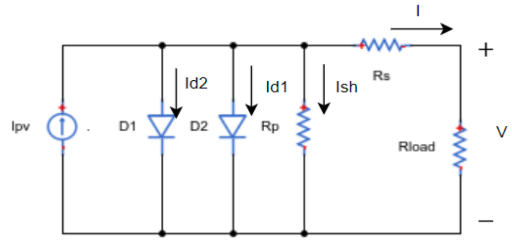

Fig 1a: Single Diode PV model

2.2 Two diode model

In the two diode model, there are two diodes (both in saturation), series resistance, parallel resistance, and current source. The mathematical model for a two-diode model of a solar cell is given as,

$$I = I_{PV} - I_{d1} - I_{d2} - I_{sh}$$

where,

$$I_{PV} = [I_{sc} + k_i(\Delta T)] * (G/1000)$$

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$$I_{d1} = I_{o1}\left[\exp\left(\frac{V + IR_s}{\alpha_1 V_{T1}}\right)\right]$$
$$I_{d2} = I_{o2}\left[\exp\left(\frac{V + IR_s}{\alpha_2 V_{T2}}\right)\right]$$
$$I_{sh} = \frac{V + IR_s}{R_P}$$

Where I_{PV} is the photon current generated due to incident light, I_{o1} and I_{o2} are the reverse saturation current of the diodes (which in general are kept equal), V_{T1} and V_{T2} are the thermal voltages of the diodes and α_1 and α_2 are the ideality factors for the diodes. The two-diode equivalent model is given in Figure1b and its extraction parameters are taken from the article [1].

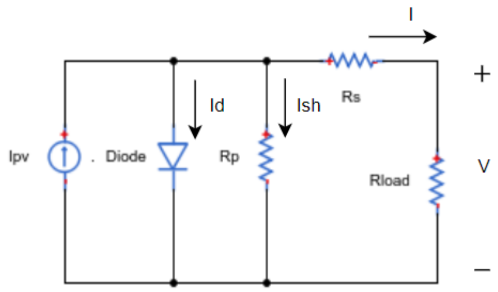

Fig 1b: Two-Diode PV model

It has already been established that the performance of a two-diode model is similar to single diode model provided, the ideality factors are set such that α_1 is unity and α_2 is between $1 \le \alpha_2 \le 1.2$, hence the performance analysis done here is for two-diode model and three-diode model

2.3 Three-diode model

In the three diode model, there are three diodes (both in saturation), series resistance, parallel resistance, and current source. The mathematical model for a three-diode model of a solar cell is given as,

$$I = I_{PV} - I_{d1} - I_{d2} - I_{d3} - I_{sh}$$

Where,

$$I_{PV} = [I_{sc} + k_i(\Delta T)] * (G/1000)$$
$$I_{d1} = I_{o1}\left[\exp\left(\frac{V + IR_s}{\alpha_1 V_{T1}}\right)\right]$$
$$I_{d2} = I_{o2}\left[\exp\left(\frac{V + IR_s}{\alpha_2 V_{T2}}\right)\right]$$
$$I_{d3} = I_{o3}\left[\exp\left(\frac{V + IR_s}{\alpha_3 V_{T3}}\right)\right]$$
$$I_{sh} = \frac{V + IR_s}{R_P}$$

Where I_{PV} is the photon current generated due to incident light, I_{o1}, I_{o2}, and I_{o3} are the reverse saturation current of the diodes (which in general are kept equal), V_{T1}, V_{T2} and V_{T3} are the thermal voltages of the diodes and α_1, α_2 and α_3 are the ideality factors for the diodes.

The three-diode equivalent model is given in Figure1c and its extraction parameters are taken from the article [4], given in Table 1

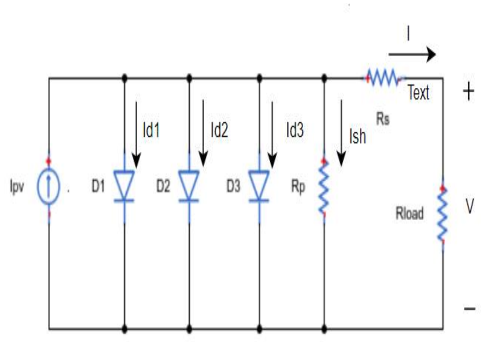

Fig 1c: Three-Diode PV model

Table1: Three-Diode model parameters

Parameter	Value
Open circuit voltage (V_{oc})	21.1 V
Short Circuit Current (I_{sc}) Series Resistance (R_s)	3.8 A 0.205Ω
Shunt Resistance (R)	578.38Ω
k_i	0.065
k_v	-0.08
I_{o1}	4.98e-08 A
I_{o2}	7.24e-10 A
I_{o3}	1.42e-07 A
α_1	1.282
α_2	1.8043
α_3	1.4364

3. PERFORMANCE OF DIFFERENT DIODE MODELS

The performance analysis for two-diode model and three-diode model is given in Figures 2a, 2b, 2c, and 2d.

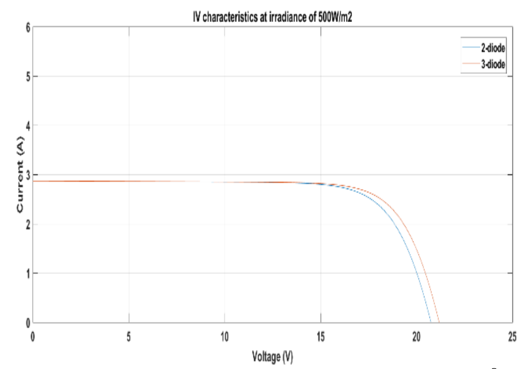

Figure 2a: IV characteristics at Irradiance of 500 W/m^2

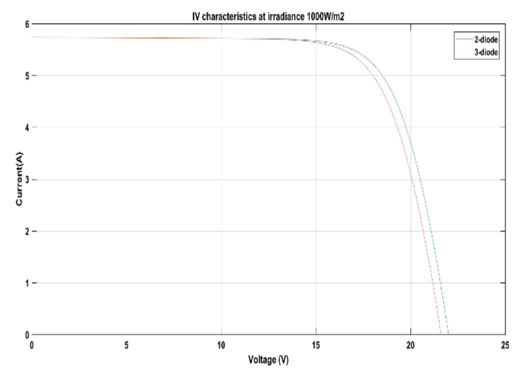

Figure 2b: IV characteristics at Irradiance of 1000 W/m^2

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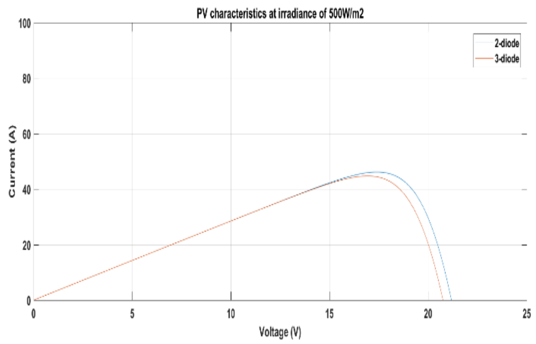

Figure 2c: PV characteristics at Irradiance of 500 W/m^2

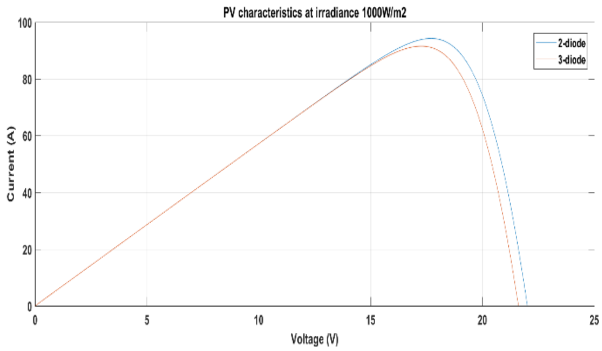

Figure 2d: PV characteristics at Irradiance of 1000 W/m^2

It is evident that with an increase in the number of diodes in the circuit the open-circuit voltage decreases, provided the ideality factors are maintained constant [5]. But when the ideality factor of diodes is varied then the results obtained are given in Figure 3, and the values for the respective ideality factor are given in table 2.

Table2: Variation of open circuit voltage with varying ideality factors of diode

Case	α_1	α_2	α_3	Open circuit Voltage (V)
1.	1.282	1.282	1.282	20.4
2.	1.282	1.282	1.382	21.32
3.	1.282	1.382	1.382	21.33
4.	1.282	1.382	1.484	21.75

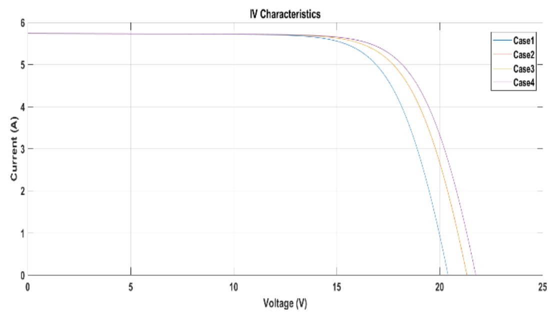

Figure3: IV characteristic variation with varying ideality factor.

4. P&O MPPT

Due to varying atmospheric conditions, there is a non-linearity in PV characteristics hence distinct maximum power points, so there is a need to maximize the power output from the PV module during these varying conditions to increase the efficiency [6]. Hence, we use maximum power point tracking along with PV modules to get maximum power for current atmospheric conditions. There are many algorithms for maximum power point tracking, but the most preferred algorithm is Perturb and Observe algorithm. The algorithm is represented via the flow chart in figure 4. The algorithm is easy to implement and requires a low number of parameters to function. The major drawback of the algorithm is the oscillations around the maximum power point, for which different controllers are used with this.

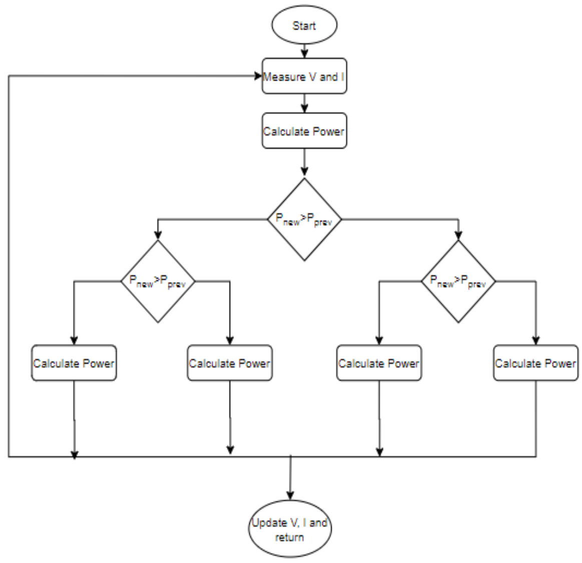

Figure 4: P&O Algorithm

5. BOOST CONVERTER

The DC-DC converter is used to regulate the output voltage with the help of high-frequency switching, inductors, and capacitor with respect to the unregulated input voltage. The output voltage is varied based on the duty cycle of the switching element and other devices are used to minimize signal noise that occurs in the output due to the presence of non-linear devices. The converters can either scale up the voltage (boost converter) or scale down the voltage (buck converter). In the paper, a boost converter is used to scale up the voltage from the PV module to support the load. The switching element used is an IGBT due to its higher efficiency compared to MOSFET and BJT. The Simulink model of boost converter used in the paper is given in figure 5

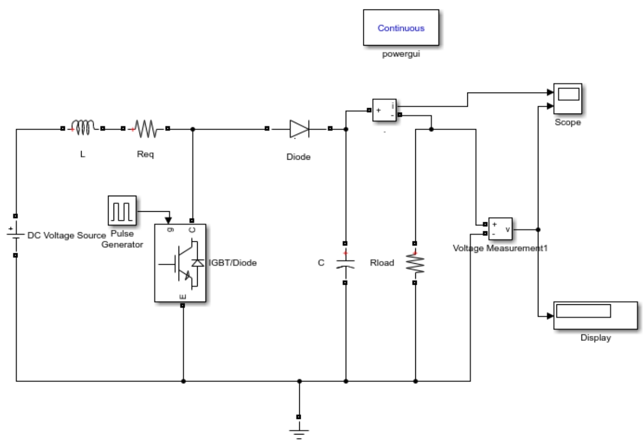

Figure 5: Boost converter

The duty cycle of IGBT is controlled via MPPT, to regulate the duty cycle under varying atmospheric conditions for maximum output. The switching frequency of IGBT is kept such that to avoid high switching losses [7]. Ideal boost converter equation is given as:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D}$$

where V_{out} is the output voltage and V_{in} is the input DC voltage. D is the duty cycle for the pulses given to the switching element. With advancing technology multilevel DC-DC converters are used with inverters in PV based generation systems

6. PERFORMANCE WITH MPPT

This section covers the performance analysis of the two-diode model and three-diode model with P&O based MPPT. The parameters for the module are used as in [5]. All the analysis is done using a mathematical model of the module in MATLAB/Simulink.

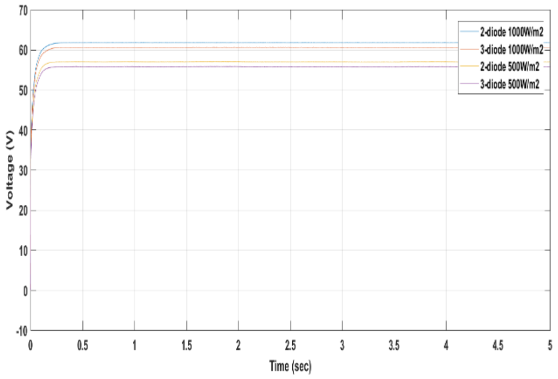

Figure 6: Output voltage variation with MPPT

7. CONCLUSION

It is evident from the analysis that if diodes are increased in the photovoltaic module, the effective output voltage will decrease. But if the ideality factor of the diodes is optimized the performance of the circuit can be improved. Further research can be done to provide an algorithm that can optimize the ideality factor ratio of the diodes for optimum performance, and use of different controllers with MPPT circuit to prevent oscillations and provide a smooth curve till steady state is achieved.

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