Comprehensive equation-based design of photovoltaic module to investigate its physical parameters and operating conditions used for small application

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Abstract
Solar photovoltaic is clean and green energy for renewable power generation, which plays a vital role to fulfil the power shortage for any region. Photovoltaic array is quite expensive and has non-linear characteristics. Under varying conditions, it takes much time to give operating curves. Before mount photovoltaic for any application or at any location, there is a vital phase of analysis, modelling, and simulation of the photovoltaic system, which helps to understand the actual behaviour in real conditions. This paper emphasizes on the stepwise procedure of modelling and simulation for the photovoltaic panel, which is proposed to use for the small application. The proposed system provides a reliable, accurate, and simple method to model the photovoltaic system. It takes a flexible solar panel of 180 W as a reference model. The I–V and P–V characteristics are further investigated at different operating conditions such as a variation of irradiance from 1000 to 400 W/m², variation of temperature from 15 to 70 °C, and vary shunt resistance from higher to low values. The equation-based modelling of the photovoltaic system is built in the MATLAB/Simulink. This methodology allows investigating the photovoltaic system on different operating conditions (varying temperature and irradiance) and physical parameters (ideality factor, series and shunt resistance) along with partial shading effect.

Keywords
Photovoltaic solar panel, renewable energy, irradiance, I–V curve, P–V curve

Introduction
Energy demand is growing day by day with the industrialization and urbanization. With the depletion of fossil fuel resources, there is a need to explore some alternating energy resources to enlighten our homes, businesses, and vehicles.¹,² The conventional way to meet the demand of the world is not suitable and perfect for the green and clean environment because of burning of fossil fuels. The household load along with an automobile has been the leading sources for the depletion of the fossil fuels.³,⁴ The power generation from the fossil fuels is destroying the environment by the exhaust of polluting gasses.³,⁵,⁶ Due to the usage of conventional energy resources to meet the energy demand of domestic and industrial load, there is an adverse effect on the environment such as increasing pollution, acid rain, and global warming.⁷–⁹ There is a need to shift all your primary loads from fossil fuels to the alternate energy resources. For this, the wind energy, tidal energy, geothermal, and solar are the best and suitable energy resources to meet the load demand of the world. Solar energy is abundant in nature and has to be utilized for the electric vehicles.¹⁰ The main advantage for these solar-based electric vehicles besides the improved fuel economy is the reduction of the carbon dioxide emissions.¹¹–¹⁴ Mathematical modelling of the photovoltaic (PV) system is giving a better understanding of its working for the researchers, and it is continuously updating. Although the models for this PV system differs depending on the software used by the researchers like Excel, C-programming, Simulink, MATLAB, and so on. Literature review suggests that many researchers have developed functions in the

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MATLAB environment to calculate the power output for the PV panel, which involves programming that is difficult for the readers to understand who lack such skills. Some other proposed models are based on the mathematical equations and built in Simulink and show the effect of temperature and irradiance, but these papers did not present simulations, which is again difficult for the researchers and the readers to follow and simulate. Although it is covered by Jena et al. and Pandiarajan and Muthu, there is a gap regarding the partial shading effect of the PV system. Especially when suggesting the use of the solar panel in electric vehicles, the partial shading effect has a vital role in achieving the maximum power output from the equipped solar panels.

This proposed model presents the complete step by step equation-based design for the PV solar cell. This proposed model is sufficient to understand the effect of all the physical parameters such as saturation current, ideality factor, series resistance, shunt resistance, and environmental operating conditions such as temperature, irradiance, and partial shading effect on the I–V and P–V characteristics of the PV module. Also, this simple and robust method of modelling allows researchers and readers to follow and simulate by themselves to do further research work. In this paper, the detailed mathematical model for the PV cell is represented in section ‘The mathematical model for PV cell’ and the stepwise Simulink circuit is presented in section ‘Stepwise Simulink circuit for PV cell’. The discussion of the simulated results is presented in the section ‘Simulation results’ whereas the outcomes of this research paper are presented in section ‘Conclusion’.

The mathematical model for PV cell

The PV cell is a device which converts the photon energy into the electricity. Now, if the PV cell is connected in series or parallel form, then the PV module is formed. This arrangement generates the green and clean energy. The primary circuit for the PV cell is shown in Figure 1. In the circuit, the $I_{ph}$ as a current source represents the cell photocurrent given in equation (2) and the output current for a solar cell is represented in equation (1)

$$I = I_{ph} - I_d$$  \hspace{1cm} (1)

where $I_d$ is the diode current (A), $I_{ph}$ is the photocurrent (A)

$$I_{ph} = [I_{sc} + K_c(T - 298)] \times \frac{G}{1000}$$  \hspace{1cm} (2)

$I_{sh}$ is the short circuit current (A), $K_c$ is the short circuit current of a cell at 25°C and 1000 W/m², $T$ is the operating temperature (K), and $G$ is the solar irradiance (W/m²). The real equivalent circuit for the solar cell is shown in Figure 2, which makes it more practical with the addition of series and shunt resistance. $R_s$ and $R_{sh}$ are known as the intrinsic resistance of the cell. Value of the series resistance is minimal, whereas the shunt resistance is substantial; hence, they may be neglected to simplify the analysis.

The output current for the real equivalent circuit for the PV cell is given in equation (3)

$$I = I_{ph} - I_d - I_{sh}$$  \hspace{1cm} (3)

$I_{sh}$ is the shunt current and can be found from the circuit as given in equation (4)

$$I_{sh} = \frac{V + IR_s}{R_{sh}}$$  \hspace{1cm} (4)

$R_s$ and $R_{sh}$ are in ohms. The voltage across the diode is given as in equation (5)

$$V_d = V + IR_s$$  \hspace{1cm} (5)

And the diode thermal voltage can be found as in equation (6)

$$V_T = \frac{nkTN_s}{q}$$  \hspace{1cm} (6)

where $n$ is the ideality factor of the diode, $k$ is the Boltzmann’s constant, $q$ is the electron charge (C), and $N_s$ is the number of cells connecting in series. The diode current is given as in equation (7)

$$I_d = I_o \left[ \exp \left( \frac{V_d}{V_T} \right) - 1 \right]$$  \hspace{1cm} (7)
Put equations (5) and (6) in equation (7) and get the diode current as in equation (8)

\[ I_d = I_o \left( \frac{q(V + IR_s)}{nkT_{ns}} \right) - 1 \]  

(8)

Here, \( I_o \) is the saturation current (A) for the diode as given in equation (9)

\[ I_o = I_{rs} \left( \frac{T}{T_n} \right)^3 \exp \left[ \frac{qE_{go}}{nk} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right] \]  

(9)

where \( T_n \) is the nominal temperature (K), \( E_{go} \) is the bandgap energy of the semiconductor, and \( I_{rs} \) is the reverse saturation current for the diode as given in equation (10)

\[ I_{rs} = \frac{I_{sc}}{\exp \left( \frac{qV_{oc}}{nkT_{ns}} \right) - 1} \]  

(10)

where \( V_{oc} \) is the open-circuit voltage (V) for the solar cell. So, to get the final output current from the PV solar cell, put the equations of saturation and reverse saturation current in the equation of diode current. Finally, equations (8) and (2) substitute into equation (3) to get the final output current for the solar cell as shown in Figure 4

\[ I = I_{ph} - I_o \left( \frac{q(V + IR_s)}{nkT_{ns}} \right) - 1 - I_{sh} \]  

(11)

The complete and comprehensive equation-based method is used to model the PV module, the I–V and P–V characteristics of the designed PV module, Figure 10 shows the complete model design. In this model, many of the tests can be performed by varying the different conditions such as temperature and irradiance, and any PV panel can be designed by changing the shunt current and open-circuit voltage of the cell.

**Stepwise Simulink circuit for PV cell**

For mathematical modelling of the PV solar cell, MATLAB/Simulink is used to build the model. The step by step design of the PV module is discussed in this paper. To implement equation (11) for the final output current of the solar cell, the first step is to model photocurrent as shown in Figure 3 and given in equation (2).

Next step is to model the diode current as given in equation (8), for this need to model saturation current as given in equation (9), again to model this saturation current need to model reverse saturation current first as given in equation (10) as shown in Figure 4.

Use the model of the reverse saturation current, as shown in Figure 4, to build the model for saturation current, as shown in Figure 5.

Finally, use the model of the saturation current of Figure 5 to build the model for the diode current as given in equation (8) and shown in Figure 6.

Now, implement the model of the shunt current, as shown in Figure 7. The next step is to implement the equation of the output current by subtracting the shunt current, diode current from the photocurrent, as shown in Figure 8.

### Table 1. Parameters for the equation-based modelling of PV module.

| Parameter | Value |
|-----------|-------|
| Rated power (\( P_{max} \)) | 180 W |
| Voltage at \( P_{max} \) (\( V_{max} \)) | 32.92 V |
| Current at \( P_{max} \) (\( I_{max} \)) | 5.48 A |
| Open circuit voltage (\( V_{oc} \)) | 39.80 V |
| Short circuit current (\( I_{sc} \)) | 8.55 A |
| Series resistance (\( R_s \)) | 0.221 Ω |
| Shunt resistance (\( R_{sh} \)) | 415.405 Ω |
| Short Circuit Current at cell (\( I_{sh} \)) | 0.0032 A |
| Nominal temperature (\( T_{ns} \)) | 298 |
| Ideality factor (\( n \)) | 1.3 |
| Bandgap energy (\( E_{go} \)) | 1.1 |
| Number of the cell connected in series (\( N_c \)) | 54 |
| Boltzmann’s constant (\( k \)) | 1.38×10^{-23} J/K |
| Electron charge (\( q \)) | 1.6×10^{-19} C |

**Simulation results**

The complete and comprehensive equation-based method is used to build the circuit in the MATLAB/Simulink to investigate its physical parameters and operating conditions as discussed in section ‘Stepwise Simulink circuit for PV cell’, and the simulation results are shown under this section. With the developed model of the PV module, the I–V and P–V characteristics are discussed here.

Figure 9 shows the final model for the implementation of the PV module.

For analysis purpose or to check the I–V and P–V characteristics of the designed PV module, Figure 10 shows the complete model design. In this model, many of the tests can be performed by varying the different conditions such as temperature and irradiance, and any PV panel can be designed by changing the shunt current and open-circuit voltage of the cell.

**PV:** photovoltaic.
Figure 3. Simulink circuit for current source represent as photocurrent of the solar cell.

Figure 4. Simulink circuit for reverse saturation current of the diode.

Figure 5. Simulink circuit for saturation current of the diode.
Shunt resistance also has the role of the power output of the solar cell. Figure 15 shows the I–V characteristics of the PV module in which the shunt resistance is changing from the higher to the lower value while the temperature and irradiance are kept constant on their optimal values 25°C and 1000 W/m², respectively.
As the shunt resistance decreases for the higher value such as 415–100, the current and voltage slightly change, which leads to a reduction in the power output.

When the shunt resistance decreases to a deficient value such as 10 and 5, the current and voltage change noticeably, which results in a reduction of the power output.
output as shown in Figure 16. So to maintain the optimal power, shunt resistance should be selected with care.

Shading effect is shown in Figure 17, where the I–V characteristics experience the multiple steps. From Figure 18, the P–V curve gives the number of peaks and the noticeable power decreases due to the partial shading on the PV panels.

**Conclusion**

This paper presents a step-by-step procedure for equation-based modelling of the PV solar cell, which serves as an aid to the researchers and readers to understand the I–V and P–V characteristics of the system. Before selection of the PV panel at any location and for any application, this study helps the readers a lot because it also represented the robust tool to check the behaviour of the PV module on different physical parameters and environmental conditions such as temperature, irradiance, shunt resistance, and the partial shading. This model is very user-friendly to understand the behaviour of the PV module on several
changing conditions. This study highlights the performance of the selected flexible solar panel for the electric vehicles under the shading effect because almost all at the day time there is a 50% portion of the vehicle is partially shading while on mobility or at parking. This research is only the first step towards the hybrid system for the electric vehicles where other renewable power generation connecting with it, such as wind energy source.

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Figure 18. Output P–V curve with partial shading effect: (a) no shaded (full irradiance 1000); (b) partial shading (Cells 1–36: 1000 irradiance, Cells 37–54: 500 irradiance); (c) partial shading (Cells 1–18: 1000 irradiance, Cells 19–36: 500 irradiance, Cells 37–54: 250 irradiance).
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