DEVELOPMENT OF POWER ELECTRONIC CIRCUIT-ORIENTED MODEL OF PHOTOVOLTAIC MODULE

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ABSTRACT

As the photovoltaic source exhibits non-linear v-I characteristics, which are dependent on solar insolation and environmental factors, the development of an accurate power electronic circuit oriented model is essential to simulate and design the photovoltaic integrated system. A circuit based model of photovoltaic array (PV) suitable for simulation studies of solar power systems is proposed in this paper. The model is realized using power system block set under MATLAB/SIMULINK. The developed model is integrated with standard power electronic model of dc-dc boost converter and the operation is verified through simulation. Then the simulation results are validated with experimental result.

KEYWORDS: Photovoltaic module, Matlab/Simulink.

1. INTRODUCTION

The use of new efficient photovoltaic (PV) module has emerged as an alternative measure of renewable green power, energy conservation and demand side management. Owing to the initial high costs, PV modules have not yet been a fully attractive alternative for electricity users who are able to buy cheaper electrical energy from utility grid. The PV power plant involves higher technology besides their initial cost. So our research objectives are focused in evolving a simpler technology with cost reduction.

The various PV configurations were taken for cost analysis and found that storage batteries account for the most PV system failures and contribute significantly to both initial and the eventual replacement cost. To reduce the complexity of the PV system, the simpler simulation model of PV module was developed.

1.1 Circuit Model

Circuit model of PV module is an essential tool to go deeply inside the operation of a device and to understand the dynamic interactions between parameters. So in continuation of above work, there is a need to develop photovoltaic source circuit-oriented models, so that PV system design studies become much simpler.

Although there are several circuit-level simulators are available in the open literature, MATLAB - SIMULINK circuit-oriented models easy to implement using simple blocks. Circuit-oriented modeling of PV module is being continuously updated to enable the researcher to have a better understanding of its working.

In this paper, in section 2, the production of I_{PV} which is dependent on solar insulation and environmental factors is modeled through iterative process, using the equations described in 3.1. A step-by-step procedure for simulating I_{PV} with user-friendly icons and dialog in MATLAB - SIMULINK block libraries is described. In section 3 the circuit-oriented model is evolved. Section 4 presents the verification of the developed model along with the power electronic circuit of DC to DC boost converter through simulations. Section 5 presents the experimental verification of simulation results. Section 6 presents results and discussion.

2. MODELLING OF PV MODULE

A PV module consists of number of solar cells connected in series and parallel to obtain desired voltage and current. Each solar cell is basically a p-n diode. As sunlight strikes a solar cell, the incident energy is converted directly into electrical energy without any mechanical effort. Transmitted light is absorbed within the semiconductor by using its energy to excite free electrons from a low energy status to an unoccupied higher energy level. When a solar cell is illuminated, excess electron-hole pairs are generated by light throughout the material, hence the p-n junction is electrically shorted and current will flow.

The equivalent circuit of a PV cell is as shown in Figure 1.

Figure 1: PV cell modeled as diode circuit

The current source I_{ph} represents the cell photocurrent. R_{sh} and R_{s} are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of R_{sh} is very large and that of R_{s} is very small, hence they may be neglected to simplify the analysis. PV cells are grouped in larger units called PV modules which are further interconnected in a parallel-series configuration to form PV arrays.

2.1 Equations of PV module

The photovoltaic module can be modeled mathematically as given in equations shown below.

The terms and their values used in the equations explained in annexure - I Module photo-current:

\[ I_{ph} = [I_{SC} + K_{c}(T - 298)] \cdot \lambda / 1000 \]  \hspace{1cm} (1)
Module reverse saturation current - $I_{rs}$:

$$I_{rs} = I_{SC} / \left[ \exp \left( \frac{q V_{OC}}{N_s kT} \right) - 1 \right]$$ (2)

The module saturation current $I_0$ varies with the cell temperature, which is given by

$$I_0 = I_n \left( \frac{T}{T_r} \right)^{3/2} \exp \left( \frac{q E_{ph}}{B k} \left( \frac{1}{T_r} - \frac{1}{T} \right) \right)$$ (3)

The current output of PV module is

$$I_{PV} = N_p I_{ph} - N_p I_0 \left[ \exp \left( \frac{q \left( V_{PP} + I_{PV} R_s \right)}{N_s A k T} \right) - 1 \right]$$ (4)

Where $V_{PP} = V_{oc}$, $N_p = 1$ and $N_s = 36$

2.2 Reference Model

Solkar make 36 W PV module is taken as the reference module for simulation and the name-plate details are given in Table 1.

Table 1: electrical characteristics data of solkar 36W PV module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>37.08 W</td>
</tr>
<tr>
<td>Voltage at Maximum power</td>
<td>16.56 V</td>
</tr>
<tr>
<td>Current at Maximum power</td>
<td>2.25 A</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>21.24 V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>2.55 A</td>
</tr>
<tr>
<td>Total number of cells in series ($N_s$)</td>
<td>36</td>
</tr>
<tr>
<td>Total number of cells in parallel ($N_p$)</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: The electrical specifications are under test conditions of irradiance of 1 kW/m², spectrum of 1.5 air mass and cell temperature of 25 °C.

2.3 Development of MATLAB-SIMULINK Model

A model of PV module with moderate complexity that includes the temperature independence of the photocurrent source, the saturation current of the diode, and a series resistance is considered based on the Shockley diode equation.

Being illuminated with radiation of sunlight, PV cell converts part of the photovoltaic potential directly into electricity with both I-V and P-V output characteristics. The model mainly contains four blocks representing four equations given above.

2.4 Block – I

Block I is shown in Figure 2. This model takes following inputs and calculates photocurrent $I_{ph}$ using equation (1).

- Insolation/ Irradiation – ($G/1000$) 1 kW/m² = 1.
- Module operating temperature $T_{ak}$ = 30 to 70°C
- Module reference temperature $T_{rk}$ = 25°C.
- Short circuit current ($I_{SC}$) at reference temp. = 2.55A

2.5 Block – II

With block II, module reverse saturation current – $I_{rs}$ is obtained using equation (2) as shown in Figure 3.
2.6 Block – III
Block III takes reverse saturation current $I_{rs}$, module reference temperature $T_{rK} = 25^\circ C$ and module operating temperature $T_{ak}$ as input and calculates module saturation current as shown in Figure 4, using equation (3).

2.7 Block – IV
Block IV provides the output $I_{pv}$ by executing the function given by the equation (4). The following function equation is used.

$$I_{pv} = u(3) - u(4) \times (\exp((u(2) \times (u(1) + u(6))) / (u(5))) - 1)$$

Block IV is shown in Figure 5.

2.8 MATLAB-SIMULINK Model
All above four blocks are interconnected as shown in Figure 6 and MATLAB SIMULINK model of PV module is shown in Figure 7.
The SIMULINK model can be used for getting the I-V and P-V output characteristics of PV module with input of solar irradiation, temperature as environment input and PN junction voltage as material input as shown in Figure.8.
2.9 PV module characteristics

With the developed model, the PV module characteristics are obtained as shown in Figures 9 and 10.

3. CIRCUIT-ORIENTED MODEL

The circuit model of the given PV module is evolved as follows. In the equivalent circuit of a PV cell, as shown in Figure 1, the voltage available across the PV cell is nothing but the PN junction voltage of 0.6V. The open circuit voltage of the PV module is 21.24V/36 cells = 0.594V ≈ 0.6V. The MATLAB-SIMULINK model developed in section 3 provides the module current \( I_{PV} \). This PV current output takes care of all irradiation, temperature, and voltage variations and is a very essential input and can be used directly in circuit model. The values of \( R_s \) and \( R_{sh} \) are taken from the literature as 0.221Ω and 415Ω respectively. The circuit model of given PV module is shown in Figure 11.

![Figure 8: I-V & PV ch. Setup of PV module](image)

![Figure 9: I-V ch at constant irradiation](image)
Figure 10: P-V characteristic at constant irradiation

Figure 11: Detailed circuit model of PV module.

Figure 12: Circuit model of PV module.
4. VERIFICATION THROUGH SIMULATION

The PV modules are being used with variety of power electronic circuits. Of these, DC-DC boost converters are used often in PV systems to step up the low module voltage to high voltage levels required by the loads. So our developed model is verified with DC-DC boost converter circuit.

4.1 Design of dc-dc boost converter

The equations of boost converter are as follows. DC voltage gain of the boost converter is given as

\[ M = \frac{V_o}{V_i} = \frac{1}{1 - D} \]

Where \( V_i \) is input voltage, \( V_o \) is output voltage and \( D \) is the duty cycle of a pulse width modulation (PWM) signal, used to control the MOSFET on and off states.

As the name of the converter suggests, the output voltage is always greater than the input voltage. The boost converter operates in the continuous conduction mode for inductor \( L > L_b \) where,

\[ L_b = \frac{(1 - D^2)DR}{2f} \]

The current supplied to the output RC circuit is discontinuous. Thus, a larger filter capacitor is required to limit the output voltage ripple. The filter capacitor \( C_{min} \) must provide the output dc current to the load when the diode \( D \) is off. The minimum value of the filter capacitance results in the ripple voltage \( V_r \) is given by

\[ C_{min} = \frac{D V_o}{V_iRF} \]

Data used for simulation studies are as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor</td>
<td>120µH</td>
</tr>
<tr>
<td>MOSFET</td>
<td>IRF P460</td>
</tr>
<tr>
<td>Power Diode</td>
<td>1N5408</td>
</tr>
<tr>
<td>Capacitor</td>
<td>330µF</td>
</tr>
<tr>
<td>Resistive Load</td>
<td>50Ω, 50W</td>
</tr>
</tbody>
</table>

4.2 DC-DC boost converter with DC Supply

The DC to DC converter is tested with battery supply as shown in figure 11 and output voltage obtained is shown in figure 12.
For input DC voltage of 19.7V, the output voltage of 54V is obtained as shown in graph.

4.3 Performance of developed model

The above developed model is verified with open loop DC to DC boost converter as shown in figure 15. The irradiation input of 1000W/m² and temperature of 35°C, the output of the circuit model is as follows.

- Input operating current to boost converter – 1.8A
- Input operating voltage to boost converter – 17.63V
- Input operating power to boost converter – 31.36Wp
- Output operating voltage from boost converter – 28.19V

![Figure 15: Verification of the developed model]
5. EXPERIMENTAL VERIFICATION OF SIMULATION RESULTS

In order to verify the circuit operation and confirm the simulation results a prototype is built as shown in figure 17.

The experimental setup with PV module is shown in figure 18.

The output voltage waveform of DC to DC boost converter is shown in figure 19.

The input and output voltage of DC to DC converter with DC input is shown in figure 20.

The input and output voltage of DC to DC converter with PV input is shown in figure 21.
6. RESULTS AND DISCUSSION
The simulation results are validated through experimental setup successfully.
Thus the developed model can be used in the design of PV load circuits.

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ANNEXURE - I

NOMENCLATURE

- $V_{pv}$ is output voltage of a PV module (V)
- $I_{pv}$ is output current of a PV module (A)
- $T_r$ is the reference temperature = 298 K
- $T$ is the module operating temperature in Kelvin
- $I_{ph}$ is the light generated current in a PV module (A)
- $I_o$ is the PV module saturation current (A)
- $A = B$ is an ideality factor = 1.6
- $k$ is Boltzmann constant = $1.3805 \times 10^{-23}$ J/K
- $q$ is Electron charge = $1.6 \times 10^{-19}$ C
- $R_s$ is the series resistance of a PV module
- $I_{SCr}$ is the PV module short-circuit current at 25°C and 1000W/m$^2$ = 2.55A
- $K_i$ is the short-circuit current temperature co-efficient at $I_{SCr}$ = 0.0017A/°C
- $\lambda$ is the PV module illumination (W/m$^2$) = 1000W/m$^2$
- $E_{go}$ is the band gap for silicon = 1.1 eV
- $N_s$ is the number of cells connected in series
- $N_p$ is the number of cells connected in parallel

REFERENCES