A Dynamic Model of Single Crystalline Photovoltaic Cells Incorporating Thermo-Electric Characteristics

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Abstract

This paper proposes a dynamic thermo-electric model that links electrical parameters with thermal parameters. In this model, the irradiance and ambient temperature are used to calculate the cell temperature based on a four-layer model that includes the PV cell and surround materials. The calculated cell temperature is then used in the electrical model to accurately adjust the PV electrical characteristics. Dynamic PV characteristics, parallel capacitive and series inductive components, are added to the conventional single-diode model. The results show the effectiveness of this model rather than other conventional models of a PV panel.

1. Introduction

Photovoltaics (PVs) are gaining more attention as clean energy sources become more widely utilized. As PV systems become larger and more complex, detailed PV cell models are needed for design and simulation.

The single-diode PV model, as shown in Fig. 1, is commonly chosen for its simplicity in calculating PV characteristics in the forward-biased region, which has been well described and simulated in [1-3]. However, the single-diode PV model lacks dynamic, reverse-bias, and thermal characteristics, which become apparent in fault conditions and high-frequency applications. In order to achieve the dynamic PV characteristics, parallel capacitive and series inductive components are added to the model. Reverse-bias and breakdown features [4] are also incorporated to investigate potential mismatch effects on PV strings.

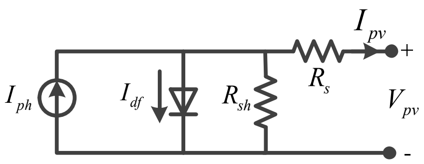

Fig. 1 Single Diode PV model equivalent circuit

Temperature and thermal factors have a significant effect on the electrical PV characteristics (output voltage and current). The heat transfer between layers of a cell changes the nominal PV cell temperature. In this work, a 4-layer single crystalline PV panel model, which has been well developed in [5], is considered to study the effects of heat distribution in the layers.

In this paper, a dynamic thermo-electric model for a string of 24 PV cells in series has been developed and tested under different ambient temperature and solar irradiance conditions. Also, temperature changes in each layer of the module and their effects on the PV electrical characteristics are shown.

2. PV Electric Model

To accurately reflect the dynamic behavior of a PV cell during operation, a dynamic PV model has been developed. A PV cell is considered to be a p-n junction with parasitic resistances, inductance, and capacitance that can be represented using circuit components, plus a current source showing photocurrent, as shown in Fig. 2. In addition to the parameters involved in single-diode model (photocurrent source I_{ph}, forward-bias conducting diode D_f, series resistance R_s, and shunt resistance R_{sh}) there is a series-connected inductance L_s, variable parallel capacitance C_p, and reverse-bias conducting diode D_r with a breakdown voltage offset V_{bd}.

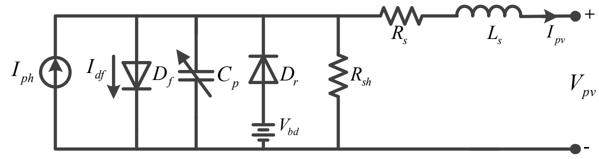

Fig. 2 Equivalent circuit for dynamic PV circuit

The model is described in the following equations based on the model inputs (G, I_{pv}). The photocurrent, which is relative to G and air mass modifier M, describes the current that is absorbed by electrons due to illumination, according to

$$I_{ph}(G,T,M)=\left[I_{scn}\left(\frac{R_s+R_{sh}}{R_{sh}}\right)+K_i(T-T_n)\right]\frac{G}{G_n}\frac{M}{M_{ref}} \tag{1}$$

The air mass modifier can be expressed using its reference value at standard test conditions (STC), according to

$$M=M_{ref}\sum_{i=0}^{4}a_i m_a^i \tag{2}$$

where m_a is the mass of air that is a function of local zenith angle:

$$ma=\frac{1}{\cos\theta_z+0.5057(96.080-\theta_z)^{-1.634}} \tag{3}$$

Forward and reverse diode currents are calculated using (4-5):

$$I_{df}(T,V_d)=\frac{I_{scn}+K_i(T-T_n)}{\exp\left(\frac{V_{ocn}+K_v(T-T_n)}{aV_t(T)}\right)-1}\left[\exp\left(\frac{V_d}{aV_t(T)}\right)-1\right] \tag{4}$$

$$I_{dr}(T,V_d)=I_{sr}\exp\left(\frac{K_rV_{bd}}{aV_t(T)}\right)\left[\exp\left(\frac{-K_rV_d}{aV_t(T)}\right)-1\right] \tag{5}$$

Thermal voltage V_t can be derived as

$$V_t(T)=\frac{kT^2}{qT_n}N_s \tag{6}$$

The shunt resistance R_{sh} is derived based on its value in STC as follows:

$$R_{sh}=\frac{G}{G_n}R_{shn} \tag{7}$$

The I-V relationship at a specific ambient temperature and irradiance can be obtained by applying Kirchhoff's current law:

$$0 = I_{ph}(G,T) - I_{df}(T,V_d) + I_{dr}(T,V_d) - I_{Rsh}(V_d) - I_{pv} \quad (8)$$

This is a nonlinear equation that can be solved for diode voltage V_d using methods such as Newton-Raphson or Halley. The output PV voltage is calculated according to:

$$V_{pv}(V_d, I_{pv}) = V_d - I_{pv}R_s - L_s \frac{dI_{pv}}{dt} \quad (9)$$

3. PV Thermal Model

To determine the PV output power, the temperature and heat distribution over different layers must be found. The single crystalline PV cell consists of 4 layers, as shown in Fig. 3.

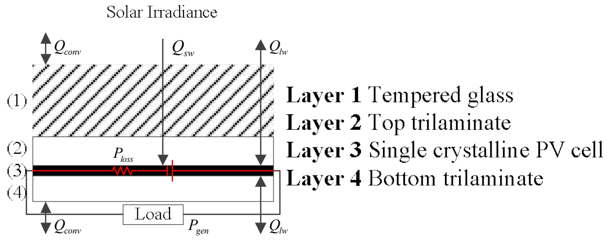

Fig. 3 Heat transfer in a PV panel

The heat transfer equations for the tempered glass face and top and bottom trilaminates are as follows:

$$C_{l1} \frac{dT_{l1}}{dt} = Q_{conv} + Q_{l2} \quad (10)$$

$$C_{l2} \frac{dT_{l2}}{dt} = Q_{l1} + Q_{l3} \quad (11)$$

$$C_{l4} \frac{dT_{l4}}{dt} = Q_{l3} + Q_{conv} \quad (12)$$

$$Q_{conv} = (h_{c,for} + h_{c,fre}) A_{l1} (T_{amb} - T_{l1}) \quad (13)$$

where $h_{c,for} = 1$ Wm^{-2}K^{-1} is the forced convection coefficient and $h_{c,fre} = 0.655(T_{lx} - T_{amb})^{\frac{1}{3}}$ Wm^{-2}K^{-1} is the free convection coefficient.

Heat distribution over the crystalline cell is modeled using the following equations:

$$C_{l3} \frac{dT}{dt} = Q_{sw} + Q_{lw} + Q_{l2} + Q_{l4} + Q_{ele} \quad (14)$$

$$Q_{sw} = \alpha_{ab}.S.A_{l3} \quad (15)$$

$$Q_{lw} = \sigma A_{l3} \left(\frac{1+\cos\beta}{2} \varepsilon_s T_s^4 + \frac{1-\cos\beta}{2} \varepsilon_g T_g^4 - \varepsilon_p T_p^4 \right) \quad (16)$$

$$Q_{ele} = R_{sh} I_{Rsh}^2 + R_s I_{pv}^2 - V_{pv} I_{pv} \quad (17)$$

where β is the tilted surface angle compared to the horizon, $\varepsilon_s = 0.95$ is the sky emissivity, $T_s = T_{amb} - 20$ K is the effective sky temperature, $\varepsilon_g = 0.95$ is the ground surface emissivity, T_g is the ground temperature, $\varepsilon_p = 0.9$ is the PV panel emissivity, and T_p is the PV cell temperature.

3. Simulation Results

The developed dynamic thermo-electric model is simulated in MATLAB Simulink. Table I shows the main input parameters.

Table I. Input parameters

Input Parameter	Description	Value
θ_z	Zenith angle	0°
T_{amb}	Ambient Temperature	$25^\circ C$
T_g	Ground temperature	$10^\circ C$
β	Tilted surface angle	0°
$A_{l1}, A_{l2}, A_{l3}, A_{l4}$	Effective area of layers	0.95m^2
R_{sh}	Parallel resistance	91.8 Ω
R_s	Series resistance	0.046 Ω

Fig. 4 shows the I-V characteristic of a 24-cell string for different illumination levels. The reverse-bias characteristics are also shown. Temperature changes in layers of cell are shown in Fig. 5. It can be seen that temperature in each layer increases, while after t=6 sec, because of convection between PV layers, they try to reach to a constant equal temperature.

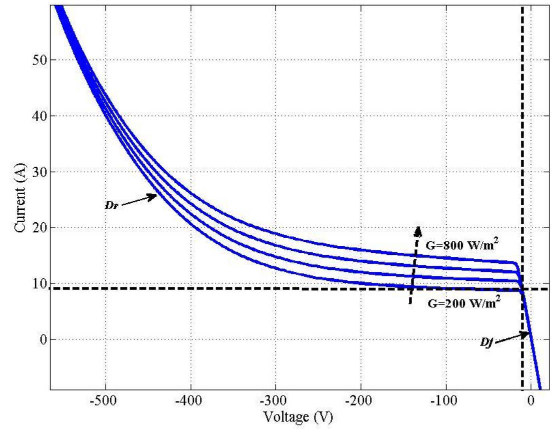

Fig. 4 I-V characteristics of proposed dynamic PV model

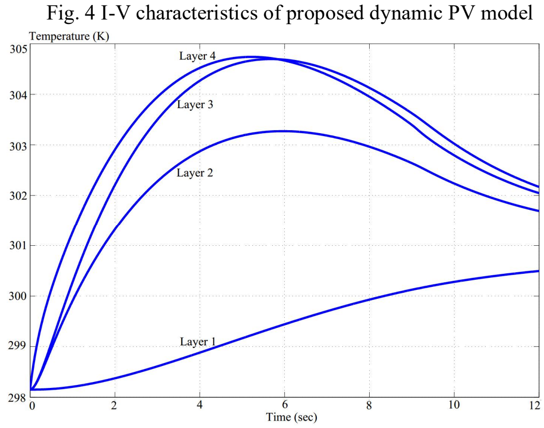

Fig. 5 Temperature variations of different layers in a PV cell

4. Conclusion

In this paper, a dynamic thermo-electric PV model corporating reverse-bias characteristics has been proposed. Also, the effects of temperature and irradiance on the PV cell output have been studied. Simulation results show how the temperature in each layer of cell affects the whole module and consequently the PV electrical characteristics. This model is useful for analysis of PV in extreme environmental conditions and also when a fault happens in the PV string.

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