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Performance Evaluation of PV Module by Dynamic Thermal Model

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Abstract

The response of the Photovoltaic module is dynamic with respect to the changes in its incomings. Steady state models of the operating temperature cannot be justified when rapidly changes of conditions occurs. In this paper, it is of interest to evaluate performance of Photovoltaic module using dynamic thermal model. Electric circuit elements are used in the proposed dynamic model of Photovoltaic module. Therefore, 'Node Analysis' method is applied for analysis of nonlinear circuit. In real conditions, the effective Photovoltaic module operating temperature is affected by randomly varying of solar radiation, ambient temperature and wind speed. Hence, these have been applied as incomings of Photovoltaic module dynamic model. Performance of Photovoltaic module has been verified on two atmospheric conditions. Finally, the effect of incomings on operating temperature of Photovoltaic module has been discussed.

Keywords: Photovoltaic, Electric Circuit, Dynamic, Thermal Model

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1. Introduction

Photovoltaic (PV) module is a converter that is used for conversion of solar energy to electrical energy. In PV modules, the absorbed energy is converted to electrical and thermal energy [1]. Increasing of the PV module operating temperature is due to produced heat [1]. This increase in operating temperature reduces the electrical efficiency of PV module. Some of researchers use the hybrid PV/Thermal systems so that the produced heat to be useful. The hybrid systems use air [2] or water [3] to generate electrical power and simultaneously produce hot water or air. In the construction of PV modules in addition to semiconductors (silicon), other materials such as glass and tedlar are used [1]. In the hybrid systems the fluid is added to these materials. Because the thermal and physical characteristics of materials are not equal, consequently the rate of heat transfer between them is different and the various layers have different temperature [4]. Therefore for determination of the exact temperature of each of these layers, it is necessary to provide a suitable model.

Several models are presented in the references. Tiwari et al. thermal model for the hybrid PV/T systems with water and air is considered, but the heat capacity of elements has been ignored [5]. Another model using electric elements for solar flat-plate thermal collector has been provided by Cristofari et al. and the performance of hybrid system to change in various parameters has been studied [6]. Four different structures of hybrid PV/T system with fluid air have been tested, and then static model has been used to analyze them by Hegazy [7]. The evaluation of electrical efficiency of hybrid PV/T system with fluid air has been done by Tiwari et al., this analysis has been performed statically and thermal

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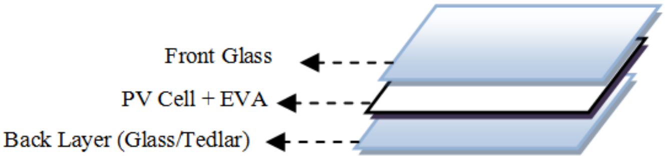


Figure 1: Simple configuration of PV module

capacity of PV modules has been ignored again [1].

Jones and Underwood have analyzed the dynamic thermal model of PV module considering the same temperature for its different layers. In addition, the proposed model has been evaluated in calm and non-calm conditions [8]. Notton et al. has presented an appropriate model for double-glass PV module; moreover, his proposed model has been tested with different forced convection losses coefficients [9].

In this paper dynamic thermal model of PV module is studied. The electrical topology of thermal model is illustrated using electric elements. Then 'node analysis method' is applied and the state equations are determined. Modeling of PV module is done for two types: glass to glass and glass to tedlar. The temperature of different layers and the electrical efficiency of the PV module are evaluated in the calm and the non calm conditions, and performance of this method is compared. Finally, the PV module operating temperature in the form of three input signals of PV is modeled and their characteristics are exposed.

2. Dynamic Thermal Model of PV module

Dynamic thermal model is used for analysis of PV module behaviour in different conditions. Fig. 1 shows the main structure of PV module. In this study PV module is divided into three isothermal regions [9]: the front glass cover (fg) (sheet of tempered glass with high transmittance), the photovoltaic cells (PV) (mono-crystalline technology) onto EVA and back cover which can be glass (back glass cover) or Tedlar.

Two types of PV modules have been considered in this paper with different covers. Some of the hypotheses considered in the modelling of PV module are as follows:

1. In this study one dimensional modelling is used due to reasonable accuracy.
2. All of layers are with uniform temperature distribution.
3. Transmittivity of ethyl vinyl acetate (EVA) is approximately 100%.
4. The ohmic losses in the PV module are negligible.

Table 1: Analogies between Thermal and Electrical Parameters [10]

Thermal Quantity	Electrical Quantity
Temperature: T, K	Voltage: V, V
Heat Flow Rate: I_h, W	Current: I, A
Thermal Resistance: θ, K/W	Electrical Resistance: R, Ohm
Heat Capacity: C_h, J/K	Capacitance: C, F
$\theta \cdot I_h = T$	$R \cdot I = V$
$I_h = C_h \cdot \frac{dT}{dt}$	$I = C \cdot \frac{dV}{dt}$

In the modeling of PV module the analogy between electrical and thermal parameters are used which is presented in table 1 [10].

For the PV module most thermal models have been given be authors that one of which has been shown in [9] by Notton et al. In this study, modified thermal model has been presented in Fig. 2.

Aforementioned circuit for glass to glass and glass to tedlar types of PV module is composed of elements of electrical circuit such as resistor (R), capacitor (C) and voltage and current sources. Study of this circuit requires calculation of the value of elements.

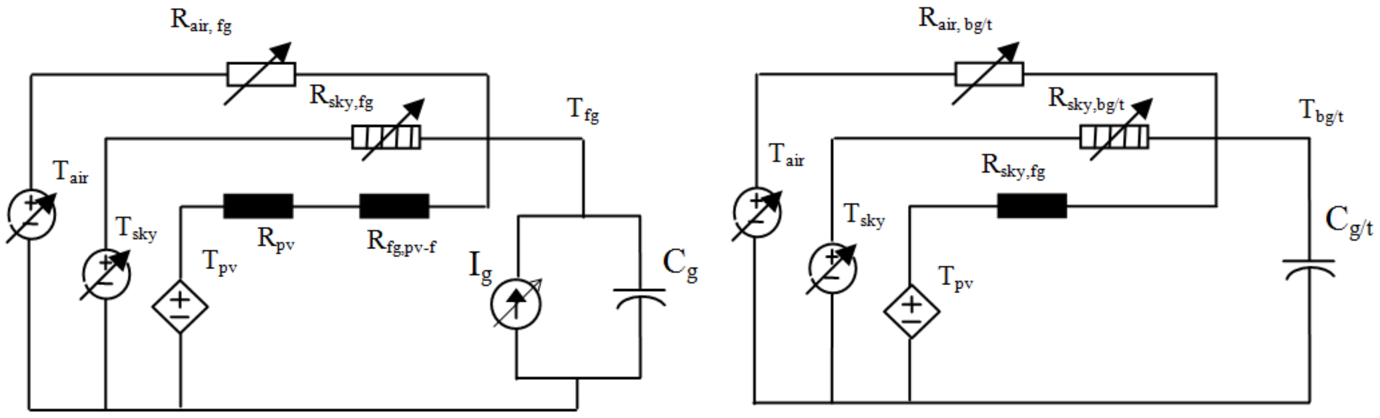
3. Electric Circuit Elements

Incomings of PV module are as functions that are time-varying; therefore all of following parameters are a function of time.

3.1. Solar Energy

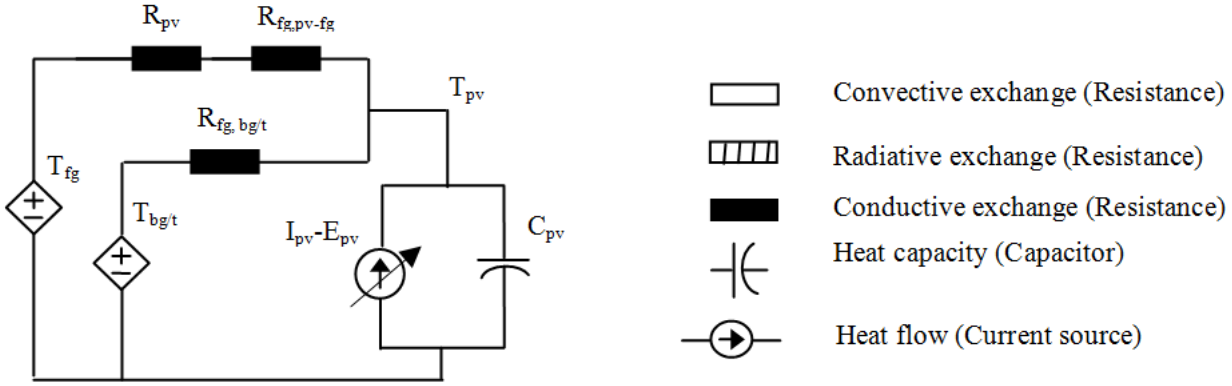
The received solar energy by top layer of PV module is a function of various parameters which are as follows:

$$I_g(t) = f(\alpha, PF, I(t), A) \tag{1}$$



2-a) First Layer

2-c) Third Layer



2-b) Second Layer

2-d) Legend of Electrical Circuit

Figure 2: Equivalent electrical circuit of PV module

Considering the above expressions for both types of PV modules the solar energy will be:

$$I_g(t) = \left[\alpha_{PV} PF_{PV} + \tau_g (1 - PF_{PV})\right] \cdot I(t) \cdot A \quad \text{glass to glass} \tag{2}$$

$$I_g(t) = [\alpha_{PV} PF_{PV} + \alpha_T (1 - PF_{PV})] \cdot I(t) \cdot A \quad \text{glass to tedlar} \tag{3}$$

The solar energy by PV cells in addition to parameters mentioned above depends on glass transmitivity. Hence, it is expressed as follows:

$$I_{pv}(t) = \tau_g \left[\alpha_{PV} PF_{PV} + \tau_g (1 - PF_{PV})\right] \cdot I(t) \cdot A \quad \text{glass to glass} \tag{4}$$

$$I_{pv}(t) = \tau_g [\alpha_{PV} PF_{PV} + \alpha_T (1 - PF_{PV})] \cdot I(t) \cdot A \quad \text{glass to tedlar} \tag{5}$$

The absorbed solar energy is considered as a current source in electric model.

3.2. Electric Power

The produced electric power is a function of efficiency, solar radiation, packing factor and module effective area:

$$E_{PV}(t) = f\left(\eta_{pv}(t), I(t), A, PF\right) \tag{6}$$

Also the PV module efficiency is a function of operating temperature and solar radiation.

3.3. Heat Transfer

The PV modules have three heat transfer paths as follows:

1. Radiation
2. Convection
3. Conduction

In the PV module, the produced heat can be exchanged in various paths, capability of heat transfer of these paths is supposed as a resistance. Its amount depends on the heat transfer method.

In this study, the equation of nodes is used; therefore using conductance instead of resistance causes the equations to be easier. Subsequently, three methods to determine the conductivity and heat transfer are investigated.

3.3.1. Radiation Heat Transfer

Jones and Underwood have introduced two methods for heat transfer, short and long wave radiation [8]. The linear model of long wave radiation conductivity has been presented by Notton et al. [9]:

$$\begin{gathered} G_{rad\_i,sky}(t) = f\left(\varepsilon, \beta, A, T_{sky}(t), T_i(t)\right) = \\ \varepsilon_g \cdot F_{i,sky} \cdot \sigma \cdot A \cdot \left(T_i(t) + T_{sky}(t)\right) \cdot \left(T_i^2(t) + T_{sky}^2(t)\right) \end{gathered} \tag{7}$$

The PV module installation slope coefficient is expressed in the form of modules configuration factor, therefore the configuration factor in the front and back layers of module in relation to the sky are as follows, respectively [9]:

$$\begin{aligned} F_{fg,sky} &= \tfrac{1}{2}(1 + \cos\beta) \\ F_{bg,sky} &= \tfrac{1}{2}(1 + \cos(\pi - \beta)) \end{aligned} \tag{8}$$

In (8) the sky temperature is used, and its calculation is presented in different expressions. Underwood for determination of sky temperature has used the following equations [8]:

$$\begin{gathered} T_{sky}(t) = T_{air}(t) - \delta T, \quad \delta T = 20\,K \\ \text{clear sky conditions} \\ T_{sky}(t) = T_{air}(t) \quad \text{cloudy sky conditions} \end{gathered} \tag{9}$$

Another equation for determination of sky temperature has been presented which is mentioned in [10]:

$$T_{sky}(t) = 0.0552 T_{air}^{1.5}(t) \quad \text{with } T_{air} \text{ in } K \tag{10}$$

3.3.2. Convection Heat Transfer

The convection conductance is calculated through the following equation [9]:

$$G_{conv} = h \cdot A \tag{11}$$

The convection heat transfer coefficient is affected from free and forced cooling [8]. The free cooling effect is more than forced cooling in the calm days. As mentioned by [9] the free convection coefficient is:

$$h_{conv,free}(t) = 1.31 \cdot \left(T_g(t) - T_{air}(t)\right)^{\frac{1}{3}} \tag{12}$$

The forced convection coefficient has an approximate linear function with wind speed. $h_{conv\_forced}(t) = 5.67 + 3.86v(t)$ and $h_{conv\_forced}(t) = 11.4 + 5.7v(t)$ these are mentioned in [9] from Mcadams and Nolay, respectively. Also, Cole and Sturrock have indicated that heat transfer coefficient is strongly dependent on wind direction. Therefore the windward surface can be expressed by:

$$h_{conv\_forced}(t) = 11.4 + 5.7v(t) \tag{13}$$

And for leeward surface is:

$$h_{conv\_forced} = 5.7 \tag{14}$$

Following expression for forced convection coefficient has been used in [9]:

$$h_{conv\_forced}(t) = 2.8 + 3v(t) \tag{15}$$

The following expressions are used for calculation of forced convection coefficient of PV module by Tiwari [1].
For windward surface:

$$h_{conv\_forced}(t) = 5.7 + 3.8v(t) \tag{16}$$

And for leeward surface (15) is applied.

For calculation of convection heat transfer coefficients different expressions has been presented by researchers. Hegazy has used only forced convection heat transfer coefficient [7]. Both free and forced convection heat transfer coefficients are considered by Kudish. It should be mentioned that he has considered wind speed effect; therefore larger coefficients are used in his modeling which is adopted from [11]. But the sum of free and forced coefficients is considered by Jones and Underwood [8].

3.3.3. Conduction Heat Transfer

The electric conductive conductance is determined by the following relationship:

$$G_{cond} = \frac{\lambda A}{L} \tag{17}$$

3.4. Heat Capacity

Thermal capacity of each layer of module PV is defined as:

$$C_{layer} = M \cdot C = \rho L A C \tag{18}$$

4. Equivalent Electric Circuit

Electric circuits are used in modeling of non-electrical systems as significant tool. Inasmuch as the electric circuits have systematic methods for analysis; therefore, their analysis will be easier than main systems.

In the preceding section for the solar energy, electric power, heat transfer losses, heat capacity and ambient temperature have been suggested the electric circuits elements as resistor, capacitor, and current and voltage source, respectively. Furthermore, based on the elements model the equivalent electric circuit is suggested (Fig. 2). The proposed circuit has three separate parts and each of which belongs to a certain layer of PV module. The effect of each layer to other layer is transferred through the dependent sources.
'Node analysis method' is used for analysis of circuits, so the nodes equations are:

$$\begin{gathered} I_g + G_{pv\_fg}\left(T_{pv} - T_{fg}\right) = C_g \tfrac{dT_{fg}}{dt} \\ + G_{air,fg}\left(T_{fg} - T_{air}\right) + G_{sky,_{fg}}\left(T_{fg} - T_{sky}\right) \end{gathered} \tag{19}$$

$$\begin{gathered} I_{pv} - E_{pv} = C_{pv} \tfrac{dT_{PV}}{dt} + G_{pv-fg}\left(T_{pv} - T_{fg}\right) \\ + G_{pv,bg/t}\left(T_{pv} - T_{bg/t}\right) \end{gathered} \tag{20}$$

$$\begin{gathered} G_{pv,bg/t}\left(T_{pv} - T_{bg/t}\right) = C_{bg/t} \tfrac{dT_{bg,t}}{dt} \\ + G_{air,bg/t}\left(T_{bg,t} - T_{air}\right) + G_{sky,bg/t}\left(T_{bg/t} - T_{sky}\right) \end{gathered} \tag{21}$$

The aforementioned equations show that circuits are consisted of nonlinear elements and sources. Therefore it can be expressed as the standard form:

$$\dot{x} = f(t, x, u) \tag{22}$$

Rewriting equations 19–21, they can be shown in standard form of nonlinear equations.
Due to the nature of nonlinear equations, numerical method will be used to determine the nodes' voltage.

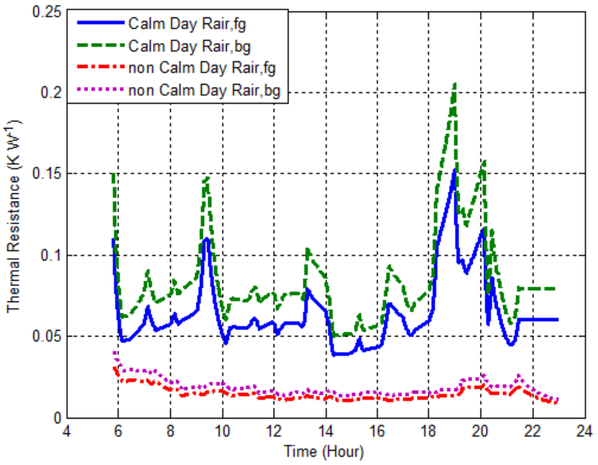


Figure 4: Thermal resistance of PV module

The coefficients G_{pv-fg}, $G_{pv-bg/t}$, C_{fg}, C_{pv} and $C_{bg/t}$ in the set of nonlinear differential equations are constant.

$$\frac{d}{dt}\begin{bmatrix} T_{fg} \\ T_{pv} \\ T_{bg/t} \end{bmatrix} = \begin{bmatrix} -\frac{(G_{pv\_fg}+G_{air,fg}+G_{sky,fg})}{C_{fg}} & \frac{G_{pv\_fg}}{C_{fg}} & 0 \\ \frac{G_{pv\_fg}}{C_{pv}} & -\frac{(G_{pv\_fg}+G_{pv,bg/t})}{C_{pv}} & \frac{G_{pv,bg/t}}{C_{pv}} \\ 0 & \frac{G_{pv,t}}{C_{bg/t}} & -\frac{(G_{pv,t}+G_{air,t}+G_{sky,t})}{C_{bg/t}} \end{bmatrix} \times \begin{bmatrix} T_{fg} \\ T_{pv} \\ T_{bg/t} \end{bmatrix} + \begin{bmatrix} \frac{G_{air,fg}.T_{air}+G_{sky,fg}.T_{sky}+I_g}{C_{fg}} \\ \frac{I_{pv}-E_{pv}}{C_{pv}} \\ \frac{G_{air,t}.T_{air}+G_{sky,t}.T_{sky}}{C_{bg/t}} \end{bmatrix} \tag{23}$$

But the other coefficients are time-varying, also the sources I_{pv}, E_{pv}, I_g always are variable. Therefore, evaluating time-varying resistances and sources will be useful in circuit analysis.

5. Results and Discussion

Dynamic thermal of PV module has been simulated with Matlab/Simulink. The parameters of module are given in Table 2. Fig. 3 shows Simulink block diagram of circuits. The inputs of electric circuit are solar radiation, ambient temperature and wind speed. The days September 15 and November 1 of 2008 in Tehran-Iran have been selected for calm and non-calm conditions, respectively. The sampling period is 10 minutes.

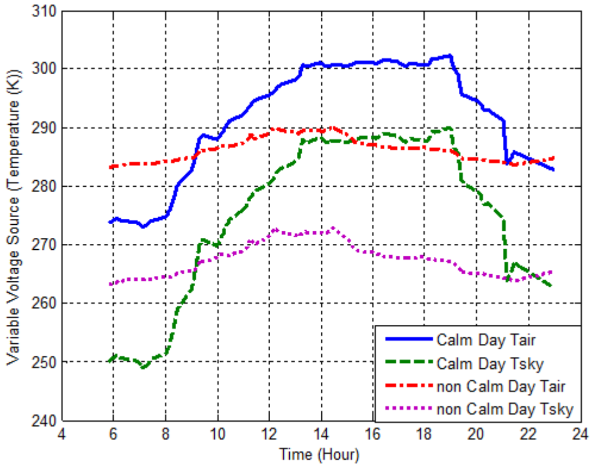


Figure 5: Voltage sources of thermal model of PV module

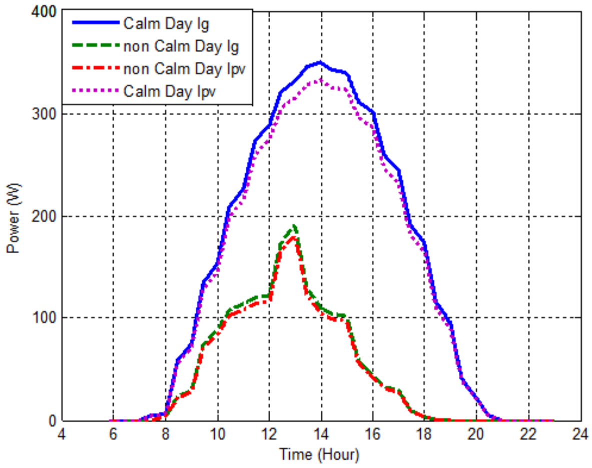


Figure 6: Current sources of thermal model of PV module

The electric circuits are composed of elements and sources. Some of them are linear and the others are nonlinear, also they are time variant or invariant. Therefore, all of elements and sources have been evaluated. The evaluation of parameters only has been done for glass to glass type of module. Thermal resistance is shown in Fig. 4; it is proportionate with temperature of sky and front or back layers of PV module. The resistance of calm and non-calm day conditions is nonlinear and almost constant, respectively.

Air and sky temperature have been considered as time-varying independent voltage sources. Fig. 5 shows that the sky temperature is dependent on the ambient temperature and is determined by (10).

Table 2: Parameters of PV module thermal model

Parameters	Values	Parameters	Values
α_{pv}	0.9	L_{pv}, m	0.0003
α_g	0.5	L_t, m	0.0005
PF_{PV}	0.83	L_g, m	0.003
β_0, K^{-1}	0.0045	K_g, $\mathrm{W{\cdot}m^{-1}K^{-1}}$	1.1
η_0	0.12	K_t, $\mathrm{W{\cdot}m^{-1}K^{-1}}$	0.033
τ_g	0.95	K_{pv}, $\mathrm{W{\cdot}m^{-1}K^{-1}}$	130
A, m^2	0.51	σ	$5.6697{\cdot}10^{-8}$
ρ_{pv}, $\mathrm{kg{\cdot}m^{-3}}$	2330	C_{pv}, $\mathrm{J{\cdot}kg^{-1}K^{-1}}$	677
ρ_t, $\mathrm{kg{\cdot}m^{-3}}$	1200	C_t, $\mathrm{J{\cdot}kg^{-1}K^{-1}}$	1250
ρ_g, $\mathrm{kg{\cdot}m^{-3}}$	3000	C_g, $\mathrm{J{\cdot}kg^{-1}K^{-1}}$	500
ε_g	0.85		

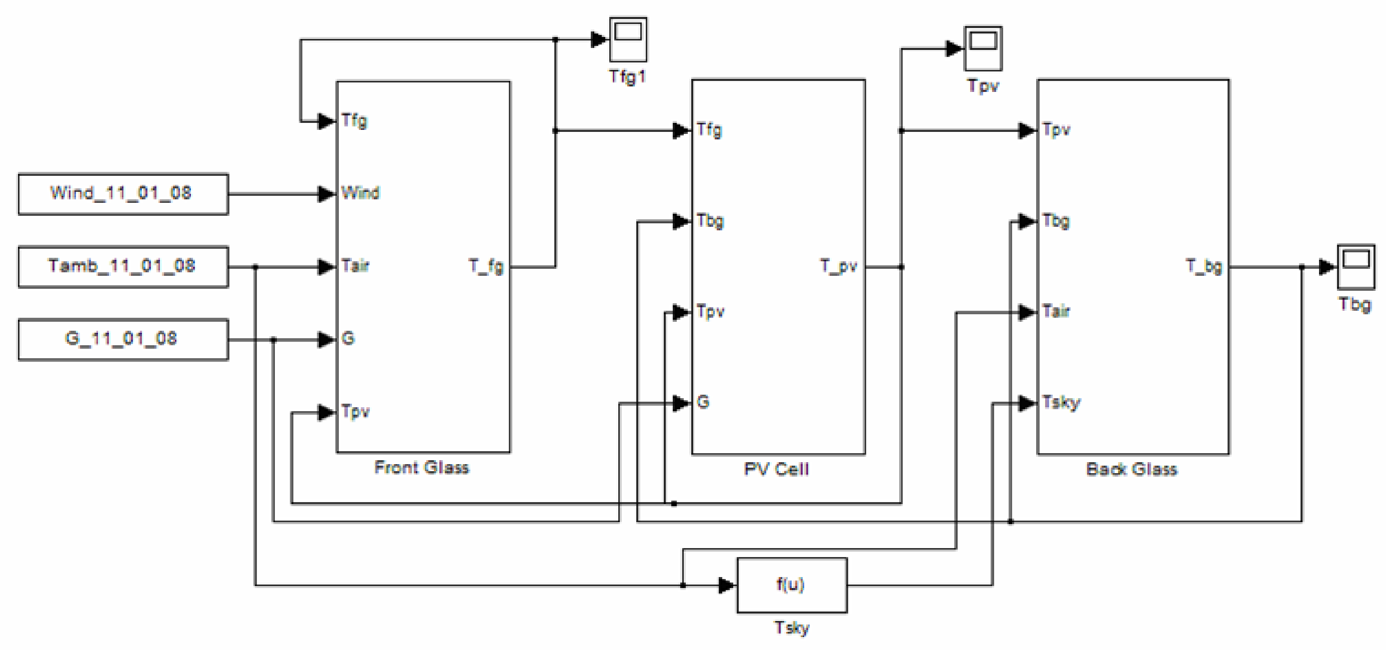


Figure 3: Simulink block diagram of electric circuit of PV module

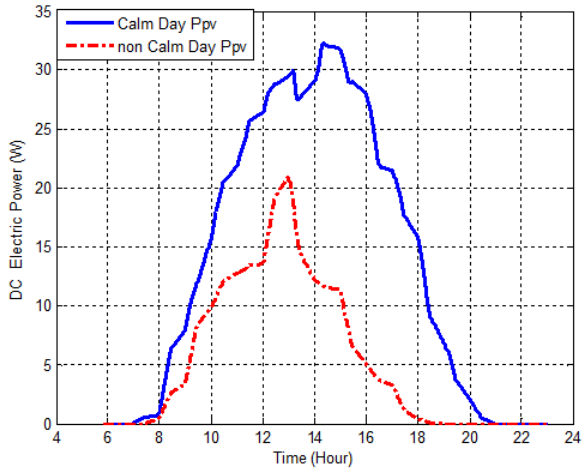


Figure 7: DC power

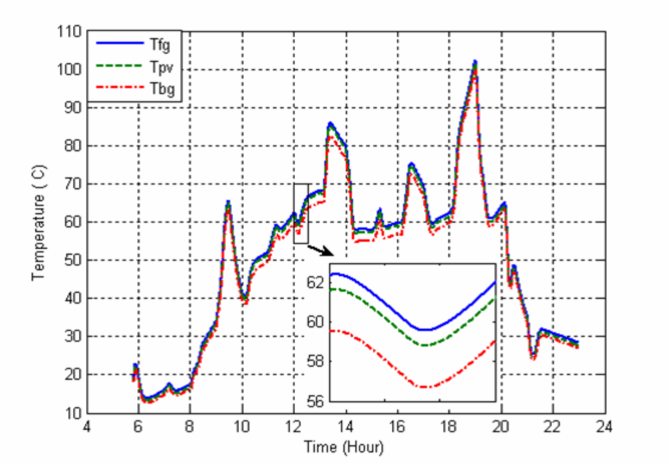


Figure 8: PV module layers temperature in calm day (glass to glass type)

The electric circuit has current sources (I_g, I_{pv}) that are time-varying and amplitude of them depends on the solar radiation, efficiency and module operating temperature (Fig. 6). The DC power (Fig. 7) has some difference with Fig. 6, because the DC power is affected by efficiency and module operating temperature.

The electric circuit has some voltage sources that depend to other nodes' voltage. Hence with determination of voltage of nodes the amounts of them are specified, too. The other elements of circuits are constant, so they are calculated easily. After determination of all of elements, the nonlinear circuit is analyzed and the voltage of nodes has been determined.

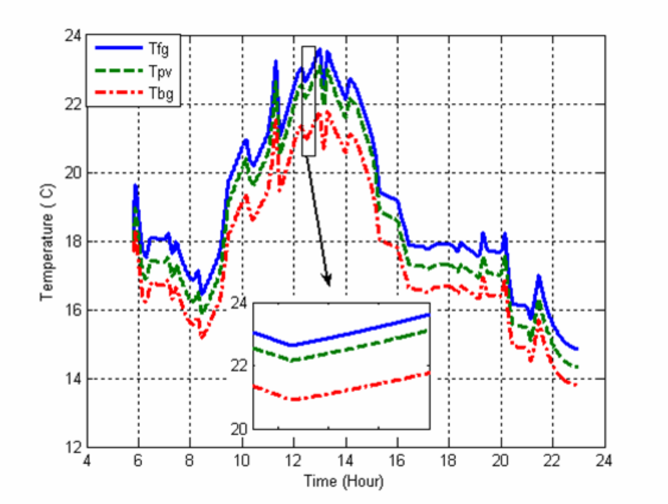


Figure 9: PV module layers temperature in non-calm day (glass to glass type)

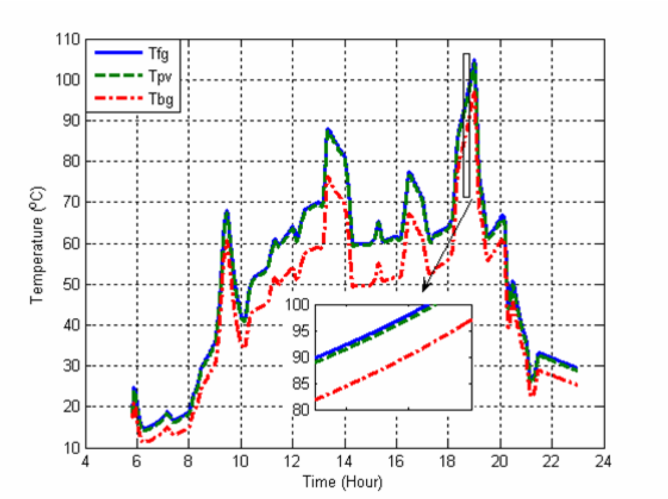


Figure 10: PV module layers temperature in calm day (glass to tedlar type)

Figs. 8–11 show voltage of nodes in calm and non-calm day conditions. Figs. 8 and 9 are for glass to glass type of module in calm and non-calm day conditions, respectively. Based on Fig. 8 $T_{fg}$and T_{pv} has minimum difference, but the difference of both T_{fg} and T_{pv} with T_{bg} are about 2°C.

In Fig. 9 difference between voltage of nodes (temperature of PV module layers) are evident and this difference in some hours is same or approximately is 0.8°C.

The difference between voltage of nodes of glass to tedlar module for calm and non-calm days has been presented in Figs. 10 and 11, respectively.

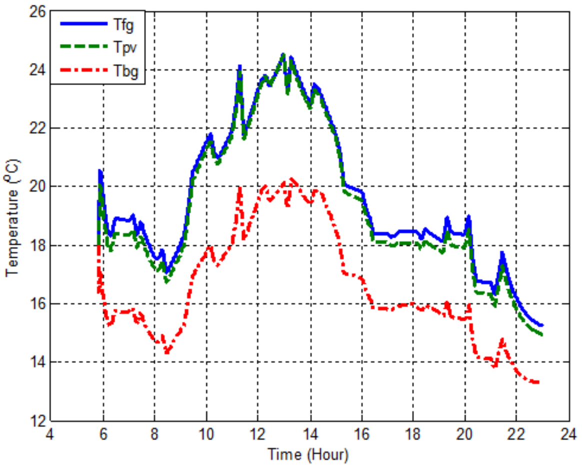


Figure 11: PV module layers temperature in non-calm day (glass to tedlar type)

In calm day conditions difference between T_{fg} and $T_{pv}$are about 0.7°C and the difference between both top layers and T_t is approximately 10°C (Fig. 10). Fig. 11 illustrates non-calm day conditions, the difference between two top layers is 0.4°C and difference between both layers and back layer is 3°C.

The voltage of nodes of PV module is a function of three different sources. So for evaluation of their effects on nodes' voltage, the following analysis has been presented.

Solar radiation, ambient temperature and wind speed are the three sources that affect the PV module temperature. Hence, like AC sources, the frequencies and amplitudes of these sources differ. Solar radiation and temperature are as a low frequency AC signal.

Their frequency is equal to the day length. The amplitude of solar radiation is bound to specified time interval from sunrise to sunset. But the amplitude of ambient temperature is not bound to time.

Furthermore its amount in the days is higher than nights. The wind speed is an AC signal and its amplitude and frequency is variable. But the wind AC signal frequency is higher than two last signals.

Considering the above explanations it can be expressed that the PV module operating temperature is affected by two low-frequency AC signals and one high-frequency AC signal which are shown in Fig. 12.

Subsequently for explicit expression about PV module operating temperature, Fig. 12 is divided into three regions. The amplitude of solar radiation in first and third regions is minimal or zero and therefore its effect on the PV module operating temperature is negligible. But in the second region, it is shown that with increasing solar radiation its effect on the PV module operating temperature is increased as well. The ambient temperature determines the primary structure for PV module operating temperature. Also the effect of wind speed on the PV module operating temperature is obvious and variation of wind speed has inverse effect on PV module operating temperature.

Previously mentioned that the module operating

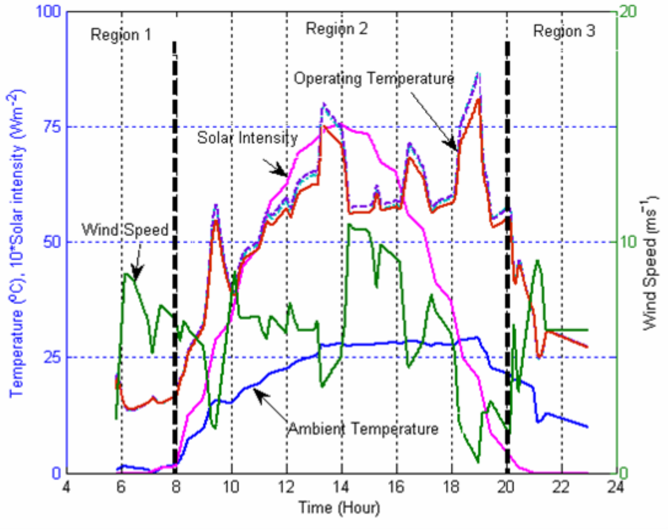


Figure 12: PV module layers temperature

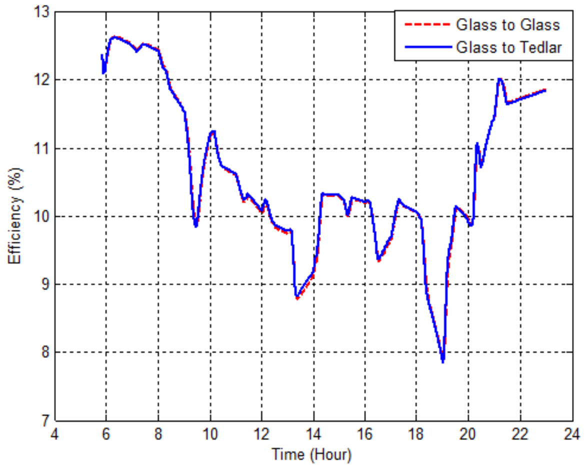


Figure 13: Hourly variation of efficiency in calm day

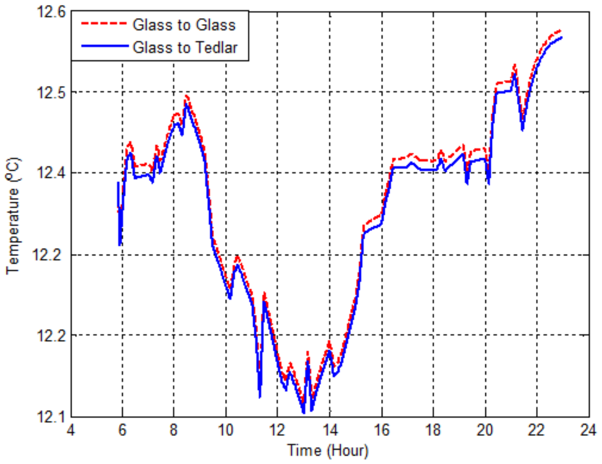


Figure 14: Hourly variation of efficiency in non-calm day

temperature has a specific effect on efficiency, and the rate of this effect on efficiency is given in Figs. 10 and 11 for calm and non-calm day conditions, respectively. Fig. 13 shows the difference between efficiency of calm day conditions for two types of modules which is about 0.1% and for non-calm day conditions this value is about 0.02%.
Also Figs. 8 and 10 show that the PV module temperature varied from 10 to 100°C explicitly. Since the temperature has a direct effect on the efficiency, so Fig. 13 shows that the changes in the efficiency are high for this situation. But unlike the above conditions, the Figs. 9 and 11 show that the changes are low and therefore based on Fig. 14 changes in the efficiency of this situation is negligible too.

6. Conclusion

The PV module operating temperature is a function of the physical characteristics and environmental conditions.therefore, the thermal model of PV module has been provided with consideration of energy sources, heat capacity of materials and heat exchange paths, then from correspondence thermal and electric elements the equivalent electric circuit has been introduced. Some elements of electric circuits such as resistors and sources are nonlinear and time-varying.

Subsequently, the node analysis method for obtaining state equations has been applied and a set of nonlinear differential equations has been provided. A numerical method has been used for determination of nodes' voltage. Different environmental conditions have been selected for evaluation of electrical circuits' capabilities and the voltage of nodes has been compared in both calm and non-calm conditions. The results have been obtained from the evaluation of electric circuits elements.

- The ambient temperature and wind speed are the two effective parameters in calculation of convection thermal resistance. That, the low and high changes in wind speed and temperature is the cause of an almost constant resistance.

- The current sources (I_g, I_{pv}) are dependent on solar radiation and $E_{pv}$is dependent on solar radiation and temperature.

- The temperature difference between layers of glass to tedlar is higher than glass to glass PV module.

- The PV module temperature is a combination of two signals:

First, solar radiation and ambient temperature are like an AC low-frequency signal, which their frequency is equal to the length of the day (24 hours). Second, the variable high amplitude and frequency AC signal, which is due to wind speed.

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