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Thevenin Equivalent of Solar PV Cell Model and Maximum Power Transfer

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***Abstract*— Photovoltaic (PV) is the conversion of solar energy into DC electrical energy using PV cells. In addition, solar energy is an important renewable energy source. In this study, it is proposed that Thevenin's equivalent PV cell model produces a voltage-current characteristic that is quite representative of the operation of the PV source. Thevenin's elements depend on ambient temperature conditions, so charging is derived and simplified to construct a model that closely predicts and demonstrates adequate PV cell characteristic for different ambient temperature conditions. This method is very useful for estimating the desired performance and also for examining different Maximum Power Point Tracking (MPPT) algorithms. Theoretically, the simulation was supplemented with test data, then used to develop an equivalent Thevenin model in which the resistance is non-linear and voltage dependent. Thevenin's method and variable pitch is to improve the maximum power transfer to the load by increasing the performance of the PV cell. These methods were modeled and studied in a simulation program.**

Keywords*— Thevenin method, PV cells, Maximum power transfer, Single diode equivalent circuit of the PV cell, Solar energy.

I. INTRODUCTION

The worldwide energy requirement is always increasing and there is a need to find alternative energy sources to meet future energy consumption. Solar, wind, biomass and other renewable energy sources have become much more important than fossil resources such as coal, gas and oil. Especially PV energy is one of the reliable, clean and sustainable energy sources. PV energy is an alternative source to fossil fuels. The main way of generating electrical energy from the sun's rays is the effect of PV. The name given to electricity production from PV is solar cell.

II. DESIGNING AND MODELLING OF SOLAR PV CELL

The equivalent circuit of the PV cell consists of a parallel current source diode and series-parallel resistors. PV cell; The current source consists of an equivalent circuit consisting of parallel and reverse diodes, series and shunt connected resistors. See Figure 1.

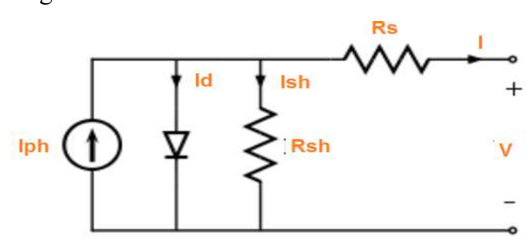

Figure 1. PV cell equivalent circuit

The equilent circuit parameters of the PV cell are: Open circuit voltage (Voc), photo current and resistors connected in series and parallel [1]-[2]. These parameters are found from the I-V characteristic curve and the efficiency can be obtained from these parameters.

$$I = I_{ph} - I_0\left(e^{-\frac{q(V+IR_S)}{nkT_C}} - 1\right) - \left(\frac{V+IR_S}{R_{sh}}\right) \quad (1)$$

Here, the "k" is Boltzmann constant, "q" is electron charge, I0 is reverse saturation current of the diode, "G" is solar irradiatiance, Iph photocurrent of the PV cell, n is the ideality coefficient of the diode, V and I are voltage and current of output [3]-[4]. The short-circuit current is obtained when the terminals of the cell are short-circuited;

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$$I_{sc} = I_{ph} - I_0(\exp(\frac{I_{sc}R_s}{nV_t}) - 1) - \frac{I_{sc}R_s}{R_{sh}} \quad (2)$$

Diode current is as given in equation (3).

$$I_d = I_0(\exp(\frac{qV}{nkT}) - 1) \quad (3)$$

PV cell photocurrent equation is given below.

$$\mathrm{I_{ph}} = [\mathrm{I_{sc}} + \mathrm{K_i}(\mathrm{T} - T_n)]\frac{\mathrm{G}}{G_n} \quad (4)$$

Where G, solar irradiance, Gn, nominal solar irradiance at 1000W/m2,T, PV cell temperature, Tn, nominal temperature, Ki is temperature. coefficient of current. Isc is the short circuit current (at V=0). The current for maximum point is defined as following;

$$\mathrm{I_{mp}} = \mathrm{I_{ph}} - \mathrm{I_0}\left(\mathrm{e}^{-\frac{\mathrm{q(V_{mp}+I_{mp}R_s)}}{\mathrm{nkT_c}}} - 1\right) - (\frac{\mathrm{V_{mp}+I_{mp}R_s}}{\mathrm{R_{sh}}}) \quad (5)$$

Diode reverse saturation current can be defined by the following equation (6).

$$\mathrm{I_0} = \mathrm{I_{0_{ref}}}(\frac{\mathrm{T}}{\mathrm{T_{nom}}})^3\exp[\left(\frac{\mathrm{T}}{\mathrm{T_{nom}}} - 1\right)\frac{\mathrm{E_q}}{\mathrm{nV_t}}] \quad (6)$$

Where I0,ref is diode saturation reverse current in the referred cell temperature condition. The fill factor would slightly increase or decrease depending on the density of the irradiance and the influence of parasitic resistance. The fill factor circuit can be written as,

$$\mathrm{FF} = \frac{I_{mp} \cdot V_{mp}}{I_{sc}V_{oc}} \quad (7)$$

FF is calculated by comparing Voc and Isc with the supplied theoretical power for maximum power. [5]-[6]. The Voc equation of the PV cell is as given in (8).

$$V_{oc} = \frac{nkT}{q}Ln(\frac{I_{ph}}{I_0} + 1) \quad (8)$$

Where, unlike the others, Tc is the temperature PV cell and n is ideality factor of the diode. It shows that the Voc depends on the saturation current and photocurrent of the PV cell. The heat generated in the PV cell is caused by changes in ambient temperature as well as changes in the intensity of solar radiation.

$$\mathrm{T} = T_{amb} + \left(\frac{NOCT - 20\,^oC}{0.8}\right)G \quad (9)$$

Where, T_{amb} is the ambient temperature and G is solar irradiance reaching the panel surface. Nominal operating cell temperature (NOCT) is an important parameter and also an effective for produced energy by PV panels.

The purpose of this research was not only to perform the advanced implementation of mathematical model of the PV cell, but also to investigate the effects of temperature on I-V and P-V characteristics of PV cell.

III. THEVENIN EQUIVALENT OF SOLAR PV CELL MODEL

On the PV cell, the photon current is highest in sunny and full open air, whereas in cloudy or overcast weather, the photocurrent decreases depending on the amount of radiation from the sun. The equivalent circuit of solar cell is given in the Fig. 2.

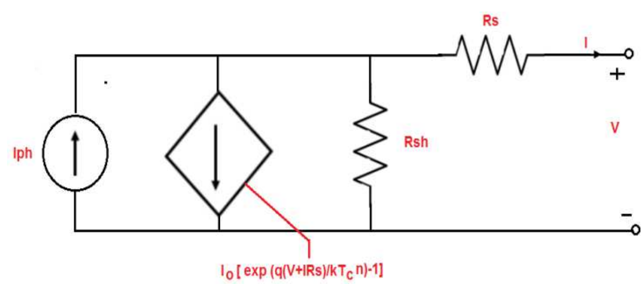

Figure 2. P-V characteristic curve of the PV cell

The energy produced by the solar panel increases related to the sunshine duration of the region. Shading in any PV cell also affects the performance parameters of another PV cell [7].

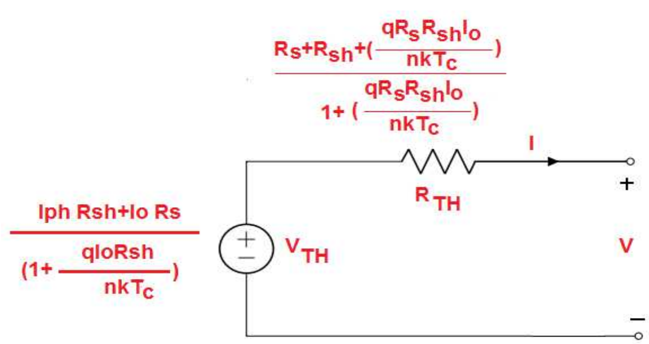

Figure 3. Schematic representation of PV cell, module and array

The proposed solar irradiance estimation method photovoltaic depend on Thevenin equivalent circuit has been developed and implemented. To further simplify this equivalent circuit of the PV cell, it should be created the equivalent circuit shown in Figure 3. Thus, by linearization, a nonlinear system can be represented by a linear model with non-constant parameters. Thevenin's theorem provides the following advantages;

- It simplifies the very complex circuit with a simple circuit, that is, reduces it to a single emf source in series with a single resistor.
- It simplifies the important part of the circuit a lot and allows us to directly see the movement of the output side.
- The theorem is particularly useful for finding the current in a particular branch of the network so that all other sources of resistance and emf are left constant so that the branch's resistance changes.

The following steps should be followed when solving circuits with Thévenin's theorem: Independent sources are canceled in the circuit (Current sources are open-circuited, voltage sources are short-circuited).

IV. Maximum power transfer from PV cell to load using the maximum power transfer theorem

Maximum power transfer calculated from Thevenin equivalent can be applied to both direct current (DC) and alternating current (AC). The purpose of the maximum power transfer theorem is to find the maximum power that can be taken from the PV cell. This is achieved by taking the load resistance equal to the Thevenin resistance.

A. Maximum power transfer theorem

The value of the maximum power to be transferred from the solar cell to the load is found by the maximum power transfer theorem. As a result, the maximum power to be transferred is obtained by taking Thevenin equivalent circuit resistance equal to the load resistance.

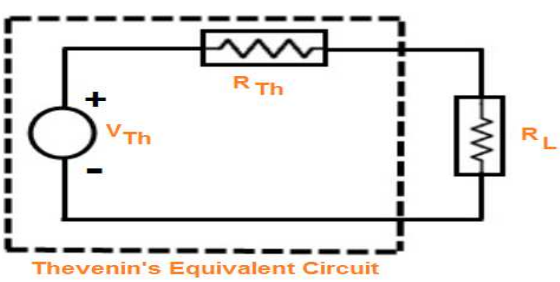

Figure 4. Thevenin equivalent circuit model

The thevenin equivalent can be found with respect to the two flyers of the circuit. After the Thevenin equivalent is found, the current and voltage values of the PV cell can be easily found.

$$I_L = \frac{V_{Th}}{R_{Th}+R_L} \quad (10)$$

The power transferred to the load is

$$P_L^2 = I_L^2 * R_L \quad (11)$$

$$= [\frac{V_{Th}}{R_{Th}+R_L}]^2 * R_L \quad (12)$$

$$\frac{dP}{dR_L} = V_{Th}^2[\frac{(R_{Th}+R_L)^2-2R_L+(R_{Th}+R_l)}{(R_{Th}+R_L)^2}] = 0$$

$$= (R_{Th} * R_L) - 2R_L = 0 \quad (13)$$

$$= R_L = R_{Th} \quad (14)$$

As a result, the power transferred from the PV cell to the load is at its maximum value when the value of thevenin resistance is equal to the load resistance. The maximum power transferred to the load,

$$P_{max} = [\frac{V_{Th}}{R_{Th}+R_L}]^2 + R_L \quad (15)$$

Thus, the maximum power is obtained as:

$$P_{max} = \frac{V_{Th}^2}{4R_{Th}} \quad (16)$$

B. Maximum power transfer from PV cell to load

The maximum power transfer theorem is used to find the load resistance for which there would be the maximum amount of power transfer from solar cell to the load. The value of Thevenin voltage is as given in eq.(17).

$$V_{Th} = \frac{I_{ph} \cdot R_{sh.} + I_0 R_s}{(1+\frac{qI_0 R_{sh}}{nkT_c})} \quad (17)$$

The value of Thevenin resistor is as given below.

$$R_{Th} = \frac{R_s + R_{sh} + (\frac{qR_sR_{sh}I_0}{nkT_c})}{(1+\frac{qR_sR_{sh}I_0}{nkT_c})} \quad (18)$$

In addition, the maximum power transferred from the PV cell to the load is as given in eq. (19).

$$P_{max} = \frac{[nkT_c(I_{ph}R_{sh}+I_0R_s)]^2}{[nkT_c+qI_0R_{sh}]^2} * \frac{[nkT_c+qR_sR_{sh}I_0]}{[nkT_c(R_s+R_{sh}+R_sR_{sh}I_0]} \quad (19)$$

In this paper, Thevenin model has been used effectively to simulate the PV cell. The parameters shown in Table 1 were used in the simulation of the PV cell and the P-V curve of the PV cell was found.

TABLE I. PV CELL SINGLE DIODE EQUIVALENT CIRCUIT PARAMETERS

Parameters	Value
Boltzmann's Constant (k)	1.3806488×10-23
Unit of Electron Charge (q)	1.6×10-19 (C)
Saturation Current of Diode(Io)	1×10-10 (A)
Diyode Ideality Factor (n)	1.3
Short Circuit Current (Isc)	3.885(A)
Series Resistance of the equivalent circuit of PV cell (Rs)	0.001 (Ω)
Shunt Resistance of the equivalent circuit of PV cell (Rsh)	1000 (Ω)
Band Gap Energy (Eg)	1.11
Temperature Coefficient (Ki)	0.0017 (A/ºC)
Solar Irradiation (G)	1000 (W/m^2)

In this study, the mathematical model of the PV cell was found and the Thevenin equivalent of this model was created. Analysis of Thevenin circuit was performed with Matlab/Simulink. P-V curve of the PV cell is as given Fig. 8.

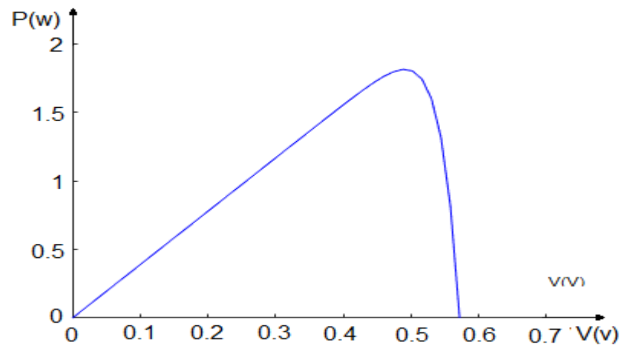

Figure 5. P-V curve of the PV cell (at 25^{0}C, 1000 W/m^2)

One of the most important factors affecting the efficiency of solar panels is temperature. Since the Photovoltaic Panel voltage is highly dependent on the ambient temperature, the panel voltage decreases as the temperature value increases.

V. CONCLUSION

In order to understand the behavior of solar cells and to examine their characteristics, an equivalent circuit consisting of elements with well-known electrical properties is needed. By creating the Thevenin equivalent of this equivalent circuit, the output current and voltage values of the PV module can be easily found. Being simple and advanced for solar cells Equivalent circuits for solar cells, simple and advanced, are given in the literature. However, in reality, solar cells are not ideal elements, they are lossy elements due to their structure. Therefore, losses are represented by resistance. In addition, the efficiency and losses of the PV panel can be found. In this study, Thevenin's equivalent of the equivalent circuit was found based on the equivalent circuit parameters of the PV cell single diode. When we find the thevenin equivalent of the PV cell, it becomes quite easy to find both the load resistance required for maximum power transfer and the value of the maximum power transferred to the load. Thevenin method simplifies a very complex circuit and facilitates its analysis. Thévenin's theorem is that after the necessary transformations are made in an electrical circuit, the circuit is represented by a voltage source and a resistor in series with it. Maximum power point tracking (MPPT) is a technique used to charge the batteries more efficiently with the electrical energy produced by the solar energy panel. This technique always aims to get the highest efficiency by following the instantaneous and variable energy production on the solar panel cells with algorithms. The use of a Thevenin-based circuit allows for relatively easy estimation of solar panel MPPT for different operating conditions.

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