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Simulation and Control of Terminal Voltage of Solar Panel

[1]Omorogiuwa, O. & [2]Aja, E. A.

[1]*Department of Electrical and Electronics Engineering, Ambrose Alli University, Ekpoma, Nigeria*
[2]*National Agency for Science and Engineering Infrastructure, Idu Industrial Area*
owenseme@yahoo.com

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ABSTRACT

This paper presents the simulation and control of terminal voltage of solar panel. The simulation and control of the terminal voltages of solar panels were achieved using mathematical models and the best conditions of operation were also determined. A model that describes the variation of the terminal voltage with other parameters was developed and simulated using MATLAB/SIMULNK programming software. The model was validated by comparing simulated results with already existing data sheet for the solar panel description used for this research. From the simulation results it was observed that the terminal voltage varies with the series resistance inversely. The result indicates that an increase in series resistance will cause a decrease in the terminal voltage. It was also observed that the terminal voltage of the solar module is directly proportional with the panel temperature. The voltage of a solar panel resulted to be inversely related to the average velocity of the wind around the panel. A simulation study was carried out by varying the wind around the panel from 0 to 100m/s and it was observed that the wind velocity is inversely proportional to the panel temperature, and hence inversely proportional to the terminal voltage. The number of cells used for the design is very much another important way to control the terminal voltage. The terminal voltage has a direct relationship with the number of connected series cells. The researchers recommend the implementation of a physical model for the control of terminal voltage in a solar panel using well designed microcontrollers and the mathematical modelling of solar arrays with parallel and series connected solar panels used in grid system power generation.

1. Introduction

Due to disadvantages of non-renewable sources of energy with respect to environmental pollution, cost and diminishing supply, there has been a tremendous surge interest and research in solar energy systems (Weiner, 2005). Solar energy is one of the renewable sources of electrical power. The solar radiation is one of the most viable renewable power sources which can be directly converted into electricity using a solar photovoltaic conversion system (Okundamiya & Nzeako, 2011). The fundamental power conversion units are the photovoltaic panels (Park *et al.*, 2014).

The generation of solar powered electrical energy depends on heat engines and photovoltaic system. To generate the solar energy, the photovoltaic array converts the photon energy received from the sun into electrical energy. Depending on the conversion and distribution scheme, solar technologies can either be

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classified as active or passive. The active solar techniques involves solar photovoltaic (PV) modules and solar thermal collectors which are used to strap up solar energy while passive technology involves orientation of a building to the Sun and selection of materials with favourable light dispersing or thermal mass properties and the design spaces, which will inherently circulate air. The solar energy is very useful in the areas of electricity generation for distribution, lightening building and heating water (Okundamiya & Omorogiuwa, 2015; Shukla *et al*., 2015).

The PV array is the basic power conversion unit of the photovoltaic conversion system. The output characteristics of photovoltaic array depends on the cell temperature, the solar radiation and output voltage of photovoltaic module. A solar cell is the main component of the photovoltaic array, which is formed by connecting different solar cells in parallel and series (Patel & Gaurag, 2013). Solar panels are used to generate electricity by harnessing the Sun's energy, thus the name solar meaning sunlight (Lorenzo *et al*., 1994). The working of the solar panel is such that when light strikes the surface of the photovoltaic module electrons are given off.

2. Methodology

Simulation and control of the terminal voltage of a PV module as considered in this research involved the analysis of the terminal voltage model of a PV module. A mathematical modelling of the solar panel was carried out to obtain a terminal voltage dependent model on power and current. The model was then modified for other control parameters such as solar irradiation and ambient wind speed. A model that describes the variation of the terminal voltage with other parameters was developed and simulated using MATLAB/SIMULNK programming software. The model was validated by comparing the simulated results with already existing data sheet for the solar panel description used for this research. Brief description of these methods is illustrated in the following sub-sections.

2.1 Terminal Voltage of a PV Module

The terminal voltage of a solar module is the output voltage across its terminals. The voltage of the solar cells get added when the cells are connected in series, therefore the terminal voltage of the PV module will be higher and equal to the sum of all the solar cells connected in series (Tian *et al*., 2012):

$$V_T = V_1 + V_2 + V_3 + V_4 \ldots\ldots\ldots\ldots\ldots . V_N \tag{1}$$

where, V_T is the terminal voltage (V) and V_1, $V_2 \ldots V_N$ are the individual solar cell voltages (V).

A model for predicting the module temperature of a solar panel has been developed at Sandia National Laboratory, USA. The model states that:

$$T_m = E * e^{a+b*WS} + T_a \tag{2}$$

where, T_m is the temperature (°C) of back-surface module, T_a is the ambient air temperature (°C), E is the solar irradiance incident on the module surface (W/m^2), WS is the wind speed measured at a standard 10m height (m/s), a is the empirically-determined coefficient determining the upper limit for module temperature at high solar irradiance and low wind speeds and b is the empirically-determined coefficient determining the rate at which module temperature drops as wind speed increases.

The voltage of a photovoltaic module can be regarded as its actual output voltage or open circuit voltage. Generally, the temperature of photovoltaic module determines the output voltage of photovoltaic modules, and the temperature is inversely proportional to the voltage.

2.2 Mathematical Modelling of a PV Module

The photovoltaic module is made up of a single diode. A solar panel consists of solar cells. The series and parallel connection of many solar cells produce a photovoltaic module. The equivalent circuit models presented in Figure 1 can be used in the simulation an individual cell, a panel or an array. G is the solar irradiance, I_s is the photo-generated current, I_{d1} is the current at diode D_1, I_p is the leakage current, R_p is the equivalent shunt resistance, R_s is the series resistance, V is the output voltage *and* I is the output current.

The thermal voltage of the solar cell is deduced by the equation:

$$V_{thc} = \frac{kT_c}{Q}, \tag{3}$$

where Q is charge of each electron in cell, k is Boltzmann's constant, and T_c is cell temperature (K). However, this depends on the unit of the Boltzmann's constant.

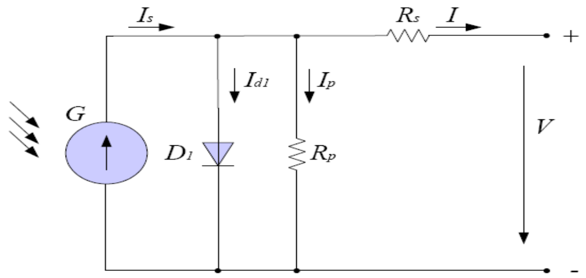


Figure 1: Equivalent circuit of a solar cell

For a particular operating cell temperature, the diode saturation current is given by the equation:

$$I_{sc} = I_{sc}^{*}\left(\frac{T_c}{T^*}\right)^3 e^{\frac{s_c Q}{m_c k}\left(\frac{1}{T^*}-\frac{1}{T_c}\right)} \tag{4}$$

where I_{sc} is diode reverse bias saturation current, I_{sc}^{*} is diode reverse bias saturation current at standard test condition, T^* is *p-n* junction cell temperature at standard temperature conditions in Kelvin, m_c is diode ideality factor, and s_c is energy band gap of the semiconductor.

The current and voltage relationship also referred to as the I-V characteristics for the models presented in Figure 1 can be written as:

$$I = I_s - I_{sc}\left[e^{\frac{(V+R_s I)}{m_c V_{thc}}} - 1\right] - \frac{V + R_s I}{R_p} \tag{5}$$

For *p-n* junction temperature and constant irradiance conditions, the short circuit current I_{shc} is the highest value of the current at the cell terminals. The short circuit current I_{shc} is given by the equation:

$$I_{shc} = I_s - I_{sc}\left[e^{\frac{(R_s I_{shc})}{m_c V_{thc}}} - 1\right] - \frac{R_s I_{shc}}{R_p} \tag{6}$$

For the short circuit system, as can be seen from the model, the open voltage, I becomes zero, which gives rise to (6).

For *p-n* junction temperature and constant irradiance conditions, the open circuit voltage V_{oc} is the highest value of the voltage at the cell terminals. The open circuit voltage V_{oc}, by simplifying (7) for the open voltage as follows:

$$I = I_s - I_{sc}\left[e^{\frac{(V+R_s I)}{m_c V_{thc}}} - 1\right] - \frac{V + R_s I}{R_p} \tag{7}$$

Rearranging for V and taking the Natural Logarithm of both sides we have that:

$$V = \ln\left(\frac{IR_p + V + R_s I}{R_p(I_s - I_{sc}} + 1\right) m_c V_{thc} - R_s I, \tag{8}$$

where V is the open circuit voltage across the terminal of the cells which is also written as V_{oc}, that is;

$$V_{oc} = V = \ln\left(\frac{IR_p + V + R_s I}{R_p(I_s - I_{sc}} + 1\right) m_c V_{thc} - R_s I \tag{9}$$

The diode ideality factor as described by is given as:

$$m_c = \frac{V_m^* + R_{so} I_m^* - V_{oc}^*}{V_{thc}\left[\ln\left(I^*{}_{shc} - \frac{V_m^*}{R_{sho}} - I_m^*\right) - \ln\left(I^*{}_{shc} - \frac{V_{oc}^*}{R_p}\right) + \frac{I_m^*}{I^*{}_{shc} - \left(\frac{V_{oc}^*}{R_{sho}}\right)}\right]} \tag{10}$$

The terminal voltage and the output power are related via:

$$P = V\left[I_s - I_{sc}\left[e^{\frac{(V+R_s I)}{m_c V_{thc}}} - 1\right] - \frac{V + R_s I}{R_p}\right] \tag{11}$$

2.3 Modification for Solar Irradiation and Ambient Wind Speed

The photovoltaic module's temperature can be written as:

$$T = 273(0.0114 + 9.158 * 10^4 ss_{stc}{}^{-1} + 3.29 * 10^{-3} T_A - 4.76 * 10^{-3} v_{lw} + 1 \tag{12}$$

The parameters in (12) are described thus, s and s_{stc} are the solar irradiation at operating condition and the nominal test condition, respectively, solar irradiation at the normal test condition has a constant value of 1000 W/m^2 and T_A is ambient temperature and v_{lw} is local wind speed.

The incident light that generates the photo current is deduced as (Jiang *et al.*, 2011):

$$I_{ph} = \left(I_{ph,stc} + \alpha_I \Delta T\right)\frac{s}{s_{stc}} \tag{13}$$

where $I_{ph,stc}$is the light generated current at STC and $\Delta T = T - T_n$, T is the panel temperature irradiation, and T_n is the nominal temperature.

The terminal circuit voltage is assumed to be influenced by the temperature of the system and the relationship similar to equation (13) is given thus:

$$V_{oc} = V_{oc,stc}(1 + \alpha_V \Delta T) + V_{thc} \ln\left(\frac{s}{s_{stc}}\right) \tag{14}$$

where $V_{oc,stc}$ is the nominal open circuit voltage measured and α_V is the voltage-temperature coefficient. Some experimental data about thermal and electrical characteristics are in datasheets of photovoltaic panels.

The datasheets of PV panels provide α, and (14) can further be simplified by assuming that parallel resistance, R_p is so large such that the third term can be ignored, and also the first term in the equation $I_s$is equal to the light generated current at standard test condition, STC. Equation (14) therefore becomes:

$$I = I_{ph,stc} - I_{sc}\left[e^{\frac{(V+R_s I)}{m_c V_{thc}}} - 1\right] \tag{15}$$

To control the terminal voltage it is necessary to obtain the relationships between it and other parameters of the system. One of such relationships is the current-voltage curve, otherwise known as the I-V curve. The I-V curve of solar cells has three important points: open circuit (V_{oc}, 0), short circuit (0, I_{shc}), and maximum power point(V_{mp}, I_{mpp}). At these important points, the equations are:

$$0 = I^*_{ph} - I_{sc}\left[e^{\frac{(V^*_{oc})}{m_c V_{thc}}} - 1\right] \tag{16}$$

$$I_{shc} = I^*_{ph} - I_{sc}\left[e^{\frac{(R_s I_{shc})}{m_c V_{thc}}} - 1\right] \tag{17}$$

$$I^*_{mmp} = I^*_{ph} - I_{sc}\left[e^{\frac{(V^*_{mpp}+R_s I^*_{mpp})}{m_c V_{thc}}} - 1\right] \tag{18}$$

Combining (13), (14) and (17), an improved solar panel model can be obtained thus:

$$I_{sc} = \frac{\left(I_{ph,stc} + \alpha_I \Delta T\right)}{\left[e^{\frac{(V^*_{oc}+\alpha_V \Delta T)}{m_c V_{thc}}} - 1\right]} \tag{19}$$

Assuming that $\frac{V^*_{oc}}{V_{thc}} \gg 1$, then he equation above can be written as:

$$I_{sc} = I_{ph,stc} e^{\frac{(V^*_{oc})}{V_{thc}}} \tag{20}$$

From (19) and (15), it can be established that:

$$V = V_{thc} \ln\left(1 + \frac{I_{ph,stc} - I}{I_{sc}}\right) - R_s I \tag{21}$$

Equations (20) and (21) can further manipulated by assuming that $e^{\frac{(V+R_s I)}{m_c V_{thc}}} \gg 1$ to obtain a more general PV module model given as:

$$V = V^*_{oc} + V_{thc} \ln\left(1 - \frac{I}{I_{ph,stc}}\right) - R_s I \tag{22}$$

Equation (22) is a simple photovoltaic mode that can be expressed by Figure 2. The diode of Figure 2 has the reverse saturation current of $I_{ph,stc}$, the thermal voltage of $V_{T,n}$ and terminal voltage, V.

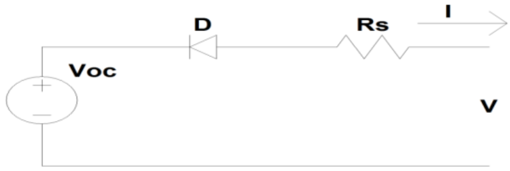


Figure 2: An equivalent circuit obtained from (22).

2.4 Modification for a Solar Panel

The current-voltage equation for a solar panel and that of a solar cell is similar, except that the module I-V (current-voltage) curve is the combination of I-V curves of all solar cells connected in the module, and (3) can be expressed as follows:

$$I = I_s - I_{sc}\left[e^{\frac{Q(V+R_sI)}{m_ckT_c}} - 1\right] - \frac{V + R_sI}{R_p} \tag{23}$$

Writing (23) in terms voltage of a single cell as well the following equation is derived:

$$V = IR_s + H\log\left[\frac{I_s - I - I_{sc}}{I_{sc}}\right], \tag{24}$$

where, $H = \frac{m_ckT_c}{Q}$.

If I_{pan} is the current of solar PV panel, V_{pan} is the voltage of solar PV panel, then, the relationship between I_{pan} and V_{pan} will be similar to that of a solar cells I-V relationship, i.e.:

$$V_{pan} = I_{pan}R_{span} + H_{pan}\log\left[\frac{I_{span} - I_{pan} - I_{scpan}}{I_{scpan}}\right], \tag{25}$$

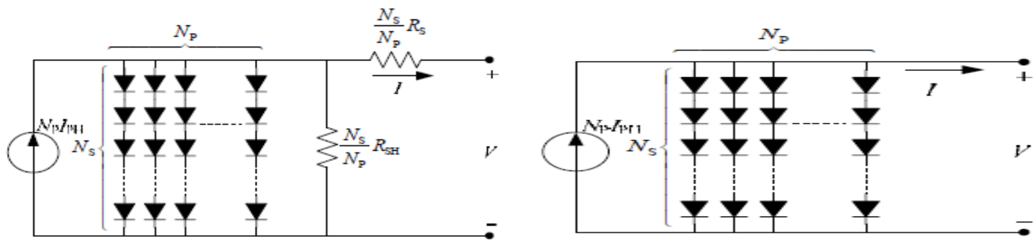
where I_{span} light generated current of panel, I_{scpan} is reversed saturation current of the panel, R_{span} is the series resistance of the panel and H_{pan} is the constant for the module. If N_S cells are connected in series then R_{span} = $N_S \times R_S$. Similarly, H_{pan}= $N_S \times H$. Hence, I_{scpan}= I_{sc} and I_{span}= I_s. Thus, the panel I_{pan}-V_{pan} equation of N_S series connected cells will be written as:

$$V_{pan} = I_{pan}N_sR_s + N_sH_{pan}\log\left[\frac{I_s - I_{pan} - I_{sc}}{I_{sc}}\right] \tag{26}$$

Similarly, the current–voltage equation for the parallel connected cells can be written as:

$$V_{pan} = I_{pan}\frac{R_s}{N_p} + H_{pan}\log\left[\frac{N_pI_s - I_{pan} - N_pI_{sc}}{N_pI_{sc}}\right] \tag{27}$$

For a parallel connection the series resistance is divided based on the number of cells in parallel (N_p) and the reverse saturation current and the light generated current get multiplied by the N_P. In this case the module factor *H* remains unchanged and is same as that of *H* of a single cell. A generalised and appropriate equivalent circuit models for the equations are shown in Figure 3.



(a) (b)

Figure 3: Equivalent circuit model of PV panel (a) General (b) Appropriate

The solar panel design data used for this simulation procedure are presented in Table 1.

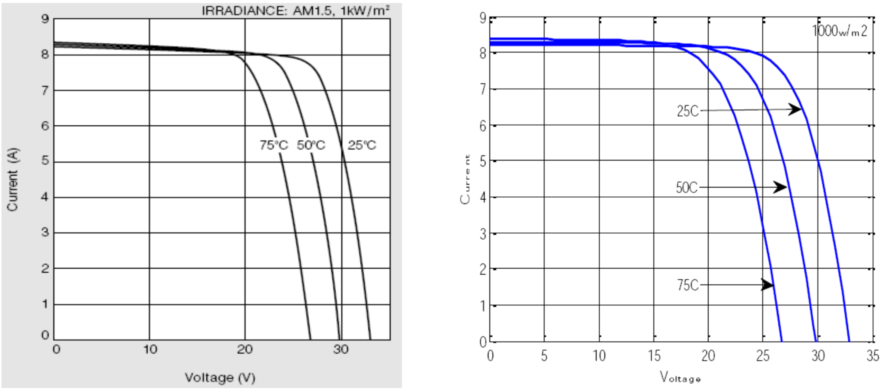
Table 1: Simulation parameters used for analysis

Parameter	**Values**
Solar radiation intensity	800W/m^2
Solar radiation intensity (STC)	1000W/m^2
Temperature of cell	40^{o}C
Boltzmann's constant (*k*)	1.38x10^{22}W/m^2-K
Charge of Electron (*Q*)	1.602x10^{-18}C
Area of Panel, A_r	0.035m^2
Number of cells connected in series (N_s)	10
Number of cells connected in parallel (N_p)	5
Current temperature coefficient (α_I)	0.5mA/^{o}C
Voltage temperature coefficient (α_V)	640V/^{o}C
Saturation current (I_{sc})	0.75mA
Ideality Factor (m_c)	5
Band gap energy(ε_G)	6.5eV
Open circuit voltage	32.9V

3. Results and Discussion

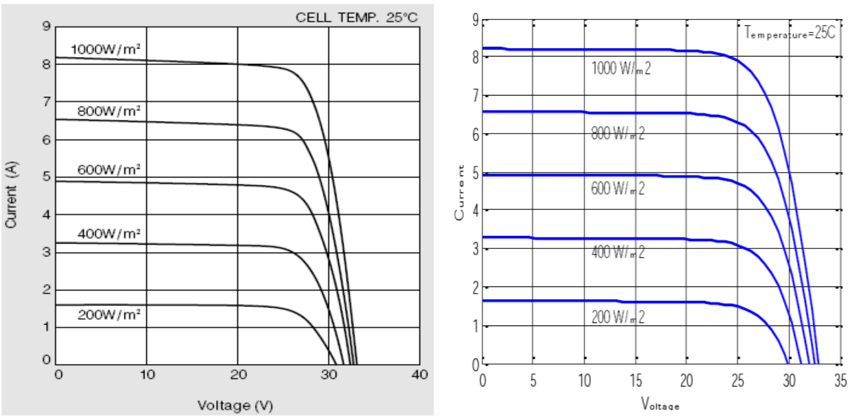
3.1 PV Model Simulation and Model Validation

By comparing the KC200GT datasheet I-V curves at different values of solar irradiance and temperature with those obtained by the MATLAB model, which are shown in Figures 5 and 6. It is obvious that the curves obtained by the model are identical to those found in the module data sheet which reveals that the model is reliable.



(a) (b)

Figure 5: Current-Voltage curves at different temperatures from (a) KC200GT data sheet (b) MATLAB simulation

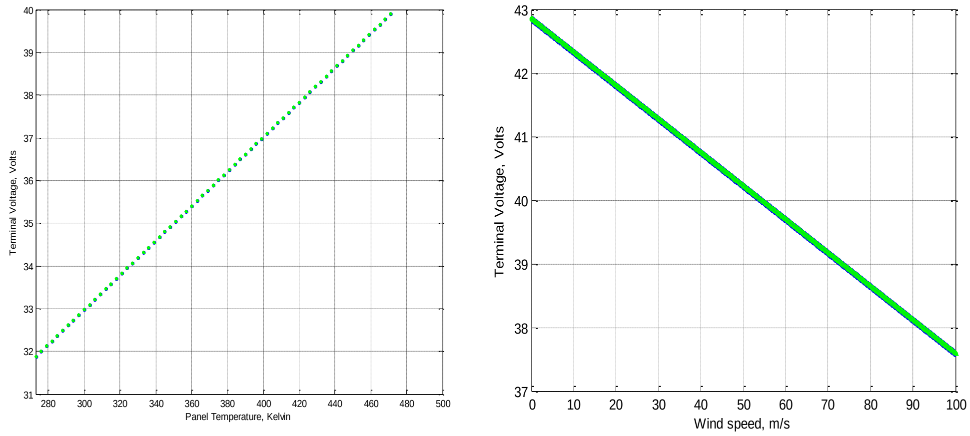


(a) (b)

Figure 6: Current-Voltage curves at radiances from (a) KC200GT data sheet and (b) MATLAB simulations

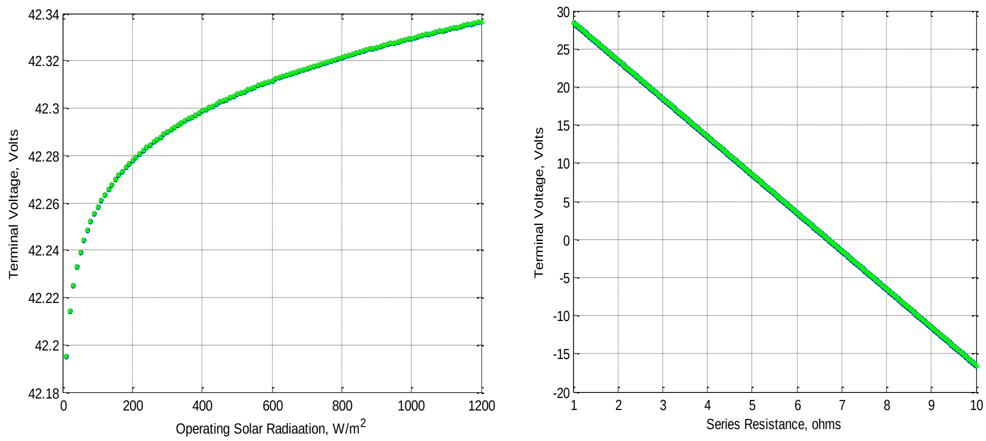
3.2 Variation of Terminal Voltage with Solar Panel Parameters

The terminal voltage varies with several parameters of the solar panel. The model for the terminal voltage was simulated with other parameters and plotted using MATLAB and the results shown in the Figures 7 and 8. As observed (Figure 7a), a direct relationship between both parameters is indicated and this suggests that the terminal velocity of a solar panel can be controlled by controlling the panel temperature. Figure 7b suggests that the terminal voltage of a solar panel is inversely related to the average velocity of the wind around the panel. A simulation study was carried out be varying the wind around the panel from 0 to 100m/s. This result shows adequacy with the previous result for terminal voltage and panel temperature. Therefore, controlling the average wind distribution the solar panel will mean controlling the terminal voltage. Figure 8a indicates an increase in terminal voltage with solar irradiation. This curve is however, similar to other radiation curves presented. Therefore shading of solar panels can be very detrimental to the performance of the solar panel. This is because shading reduces the radiation the panel receives and from this result, it will in turn reduce the terminal voltage of the panel. The terminal voltage can also be controlled by using an appropriate series resistance set up that gives the required terminal voltage.



(a) (b)

Figure 7: Variation of terminal voltage with (a) panel temperature (b) wind speed for a solar panel

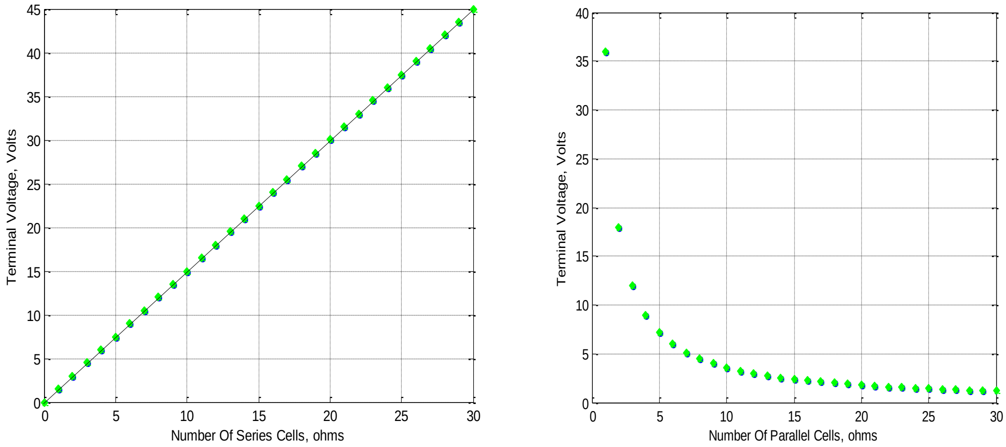


(a) (b)

Figure 8: Variation of terminal voltage with (a) operating solar radiation of the solar panel (b) series resistance on the terminal voltage

A simulation performed with respect to the effect of series resistance in the panel on the terminal voltage was performed and the result is shown in Figure 8b. The result shows that the terminal voltage varies with the series resistance inversely. The result shows that an increase in series resistance will cause a decrease in the terminal voltage. From Figure 8b, it can be observed that for the model of PV module used for this analysis, it will have a zero terminal voltage when the series resistance is more than 6.67 ohms. The output data obtained for the solar panel under use shows that a series resistance of 4.15 ohms, the terminal voltage was 14.2 volts at the operating conditions used for this analysis. A simulation result showing the variation of terminal voltage with number of cells connected in series. This is shown in Figure 9a. From the result it can be seen that the number of series connected solar cells will increase the terminal voltage of the resulting PV panel. As can be seen from the Figure 9a, at the point where the number of connected solar cells is equal to 0V, the terminal voltage was also equal to 0V. Indicating that at a the point where no cells has been connected to form a solar panel, the terminal voltage of the solar panel will be equal 0V and increase as number of cells increases.

It can be seen from Figure 9 (a and b) that the terminal voltage has a direct relationship with the number of connected series cells. That is the greater the number of series connected solar cells the greater the terminal voltage. For parallel connected solar cells in a solar panel, a right sloping down curve was obtained which indicates that Terminal voltage is inversely related to the number of parallel connected solar cells. Additionally, from the simulation data used, to produce the same terminal voltage as series connected series panel, a greater panel current is required.



(a) (b)

Figure 9: Terminal voltage versus number of connected: (a) series cells (b) parallel cells; in the panel

4. Conclusion

Understanding the behaviour of physical systems requires a provision of a mathematical model that best describes the system. In this paper, a mathematical model, which describes the terminal voltage of a solar photovoltaic system is presented. This model can enable the establishment of a factual control principle for the optimal design of the system as the correct rating and number of panels should be considered in the design of a photovoltaic panel module. The number of cells used for the design is very much important way to control the terminal voltage. The terminal voltage has a direct relationship with the number of connected series cells. This paper recommends the implementation of a physical model for the control of terminal voltage of a solar panel using well designed microcontrollers and the mathematical modelling of solar arrays with parallel and series connected solar panels used in grid system power generation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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