Maximum Power Point Analysis Using Simulink/Matlab for a Hybrid Solar Photovoltaic/Battery Storage system.

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Abstract—Electricity generation using solar photovoltaic systems pose a unique challenge to improve the efficiency and to minimise the manufacturing cost. Research and development in this area has been expanding as it is environmentally friendly and helps the planet to reduce the greenhouse gas emission while reducing the carbon footprint. As a result, solar photovoltaic (PV) electrical power generation systems have become more popular and limelight of sustainable energy research. This paper describes the dynamic modeling and simulation of a sustainable renewable hybrid energy system with solar PV array and a battery storage system. Simulink was used to study the characteristics of temperature and irradiation effect along with the manufacturer’s data to validate the results. The Matlab/Simulink based study therefore also points out significance of locating maximum power point for a given Module/Array.

Keywords— Simulink/Matlab, Photovoltaic, Maximum power point, Battery storage, Control systems, Hybrid energy, Simulation.

I. INTRODUCTION

Hybrid energy systems development using solar photovoltaic (PV) arrays combed with wind turbines, proton exchange membrane fuel cells (PEMFC), battery storage systems have become very popular due to increasing oil prices in the global market. Though the initial cost of these hybrid systems are still very much higher than the electricity generation cost by using fossil fuel plants, they have proved environmentally friendly[6] and low maintenance cost in the long run. Capital investment subsidy introduced by many governments to tackle the alarming effect of greenhouse gases [6][7], have attracted many manufacturing companies to develop technological solutions to use hybrid energy power systems effectively and efficiently. Though, there have been considerable developments in this signposted area, still there are many technological challenges unanswered relevant to hybrid control systems designs.

II. METHODOLOGY

A. Literature review in the context of dynamic modeling of solar photovoltaic arrays and battery storage systems.
B. Mathematical Modeling and simulation
C. Analysis and validation of simulation results.
D. Conclusion.

III. LITERATURE REVIEW

A. Solar Cell

A solar cell (also called photovoltaic (PV) cell as shown in Fig.1) is a unit that converts light energy into the electrical energy by the photovoltaic effect. The generated current, voltage and its resistance characteristics will vary depending upon the radiant light and the ambient temperature. Similar to transistor materials solar cells are made up of semiconductor materials like silicon, gallium arsenide, copper indium gallium di-selenide (CIGDS), cadmium telluride (CdTe) and amorphous silicon (a-Si) [31], [32]. Current solar cells in the market use mainly monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide/sulfide.[33]

Solar cells can be used as portable chargers: Monocrystalline solar charger. Excitonic Solar cells which uses nanotube arrays can absorb larger fraction of solar spectrum.

Fig.1. Solar Cell (http://en.wikipedia.org/wiki/Solar_cell)
When making solar cells bulk purified material is cut into very thin layers (wafers) of 180-240 micro meters thick and in between organic dyes and organic polymers are deposited to support the substrate. Polycrystalline silicon or multicrystalline silicon is widely used as it is less expensive to produce though it is slightly less efficient[32]. Monocrystalline silicon solar cells are expensive than the Polycrystalline as Monocrystalline cells(c-Si) have Single-crystal wafer cells. Boron or phosphorous dopant impurity atoms are added to molten silicon to get the n-type or p-type charging effect [33].

B. Efficiency of a Photovoltaic System

When the sun light hits the semiconductor surface of a solar cell, electron springs up and attracted towards the N-type semiconductor material. This will cause more negatives in the N-type and more positives in the P-type semiconductors generating a higher flow of electricity. This is known as the Photovoltaic effect. The amount of current generated by a PV cell depends on its efficiency (type of PV cell) its size (surface area) and the intensity of sunlight striking the surface. A single solar cell can only create a little amount of power and hence to get a larger effect solar cells are either connected in series or parallel. Solar array or PV module is made up of many solar cells connected either in series or parallel [17]. Cross section of a PV cell is shown in Fig.2.

When solar cells are connected in parallel it can produce high current while keeping the voltage constant. Depending upon the requirement cells can be connected in series and parallel to make one module that gives high current and voltage.

There are three main types of PV cells available in the market. They are: monocrystalline, polycrystalline and thin film. The monocrystalline and polycrystalline PV cells are manufactured using microelectronic manufacturing technology. The efficiency of monocrystalline cells are in the range of 10%-15%, while polycrystalline (or multicrystalline) PV cells are in the range of 9%-12%. For thin film cells, the efficiency is 10% for a-Si(amorphous Silicon), 12% for CuInSe2 and 9% for CdTe [31],[33]. Technology in this area has been rapidly developing and it has found that different technologies can achieve efficiencies up to 20%. GaInP/GaInAs/Ge multi-junction solar cells can get the efficiency up to 40%. The highest efficiency so far recorded was by using multiple junction cells at high solar concentrations (43.5% using 418 x concentrations).They are still under experimental stage. Thermodynamically it is understood that the maximum theoretically possible conversion efficiency for sunlight is 86% according to the Carnot limit. All of these measurements were taken under standard conditions: measured under the global AM1.5(1000 W/m²) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

IV. MATHEMATICAL MODELING OF A SOLAR PV SYSTEMS

The model of a solar cell which is shown in Fig. 3. has been used by many researchers in [2][11][14][21]. Where G and T are irradiance and temperature respectively. Solar cell is basically a p-n semiconductor junction that directly converts light energy into electricity.

\[ I_{ph} = \text{Photo generated current depending on irradiance} \]
\[ G \text{ and temperature} \ (T) \]
\[ R_{sh} = \text{Intrinsic shunt resistance of the cell} \]
\[ R_s = \text{Series resistance} \]

Usually \( R_{sh} \) is very large and \( R_s \) is very small compared to \( R_{sh} \). Hence, \( R_s \) may be neglected to simplify the mathematical model. The output current, \( I \) can be written as: (Kirchhoff’s current law)

\[ I = I_{ph} - I_s - I_{sh} \]  \hspace{1cm} (1)

These currents are defined as given in [21]:

\[ I_{ph} = \frac{G}{G_{ref}} (I_{ph,ref} + \mu_{ke} (T - T_{ref})) \]  \hspace{1cm} (2)
From diode theory it is known that:

\[ I_d = I_{sat} \left[ \exp \left( \frac{V + R_s I}{n V_t} \right) - 1 \right] \]  
\[ I_{sh} = \frac{V + R_s I}{R_{sh}} \]  

Now equation (1) can be re-written by substituting for \( I_d \) and \( I_{sh} \):

\[ I = I_{ph} - I_d - I_{sh} \]  
\[ I = I_{ph} - I_{sat} \left[ \exp \left( \frac{V + R_s I}{n V_t} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \]  

These currents are defined as given in [21]:

Where:
\( I, V \) : output current and voltage.
\( I_{ph,ref} \) : irradiance at standard test conditions (STCs): 1000 W/m² and 25°C.
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\( T \) : is the temperature conditions of work.
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Equation (5) is a nonlinear equation that represents the relationship between \( I \) and \( V \). It is used in research papers [4][16][23] [28],[29],[30][36]. Gupta, SC.; et. al in [29] stated that the equation (5) has no analytical solution. It is also noted that many researchers assumed the PV model given for a single cell will behave in the same manner for series connections. Since \( I \) is there in both side of equation (5) empirical solutions have been given by various researchers to make the \( I \) or \( V \) as the subject of equation (5). The same formula with little modification to include either a single diode model or two diodes model have been used in [13],[15],[22],[24],[25],[27][36]. Uzunoglu, M., et al in [13] used an approximate solution for output voltage. Kalanta, M.; et. Al in [13] presented a simple empirical formula for their research work as a solution for \( I \) and \( V \). According to their work the formula given below, includes the number of modules in series and parallel:

\[ I_p = M I_l - M I_o \left[ \exp \left( \frac{q \left( NV + I_o R_N \right)}{N M k T_p} \right) - 1 \right] - \frac{NV + I_o R_N}{N M R_{sh}} \]  

Where:
\( I_p \) : in this equation is the output current of the panel.
\( I_l \) : is the light generated current per module( or \( I_{ph} \) in the other models)
\( I_o \) : reverse saturation current per module which is equal to \( I_{sat} \)
\( M \) : number of module strings in parallel, \( N \) : number of modules in each series string
\( R_s \) : diode series resistance per module, \( R_{sh} \) : diode shunt resistance per module. \( Q \) : electric charge, \( k \) is the Boltzmann constant and \( T_p \) : cell temp in Kelvin. An approximated model was used by Badawe, M. et. al [20] taking into account of \( I-V \) and \( P-V \) characteristic curves separately. An easy empirical formula was presented in [35] to model a solar system

\[ P_{pv} = A_m \eta_m P_i \eta_{pc} I \]  

Where:
Where: \(A_m\) is the array area, \(\eta_m\) is the module reference efficiency (assumed to be 0.11), \(P_t\) is the packing factor (assumed to be 0.9), \(\eta_{pc}\) is the power conditioning efficiency (assumed to be 0.86), and \(I\) is the hourly insolation in W/m\(^2\).

Solar cell mathematical model and the Simulink model presented by Chen HC.; et. al in [27] gives a very good approximated model covering all constraints and variables. PV model presented by Mousavi, SM; in [19] can be considered as the easiest model out of many research papers. The PV mathematical model that was presented in 1993 in [12] was revisited by Carlson, in 1995 and then again by Faith Onur Hocao Glu in 2011 was represented by the formula:

\[
P = A_{pv}x^2 + B_{pv}x + C_{pv} \tag{8}\]

Where \(x = \) solar radiation W/m\(^2\), \(P\) is the power generation [W] and \(A_{pv}, B_{pv}, and C_{pv}\) are constants, which can be derived from measured data. Surprisingly this equation seems to be the answer for all our nonlinear, exponential relationships [12]. Experimental results from a solar cell array with series and parallel connections can be used to verify the mathematical model given in equation (8).

V. IMPLEMENTED MATHEMATICAL MODEL

Mathematical model implemented this this paper was the model presented in [36].

\[
I_{ph} = [I_{SCr} + K_r(T_{op} - 298)] * \lambda / 1000 \tag{9}\]

\[
I_{rs} = I_{SCr} / [\exp(qV_{oc} / N_s kAT) - 1] \tag{10}\]

\[
I_o = I_{rs} \left[ \frac{T_{op}}{T_{ref}} \right]^3 \exp \left[ \frac{q * E_{go}}{Bk} \left\{ \frac{1}{T_{ref}} - \frac{1}{T_{op}} \right\} \right] \tag{11}\]

\[
I_{pv} = N_p * I_{ph} - N_p * I_{o} \left[ \exp \left\{ \frac{q * (V_{pv} + I_{pv} R_{I})}{N_s kA T_{op}} \right\} - 1 \right] \tag{12}\]

(For SOLKAR PV module: \(N_p=1, N_s=36, I_{sc}=2.55A, V_{oc}=21.24V, I_{mp}=2.25, V_{oc}\) at maximum power = 16.56V)
Fig. 6. Output V_pv – I_pv characteristics with varying temperature keeping Irradiance constant.

Simulation results shown by V_pv versus I_pv and the V_pv versus Module power . Fig.6 and Fig.7 respectively indicates when the temperature increases the increase of current is marginal but the decrease of voltage and the output power were very high.

Fig. 7. V_pv(V) versus Output power(W) with varying temperature and constant Irradiation.

VI. USING MATLAB

Matlab code used to plot the output voltage against the output current under varying temperature conditions:

clear all
clc
rs=0.1; %Rs is the series resistance of 
a PV module
np=1; %Np is the number of cells 
%connected in parallel
ns=36; %Ns is the number of cells 
%connected in series

voc=21.24; %voc=voc
iscr=2.55; %ISCr is the PV module 
%short-circuit current at 25 C
%and 1000W/m2 = 2.55A
Tr=298; %Tr is the reference 
%temperature = 298 K
a=1.6;b=1.6; %A = B is an ideality factor = 1.6
k=1.3805e-23; %k is Boltzman constant = 
% 1.3805 × 10-23 J/K
q=1.6e-19; %q is Electron charge = 1.6 × 
%10-19 C
ki=0.0017; %Ki is the short-circuit 
%current temperature
%co-efficient at ISC= 
%0.0017A /0C
lamda=1000; %is the PV module 
%illumination (W/m2) = 1000W/m2
ego=1.1; %Ego is the band gap for 
%silicon = 1.1 eV

Top=300; %Top is the module operating 
%temperature in Kelvin
iph=(iscr+ki*(Top-298))*lamda/1000; 
%Iph is the light generated current 
in a PV module (A): The current 
%source
%Iph represents the cell 
%photocurrent
m=(q*voc)/(ns*a*k*Top);
irs=iscr/(exp(m)-1);%Module reverse %saturation current
io=irs*((Top/Tr)^3)*exp((q*ego/b*k)*(1/Tr-1/Top)); %Io 
%is the PV module saturation current (A)

ipv=2.5; %Ipv is output current of a PV 
%module (A)

v=0:1:23; %Vpv is output voltage of a 
%PV module (V)

ipv=zeros(size(vp));
for i=1:length(vp)
    ipv(i)=np*iph-
    np*io*(exp((q*(vpv(i)+ipv(i)*rs)/(ns*k*a*Top)))-1)); 
end

figure(1)
set(gcf, 'Color', 'w')
plot(vpv,ipv)
xlim([0 25])
ylim([0 3])
xlabel('Module Voltage (Vpv)')
ylabel('Module Current (Ipv)')
title('Power curve from Matlab at Lamda =800:Solkar 
Module')
As shown in Fig.8, there is a slight difference between
the readings of Maximum power point when used Matlab
code and the Simulink blocks. The difference could be due
to initial conditions and due to different numerical
approximation method used in Simulink and Matlab. The
differences is not a trivial phenomenon for the design
purposes as it is very minor.

As shown in Fig.9, there is a slight difference between
the graphs of Matlab code generated plots against the
Simulink plots. Ipv, and Vpv plot difference explains the
when it is plot for the power. Simulink plot indicates the
lower values than Matlab code generated plots.

VII. DYNAMIC MODELING OF A LITHIUM-ION BATTERY
STORAGE SYSTEM

To implement the battery electrical model, a Lithium-Ion
battery cell was considered as a series circuit with
controlled voltage source and a battery internal resistance
in the circuit given in [37].

E : No load voltage(V)
E_0 : Battery constant voltage(V)
K : Polarization voltage(V)
Q : Battery capacity(Ah)
A,B : Exponential constants
q : Charge

The equation for the controlled voltage is described as
given in [37]:

\[ E = E_0 - K \frac{Q}{Q - q} + A \exp(-Bq) \]  

\[ V_{battery} = E - i^*R_i \]  

(i and R_i symbolizes the battery discharge and internal
resistances.)

The temperature makes difference on three basic
variables of the electrical model which are polarization
voltage K, battery constant E_0 and the exponential
coefficient A & B. To make the Model simpler [38],
thermal effect on A has been ignored since A & E are
highly related. B coefficient akes significant difference on
exponential part of the characteristic curve. As given in
[38]:

\[ x_n = f(T) = A + BT + CT^2 \]  

\[ n = f(K, E_0, B, C) \]  

The charge and discharge efficiency of Li-ion batteries
are high compared to lead-acid or NiMh (Nickel Metal
Hydride) batteries(80%-90% range)[38].

\[ x_n(T) = f(T) = 0.876 - 0.028T + 4.218*10^{-4} * T^2 \]  

\[ x_{E_0}(T) = f(T) = 0.986 + 4.97*10^{-4} * T - 6.6*10^{-5} * T^2 \]  

\[ x_q(T) = f(T) = 0.733 - 0.045 * T + 9.63*10^{-4} * T^2 \]
Combining equations (17), (18) and (19):

\[ E(q,T) = x_{E0}(T) * E_0 - x_K(T) * K * \left( \frac{Q}{Q-q} \right) + A \exp^{-x_p R_T q} \]

(20)

After the battery is discharged when the simulation model is turned on for charging the Panasonic CRG17500 model shows that it is gradually charging up to the specified level (Fig. 10).

![Simulink model of the Li-Ion Battery storage system](image1)

**Specification of Li-Ion battery CRG17500 model is used for the simulation**

- Nominal Voltage = 3.6V
- Std. Capacity = 830mAh
- Dimensions: Diameter 16.9 mm
- Height 49.6 mm
- Weight 25g
- Total equivalent impedance = 150mOhms.

R2 = 40mOhms and C = 4F as given in [2].

q is a ramp input slope and is 0.001 was used for the simulation which makes q increase by 1 mAh per time unit. Voltage versus time curve indicates the discharge characteristics.

![Time versus battery voltage (v) – discharging](image2)

**VIII. CONCLUSION**

Generalized PV model and a battery storage model have been developed with Matlab/Simulink and the models were verified with the previous research data. The proposed PV model takes sunlight irradiance and cell temperature as input parameters and outputs the I-V and P-V characteristics under various conditions. Though the maximum power point data extracted from Simulink and Matlab were slightly different they were not far apart. However, when experimental data is available these differences can be verified. These generalized models can be used to combine with wind generators and the PRMFCs to produce complex hybrid electricity generation systems to boost the Grid power supply.

**REFERENCES**


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