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Temperature Considerations in Solar Arrays

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Abstract-**Temperature is an important consideration in the operation of photovoltaic (PV) arrays. In particular, daily and seasonal temperature variations are a limitation on the application of solar power to homes. At lower temperatures, PV systems produce more power. For higher temperatures, optimum operation requires modification of electrical load and removal of excess heat. Several technologies and approaches are available. To pursue this system optimization, PV cells were investigated at different temperatures. These investigations are compared with simulated theoretical results to draw more specific conclusions that can be applied to a solar house. A temperature reduction of 60°C improved the power by up to twenty-seven percent with the current test cell. The simulations matched this conclusion and can be applied to the PV array used on a house. The University of Missouri-Rolla (UMR) and Rolla Technical Institute (RTI) jointly built a solar house for the 2002 National Solar Decathlon Competition. This house is the motivation and testbed for our research. The first application is to cool the cell; then compare the additional amount of power produced with the amount of power required to cool the cell. The feasibility of cooling the array is discussed. This paper first gives a description of the UMR/RTI solar house, a literature review, and overview. Temperature-dependence theory and experiments is given next. The third portion shows simulations including current-voltage curves and an analysis of load lines and temperature. The direct application of this research to the solar house and proposals for design considerations are summarized.**

I. INTRODUCTION

The National Solar Decathlon was held from September 26 to October 6, 2002, and consisted of a student competition to design and operate the most attractive and effective solar-powered house. The University of Missouri-Rolla competed in this competition, building a solar-powered house that the Project manager lives in today (see Fig. 1.1). This competition has inspired a number of universities to focus on solar research and find more and better solutions to the problems associated with solar power. A consideration for any engineered project is the environment in which it will be located. Photovoltaic (PV) cells can be found in environments ranging from space to earth-bound climates. Temperature is a prominent factor in these environments whether the application is the Mars rovers, Sprit and Opportunity, or the houses in the National Solar Decathlon Competition. The performance of PV cells and arrays is dependent on temperature.

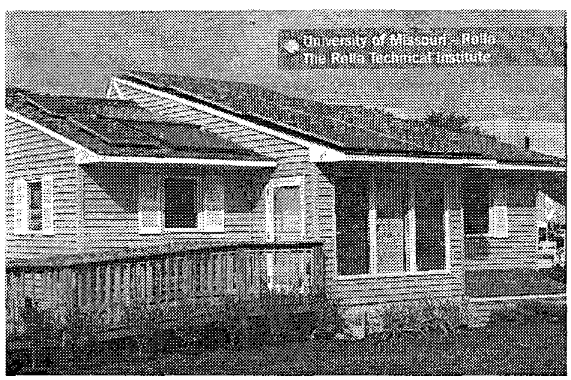

Fig. 1.1. University of Missouri-Rolla – Rolla Technical Institute Solar House

This paper examines temperature variations that limit the application of solar power to homes. Daily and seasonal temperature changes are of interest. At lower temperatures, PV systems produce more power. For higher temperatures, optimum operation requires modification of electrical load and removal of excess heat. Several technologies and approaches are available to improve PV system efficiency. A experimental study of temperature dependence in solar cells and an associated mathematical model provides insight into the management of solar power systems. The UMR-RTI house, literature review, overview, experiment work, and mathematical simulation are discussed. The study of the temperature dependence in this paper is not application specific; however, this paper will include the direct application of the research to the solar house and proposals for design consideration.

THE UMR-RTI SOLAR HOUSE

The UMR-RTI Team was the only team with a union between a university and technical school at the competition. This unique combination provided a surplus of educational opportunities including selecting and optimizing technologies, along with the principle education of solar energy. The students at the technical institute through their experiences provide what technologies are being used and the most efficient ways to use them. The students at the university provided the education of the applied sciences used in choosing the best technologies form the ones presented and then optimized those technologies. The partnership between a University and a technical institute has and will provide the education that is needed to make the technologies in use better and bring more technologies quicker.

A useful and economical approach to designing the UMR-RTI Solar house, as well as the other competitors, is to match the PV array to the house and its load. Having as large an array as possible does not necessarily produce a more efficient house. The UMR-RTI house has about a 4-kilowatt array with two 120V inverters. The peak load on this house can exceed the array output. Furthermore, the array output is limited by the amount and direction of sunlight. For simplicity, the PV array is mounted to the roof; the direction and inclination of the array is fixed. Consequently, the efficiency of the total system varies with time of day, cloud cover, etc. A design team must incorporate other measures to maximize the efficiency. After monitoring the power of the cells and the environment, the strong influence of temperature was noted. The PV array preformed much better when cool. A desire for a more thorough understanding of the temperature dependence led to the material in this paper.

LITERATURE REVIEW

Much work has been done on Photovoltaic (PV) cells. Many studies included information on temperature dependence. The loss mechanisms differ for high and low temperatures. At high temperatures, two predominating effects can cause efficiency to drop. As thermal energy increases, (1) lattice vibrations interfere with the free passing of charge carriers and (2) the junction begins to lose its power to separate charges. Low-temperature losses are, if any, more complex and less understood. They are important, however, only for deep-space PV applications [1].

Efficiency losses for PV systems can be minimized in the presence of temperature variations. In most cases, good solutions are a temperature-dependent charge controller or a maximum power tracker. Both devices improve the overall system efficiency at higher temperatures where the performance is poor [2].

In nearly all systems with battery storage, a charge controller is a common component. The controller should be adjusted to ensure optimal battery system performance under various charging, discharging, and temperature conditions [2]. The charging and discharging conditions are easily analyzed. Consequently, a charge controller is very useful for battery storage. However, temperature conditions are much harder to monitor and control. A temperature dependant charge controller is less common. A device that does in effect include the temperature dependence problems is a maximum power tracker.

Maximum power trackers generally employ pulse-width modulation techniques to switch from an input dc voltage to an output dc voltage at a different level, similar to a switching dc power supply. The maximum power tracker employs a feedback loop to sense the output voltage accordingly until the output power is maximized [2]. This feedback loop pays no consideration to the operating temperature, only the power. This process is acceptable because the power is what one would maximize with a known temperature. The temperature does not have to be explicitly known.

This paper is a scientific study and comparison to known research with respect to the temperature dependence of solar cells. It includes an experiment to measure the temperature dependence of a cell's current-voltage, e.g. I-V, characteristic. The experimental results are compared with mathematical simulations and different loading effects are explored. The research is discussed in relation to the solar house. Options for design optimization and features are described.

II. THEORY

A. Solar Cell Characteristic

The photovoltaic (PV) effect is the process by which solar cells convert light energy into electrical energy. Not all wavelengths can contribute to this process. Absorption occurs when each incident photon carries sufficient energy to excite an electron from a lower energy state. For each incident absorbed photon, an electron-hole pair will be generated and can potentially contribute to a current. Some excess energy will dissipate as heat. There are efficiencies associated with each step in the conversion process.

Solar cells use p-n junction structure to produce electrical energy from incident photons [3]. When solar cells are exposed to appropriate wavelengths, electrons in the p-type region will be excited from valence band to conduction band. The excited carriers flow across and out of the junction. Hence, power is supplied to an attached load. This situation is shown in Fig.2.1.

For an ideal solar cell, no resistance loss is associated with the photovoltaic process. In physical devices, series resistance loss and shunt resistance loss are present within the solar cell. The series resistance is caused by metal-semiconductor contact, ohmic resistance in the metal and ohmic resistance in the semiconductor substrate; the shunt resistance is cause by leakage currents at the edge [4]. The equivalent circuit is shown in Fig.2.2.

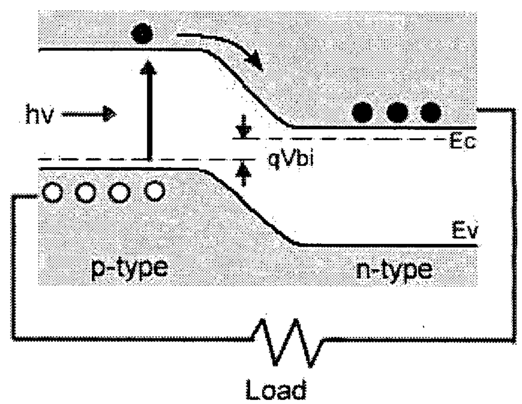

Fig. 2.1. Semiconductor p-n junction under illumination

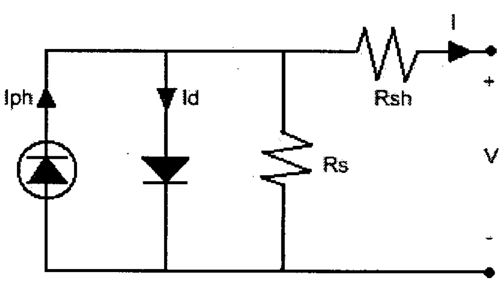

Fig. 2.2 Equivalent circuit of the solar cell

The characteristic equation can be derived from the Kirchhoff's current law:

$$I = I_{ph} - I_d = I_{ph} - I_S\left[\exp\left(q\cdot\frac{V+I\cdot R_S}{nkT}\right)-1\right] - \frac{V+I\cdot R_S}{Rsh} \quad (1)$$

I_{ph}: photon generated current

I_s: diode saturation current

k: Boltzmann's constant(1.38×10^{-23} J/K)

q: electric charge(1.69×10^{-19} C)

n: ideal factor(between 1 and 2, base on different kind of solar cells)

R_s: series resistance

R_{sh}: shunt resistance

T: absolute temperature

Fig. 2.3 describes the characteristic curve of the solar cells, which reflect the equation above.

When the load is equal to zero, the short circuit current I_{sc} is present and about equal to photon-generated current I_{ph}. Voc is the voltage measured at two terminals of the solar cell when no current flows out of the cell. On this curve, each operating point has its corresponding output power which is multiplexing the voltage value and current value at that point. The maximum power point (MPP) P_m is defined as the operating point where a solar cell has the maximum power output value. This point is around the knee of the curve as shown in Fig. 2.4. At this point, the voltage is V_m and the current is I_m. The efficiency of the solar cell η is defined as

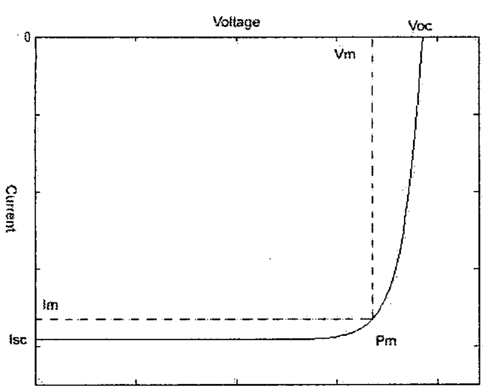

Fig. 2.3. Characteristic curve of the solar cell

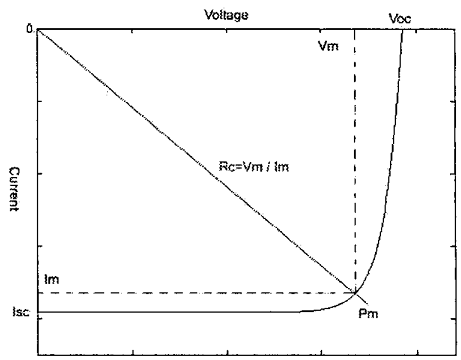

Fig. 2.4. Characteristic resistance load line

the ratio of generated power to the incident power of light.

$$\eta = \frac{I_m V_m}{P_{light}} \quad (2)$$

The characteristic resistance is the load corresponding to the maximum power point. In order to operate at the MPP, the load is matched to the characteristic resistance. Since the current-voltage curve will be changed by different light irradiance and temperature, the characteristic resistance will vary at different conditions.

B. *Temperature Effect*

Consider the current-voltage characteristic in the p-n step junction. In the ideal diode (with low-level injection), the diffusion current is [5] :

$$J = J_p + J_n = J_s\left(e^{\frac{qV}{kT}} - 1\right) = \left(\frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n}\right)\left(e^{\frac{qV}{kT}} - 1\right) \quad (3)$$

Where J_s is the saturation current density, D is the diffusion coefficient and L is the diffusion length of electrons or holes, which is equal to $\sqrt{D\tau}$ where τ is the minority lifetime. The p_{no} and n_{po} represent electron and hole densities in n-type region and p-type region at thermal equilibrium. Also, n_i is the intrinsic carrier density which has the relationship of $p_{no}\, n_{po} = n_i$.

The short-circuit circuit tends to increase with increasing temperature. When temperature increases, the diffusion coefficient diffusion D, the minority life time τ, the diffusion length L and the intrinsic carrier density will increase. The change of these parameters will enhance diffusion, i.e, a larger D. The photocurrent generated by the solar cell is the sum of electron diffusion current, hole diffusion current and dominant generation current in the depletion region. The generation current in the ideal depletion region is independent of temperature, so the increase of diffusion will result in an increase of photocurrent.

The open-circuit voltage tends to decrease with increasing temperature. The open circuit voltage V_{oc} can be obtained from the solar cell characteristic equation (1).

$$V_{oc} \cong \frac{kT}{q}\ln\left(\frac{I_{ph}}{I_s}+1\right) \cong \frac{kT}{q}\ln\left(\frac{I_{ph}}{I_s}\right) \quad (4)$$

When temperature increases, the amount of saturation current will increase more than the amount of photocurrent and therefore makes V_{oc} decreased rapidly. The effect of temperature is shown in Fig. 2.5.

III. EXPERIMENT

At higher temperatures, solar arrays will produce less output power than at lower temperatures. To experimentally show this theoretical characteristic, an experiment was designed

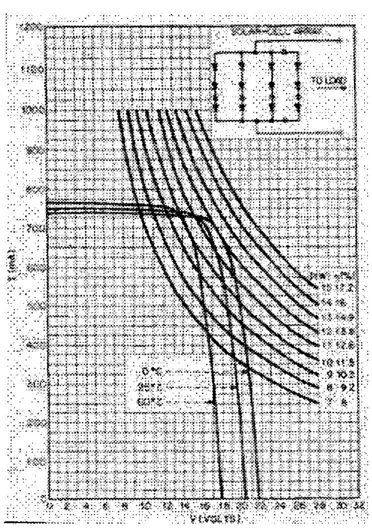

Fig. 2.5. I-V curves at different temperature [5]

to measure the relationship among current, voltage and temperature of the solar arrays. The experiment equipments, setting and result are shown as follows.

A. Experiment Description

Experimental Task

The purpose of this experiment is to find the current and voltage characteristics of the solar cell. Through the entire procedure, the light intensity is fixed and measurements are taken at different temperatures. Without the varying of light intensity, a plot of the I-V curve at different temperatures can be used to find out how the temperature affects the solar cell operation.

Experimental Setup

Solar arrays and solar panels are too large for laboratory testing. Therefore, a smaller unit of the solar system, a solar cell, is chosen as the test material. Because solar arrays are constructed from different configurations of solar cells, this test result can be applied to solar arrays as well.

The experiment set up is showed in the Fig. 3.1. The resistance decade box can provide different loading values to measure current as a function of voltage.

To demonstrate temperature effects, the first step is to eliminate other effects that will influence data acquisition. The light source is hooked up on the lighting track still above the aquarium tank and the solar cell is set at the same distance

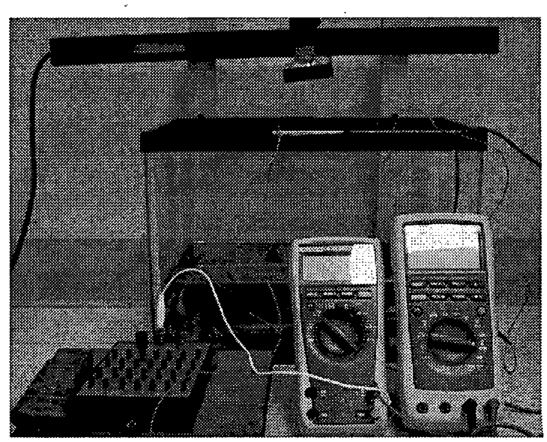

Fig. 3.1 Experiment setup

away from that light source all the time. Hence, the incident light intensity on the cell does not vary.

The solar cell is attached to a metal pan. The pan is placed in the water tank. Adding ice in to the water tank or heating up the water can provide different temperature conditions. Note that the solar cell is not immersed. This arrangement is used to prevent light scattering. The operating temperature of the cell is measured directly by infrared thermometer (as opposed to measuring the temperature of the water).

Test Circuit

Fig. 3.2 is the circuit for measuring current and voltage characteristics. Using the decade box to vary the load from a short circuit to open circuit condition, all the voltages and currents generated by the solar cell are recorded, i.e. the current –voltage curve is obtained.

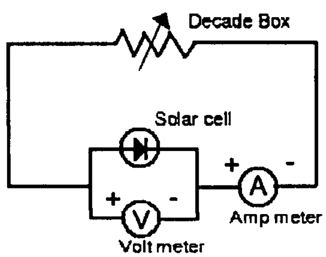

Fig. 3.2. Circuit for measuring solar cell characteristic

B. Experiment Result

Each temperature has a unique current-voltage characteristic curve. The characteristic curves in Fig. 3.3 demonstrate how the temperature affects solar cell operation. The results for each measured temperature are indicated in different colors. The data was obtained from four different temperature conditions: 1°C, 23°C, 41°C and 60°C. With the rising temperature, the solar cell short-circuit current is increased slightly but the open-circuit voltage is decreased at a larger rate. Why this effect is a concern of solar cell operation can be shown easily in Fig. 3.4. From the output power curve, the maximum output at each temperature is: P_{1}=131.63 mW, P_{23}=142.02 mW, P_{41}=156.08 mW and P_{60}=167.75 mW. Obviously, the maximum power output of the solar cell is greater at lower temperatures than at higher temperature. As expected from the theoretical considerations, more power can be drawn from a PV system by operating at lower temperature for the same solar panels or solar arrays, under the same amount of light irradiation,

Short-circuit current is increased 0.077 mA/°C and open-circuit voltage is decreased 6.3 mV/°C in average. The power loss is about 0.62mW/°C.

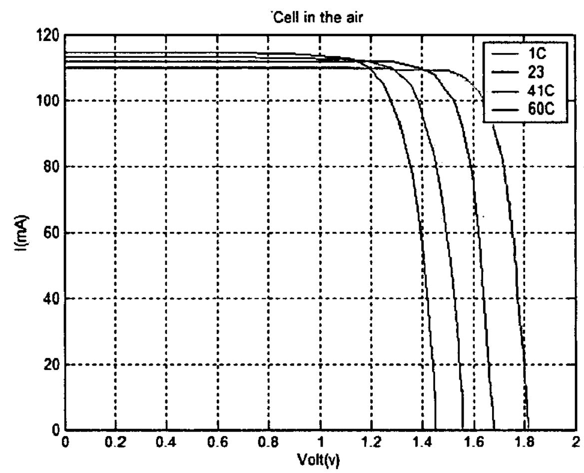

Fig. 3.3. I-V characteristic curve as a Function of Temperature

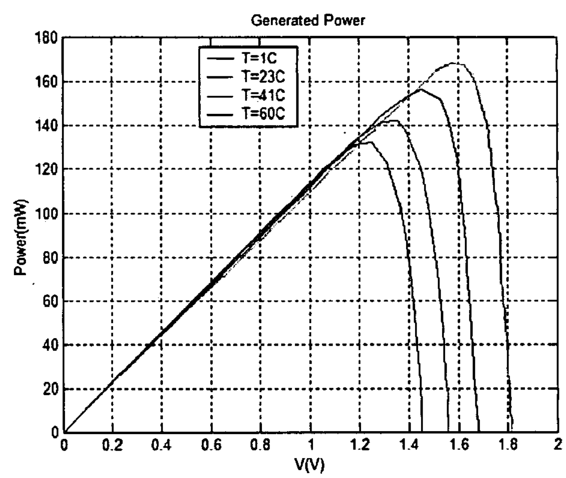

Fig. 3.4. Power output as a Function of Temperature

IV. SIMULATIONS

The purpose of this section is using a computer program to reproduce the current-voltage curves of the solar cells from the theoretical equation. The experimental and theoretical curves are matched by adjusting the appropriate parameters for a good curve fit. A real PV system can be simulated under different operating conditions.

A. Simulation of Theoretical Solar Cell

Once the saturation current, interior series resistance and shunt resistance of the tested solar cell are determined from the curve-fitting procedure, the current-voltage curve can be found by running a computer program. Fig. 4.1 is obtained from MATLAB for solving equation (1).

$$I = I_D - I_{ph} = I_s\left[\exp\left(q\cdot\frac{V+I\cdot R_s}{nkT}\right)-1\right]+\frac{V+I\cdot R_s}{R_p}-I_{ph}$$

See the Appendix for MATLAB code.

A good curve fit was obtained. In Fig. 4.2,the simulated results are compared with the associated experimental curves; there is only a slight difference between the experimental curves and the simulated curves.

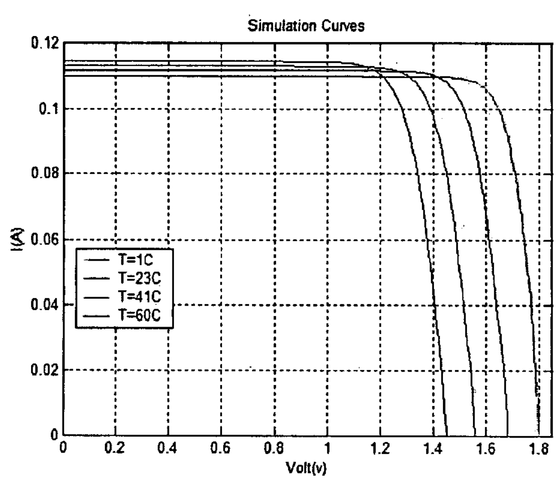

Fig. 4.1. Simulated I-V Curves

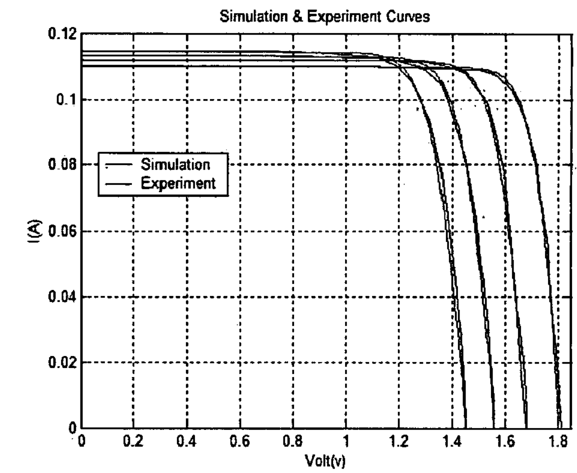

Fig. 4.2. Comparisons of Simulation and Experiment

B. Simulate for Different Loading Conditions

Characteristic Resistance

As was mentioned in section 2, the characteristic resistance is defined as the corresponding load when the cell is operating at the maximum power point. Fig. 4.3 illustrates the characteristic resistances load lines at each tested temperature. This comparison indicates that solar cells have higher characteristic resistance with lower temperature.

Different Loading Conditions

In Fig. 4.4, the I-V curve is separated by a load line into two regions. Region I contains those operating points that

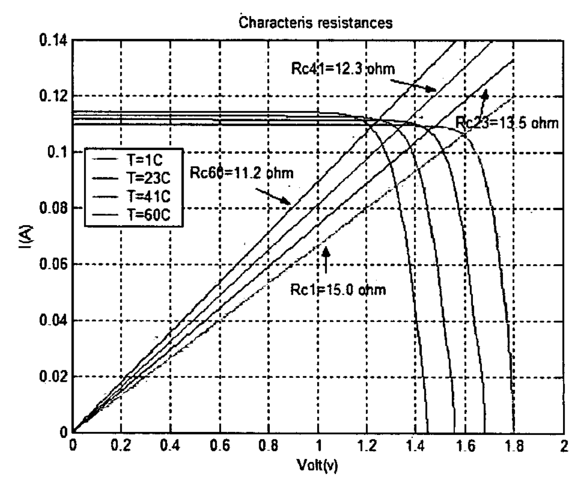

Fig. 4.3. Characteristic resistances at each temperature

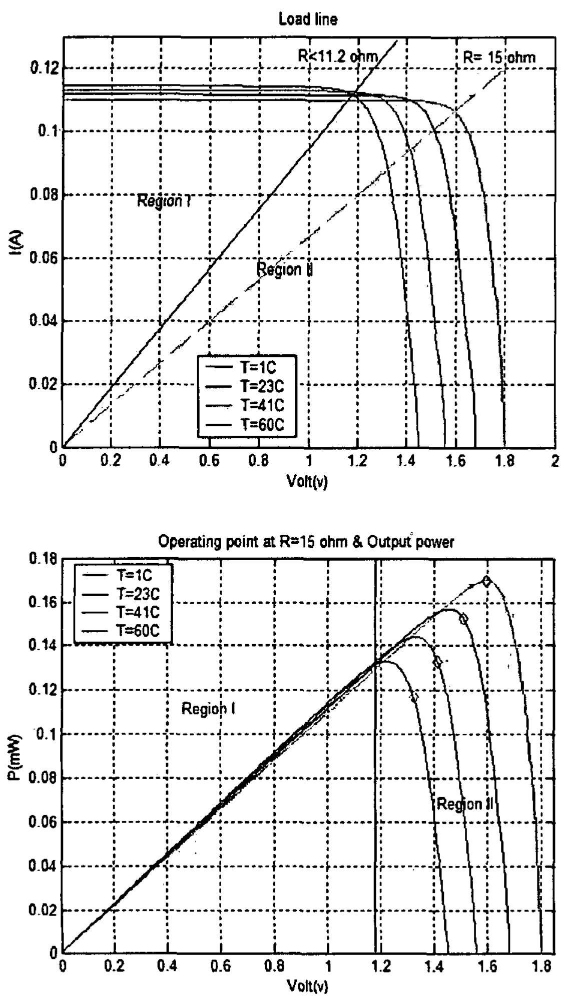

Fig. 4.4. Two loading regions and corresponding power curves

have smaller loading resistance compared to the characteristic resistance at temperature 60°C; on the other hand, region II is operated under larger loading conditions. The load line for peak power at 1°C is shown for reference.

The load line and the current-voltage curves have four intersection points corresponding to four different temperatures. Each point tells how much current, voltage and even output power the solar cell will provide under that given condition. Consider region I, when the solar cell is operating under these loading conditions. There are only slight differences of voltage and current at different temperatures. Since the output power is defined as the product of voltage and current, the power difference due to temperature will not be significant. The solar arrays can operate without a charge controller to adjust the loading in this region. Cooling down the solar array will not gain power output, but it will consume power to operate the cooling system.

From the power graph in Region II, the solar cell with lower operating temperature produces higher output power. For a 15 ohm loading case, the output power at each temperature are P_1=169.7mW, P_{23}=152.4mW, P_{41}= 133.1mW and P_{60}=116.5mW. This loading condition has about 50mW power difference for a 60 degree Centigrade temperature difference.

To obtain the most efficient operation, there are two approaches one could apply. The first approach is cooling down the cell to as low a temperature as possible; the other approach is choosing the load to match the characteristic resistance. Semiconductor devices act like insulators under extremely low temperatures [6]. Due to this consideration, operating solar arrays at extremely low temperatures is not a practical method. Therefore, load adjustment can provide flexible, electrical management options.

V. DESIGN CONSIDERATIONS

The primary design considerations are as mentioned in the introduction. Maximum power trackers can be used to track the available illumination and to maximize the power delivered from the sun. Charge controllers can regulate the difference between the cell output and the battery. Battery performance and solar cell output is improved. Controlling the temperature of the cell is another option as demonstrated in this work. Design considerations include insulating the cells from heat sources and providing for good heat transfer away from the cells. Even with a maximum power tracker, the available power will decrease if the cell temperature increases. If the cells can be mounted on a surface that can be cooled, a great degree of control is possible. However, the cooling process will take energy. This energy must be less than the power gain from the PV system. The simulations can provide a way to quantify the available power increase from cooling. The final approach is to match the load to the temperature when this process will produce a gain in power. The MPP can be tracked. A well-designed solar system will combine these approaches.

APPENDIX

Matlab script file for simulated I-V curves:

```
% T_m= Temperature at m Deg C
% Calculation for I0 Use data took form experiment
% I=IL-I0*(exp(q*(V+I*Rs)/(n*k*T))-1)-(V+I*Rs)/Rsh
% set Q=q*(V+I*Rs)/(n*k*T); M=(V+I*Rs)/Rsh
% I=IL-I0*(exp(Q)-1)-M
% I0=(IL-M-I)/(exp(Q)-1)
clear all; close all; clc;
q=1.6e-19;
k=1.38e-23;
Rs=0.5; % Series resistance
Rsh=4300; %Shunt resistance
n=2;
% Experiment data
T_1=273+1;
Isc_1=110.1e-3;
Voc_1=1.8134;
IL_1=Isc_1;
Q_1=(q*Voc_1)/(n*k*T_1);
M_1=Voc_1/Rsh;
I0_1=abs(Isc_1-M_1)/(exp(Q_1)-1);

% Find I value form short circuit to open circuit
V_1=0:0.005:1.8135;
  I_1=IL_1-I0_1*(exp(q*V_1/(n*k*T_1))-1)-V_1/Rsh;
for x=1:15
  Vd_1=V_1+Rs*I_1;
  I_1=IL_1-I0_1*(exp(q*Vd_1/(n*k*T_1))-1)-Vd_1/Rsh;
end
I_1;
plot(V_1,I_1,'r');
title('Cell in the air')
xlabel('Volt(v)')
ylabel('I(A)')
hold on; grid on;
```

REFERENCE

[1] Solar Energy Research Institute, *Basic Photovoltaic Principles Methods*, (Van Nostrand Reinhold Company Inc), Chap. 3 pg32-34.

[2] Roger A. Messenger, Jerry Ventre, *Photovoltaic Systems Engineering*, 2nd edition (CRC press), pp.71-76

[3] D. Pulfrey, *Photovoltaic Power Generation.* Van Nostrand Reinlold Company, pp.66-68

[4] S. Fonash, *Crystal Silicon Solar Cell*, Academic Press, pp79

[5] S.M.Sze, *Physics of Semiconductor Devices 2nd Edition*, John Wiley & Sons, Chap.4, pp.805-809.

[6] K. Takahashi, M. Konagai, Amorphous Silicon Solar Cells, John Wiley and Sons, pp.109-112