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Temperature Characterization of Solar Module Voltage Generation

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Abstract: ***The silicon solar module voltage generation at various periods of the day has been studied. Two mono-crystalline modules with and without cooling system have been designed and built. The experimental investigation performed on both modules under the same ambient conditions shows a significant performance variation both within the various periods of the day and between the cooled and uncooled modules. The voltage generation is found to be affected by changes in module surface temperature which is a function of the ambient temperature. It is thought that low module surface temperature aids the preservation of the orderliness of electron activities hence improved voltage generation.***

Keywords: Photovoltaic, Mono-crystalline, Module, Silicon, Voltage, Cooling System

1. Introduction

The energy from the sun is propagated to the earth in the form of electromagnetic radiation at extremely large and relatively constant rate. This energy is received globally with varying intensity at various regions of the world. This is a major form of renewable energy. This vast amount of energy, from the sun, can be converted into useful heat and electricity using solar conversion techniques. Since the energy emitted by the sun varies with location and season of the year, a thorough understanding of the parameters involved is necessary. Temperature because of its wide variation in different regions of the world is one of those important parameters.

The solar cell is a unit of a photovoltaic system that converts solar energy into electricity. The voltage generated by individual silicon solar cells is very low about 0.5 volts [1] and increasing the voltage generation involves increasing the number of cells in series connection to form modules. However, it has been observed through previous research work that voltage generation of the silicon solar cell is affected by temperature. Nigeria is situated 4°N of the equator and the daily ambient average temperature over the year could be as high as 30oC. This can explain the interest in studying variation of voltage generation of the silicon solar cell with temperature. Other studies have recognized that the ambient temperature has a significant effect on the voltage generated by the solar cell. In particular, two of these studies [2] and [3] have shown that the efficiency and output of PV module voltage generation is inversely proportional to its temperature. At lower temperatures, the voltage generation is higher due to the orderliness in vibration of the silicon electrons. As the temperature increases, the vibration become more randomly and the net effect is lower voltage generation. More than 50% of the incident solar energy is thermally converted into heating the solar cell which as a result increases the operating temperature of the photovoltaic module [4]. Investigation on the electrical efficiency of a hybrid photovoltaic/thermal (pv/t) solar system with and without cooling shows that the efficiency rises from 8.6% to 12.5% by varying the air flow rate through the duct, and hence the operating temperature of the module [5]. In order to increase the voltage generation of the photovoltaic cell, the module surface temperature should therefore be maintained at low levels. The existing literature has identified a number of alternative approaches to increase the efficiency of the voltage generation of the photovoltaic cell. The result of inherent relationship between crystalline silicon solar cell module and temperature has been studied [6].

Several studies in the literatures have suggested ways through which the open circuit voltage generation efficiency can be improved. Since module cell temperature is a function of the ambient temperature and solar irradiance, cooling the photovoltaic module will reduce the heat build-up on the cells thereby increasing the voltage output. The air cooling of the module to decrease the cell temperature and improve the power output through increased voltage has been suggested [7].

Temperature and temperature gradient on the module are critical consideration in enhancing the efficiency of the photovoltaic module [8]. According to the author, significant application of the PV system depends on the efficient contribution of the air-cooled system attached to it. An experimental result on solar module cooling using silicon oil [9] showed that the maximum power delivered by the module and hence efficiency increased. The cooling employed according to the author, maintains the temperature limit within the range of 45°C - 55°C. The electricity production in a PV/T hybrid module decreases with increasing panel temperature [10]. The author also suggested that better efficiency of the module is achieved by using slats as part of surface absorber. In another study, water immersion technique was used to improve the electrical performance of PV panel [11]. Many studies have identified that module performance depends on temperature level and as such different cooling techniques have been employed to reduce the cell surface temperature and thereby improve the voltage generation to enhance the module maximum power output and overall module efficiency. Studies have been carried out using air at ambient temperature as the medium for cooling the module surface temperature. The effectiveness of this method is limited because of the low temperature difference between the module surface and the ambient air. The purpose of this work is therefore to examine the potential of using an air-conditioner cooling system to characterise photovoltaic voltage generation with temperature at various periods of the day.

2. The Experiment

In this work, comparative studies of the open circuit voltages of two mono-crystalline photovoltaic modules have been carried out. One of the modules was left uncooled while an air-conditional system (AC) was employed to cool the other. A double pass system was created which allowed for the cooling of the top and bottom surfaces of the module by the AC. The experiments were conducted outdoor under the same atmospheric condition in Kaduna, Nigeria. The experimental setup shown in figure 1a and 1b were designed to investigate the effect of ambient temperature on the open circuit voltage, and also to compare the performances of the AC cooled and uncooled modules at various periods of the day. Two mono-crystalline solar modules each rated 9 Volts, were used in the experiments. An inlet and outlet flow paths were designed to control the cooled air flow distribution on top and bottom of the module, thereby reducing the heat build-up and the module cell temperature. In each of days the experiment was carried out, the work lasted for a period of 8 hours (9am – 5pm). The ambient temperature, module surface temperatures and voltages for the cooled and uncooled modules were recorded every 10 minutes using thermocouples and voltmeters respectively. Photographs of the experimental setup are given in figure 2.

3. Temperature effect

The effect of temperature on photovoltaic cell has been shown to have maximum negative effect on the open circuit output voltage of the cell. Increase in temperature reduces the intrinsic band gap of the semiconductor to decrease the open circuit voltage. Higher voltage is generated as the temperature drops and, conversely, lower voltage is generated at high temperature. One study [12] has gone a step further to express the open voltage in terms of cell temperature and some other parameters as shown in equation below.

$$V_{oc} = \frac{E_g}{q} - \frac{nkT}{q}\left(\ln\frac{I_{0\ max}}{I_{sc}}\right)$$

Where Voc is the open circuit voltage, Eg is the energy band gap and it in, q is electron charge, n is the ideality factor, k is the Boltzmann's constant, T is temperature, Isc is short circuit current and I_(0 max) maximum reverse saturation current. Temperature affects the photovoltaic power output P= I_(sc)* V_oc and also forms part of the reason for efficiency drop of the photovoltaic module.

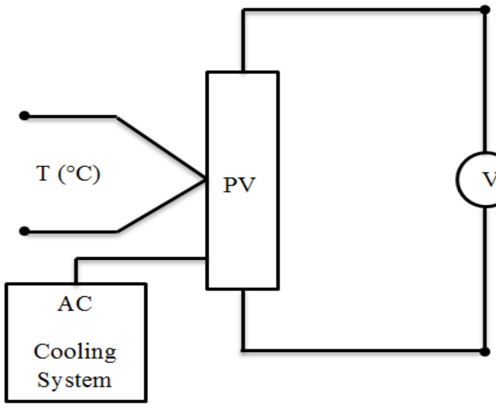

Figure 1(a): Schematic representation of cooled module

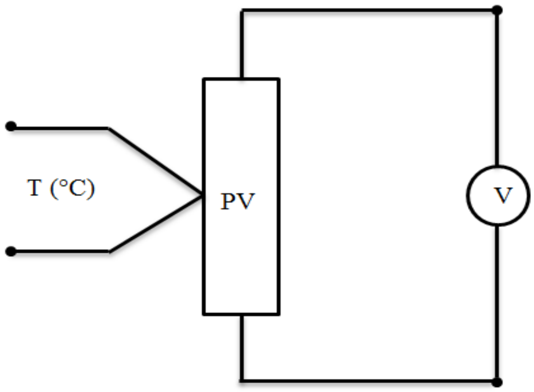

Figure 1(b): Schematic representation of uncooled module

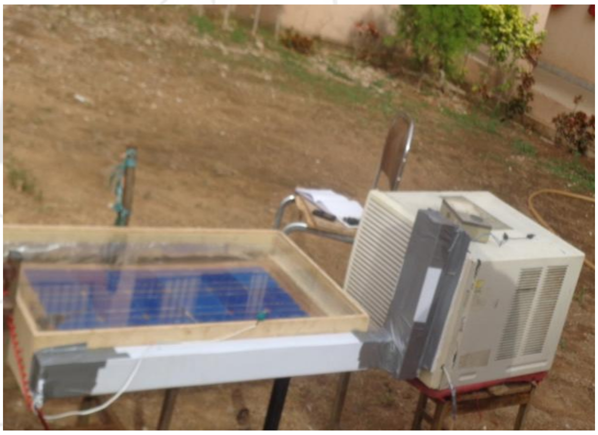
Figure 2: Cooled module

4. Results and Discussion

The temperature and voltage time profile for the cooled and uncooled system for different period of the day, under the same meteorological condition are presented in the figures 3 to 8. Data for the morning period, 0900 to 1159 hours are plotted in figures 3 and 4. Figures 5 and 6 are for the afternoon data and this covers the period 1200 to 1459 hours. The last two figures 7 and 8 are for the evening period, 1500 to 1700 hours. In each of these figures, the curves for ambient temperature, module temperature and module voltage are plotted against the time of the day for both cooled and uncooled experimental rigs.

In the morning period, as would be expected, the module temperature for the uncooled module is always higher than that of the cooled rig. For each of the modules, the temperature rises from a low level to peak at 1159 hours. The module voltage in each case, falls as the morning progresses. The fall in module voltage is more pronounced for the uncooled setup compared with the cooled. In other words, the voltage generated by cooled module at any given time is always higher than that of the uncooled module. The ambient temperature at any given time is the same in the two cases.

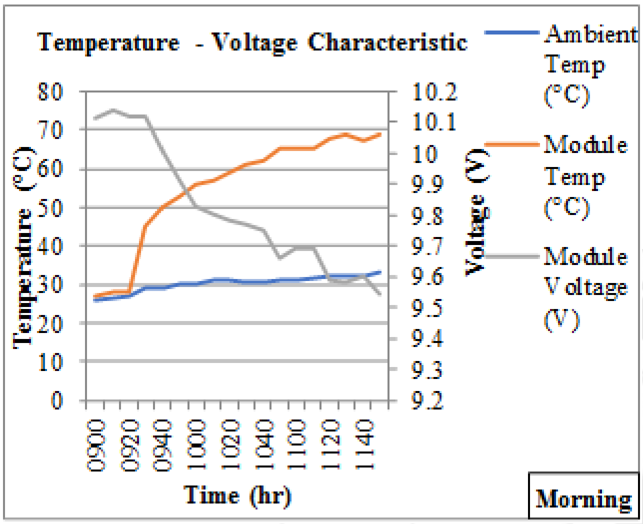

Figure 3: Cooled module voltage and temperature time characteristic for morning

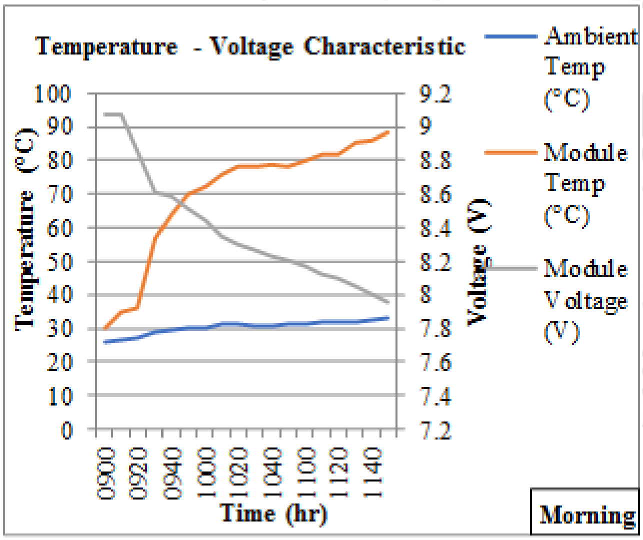

Figure 4: Uncooled module voltage and temperature time characteristic for morning

The module temperature peaks within the afternoon period, 1200 to 1459 hours and correspondingly, the net voltage generated by each of the modules is lowest within this period. In particular, for the uncooled module, a deep trough is formed roughly between of 1300 to 1400 hours when the sun is most intense in Kaduna, the location. The spikes vividly shown in fig. 5 can be related and explained by the sun being temporarily overcast by cloud. This low in voltage generation in the afternoon period can further be explained in a physical sense by the randomness in electron movements whose net effect is reduced voltage generation

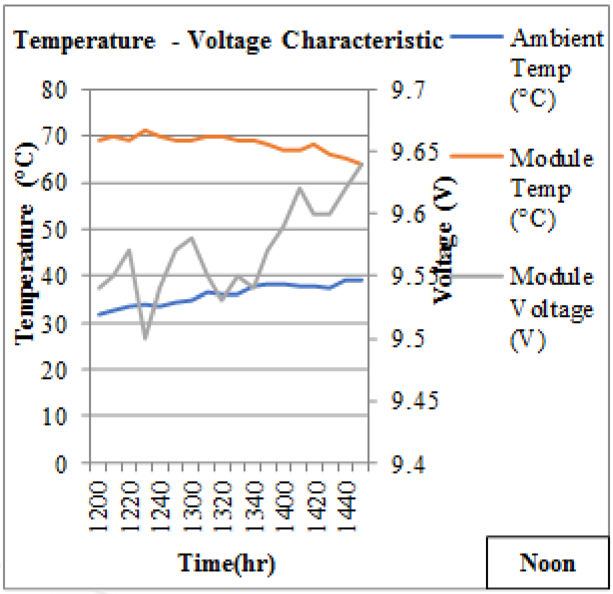

Figure 5: Cooled module voltage and temperature time characteristic for noon period

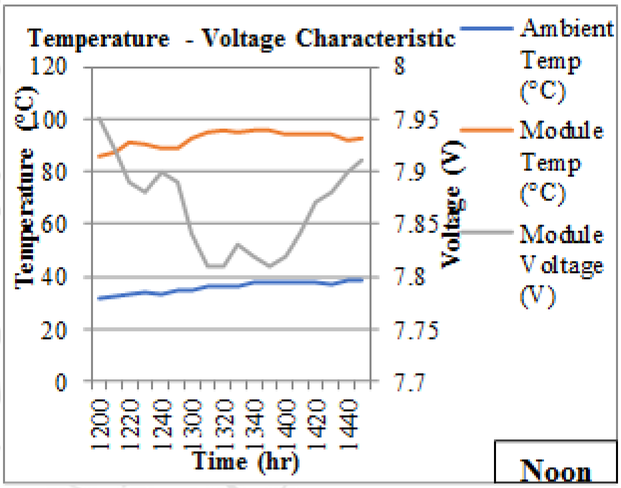

Figure 6: Uncooled module voltage and temperature time characteristic for noon period

In the evening period, figures 7 and 8, as the intensity of the sun decreases, the ambient and hence module temperatures are correspondingly reduced to favour enhanced voltage generation. The evening period is characterized by decreasing temperature and increasing generated voltage. The results show that the voltage generation of photovoltaic modules largely depends on module surface temperature. These results are consistent with other studies [3-7] even though different approaches were employed

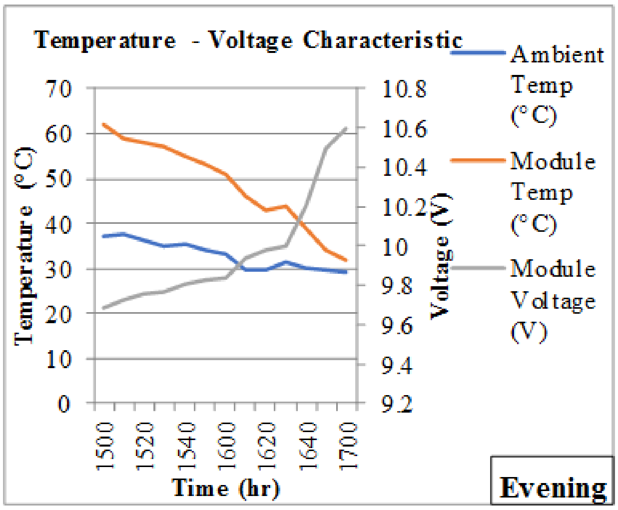

Figure 7: Cooled module voltage and temperature time characteristic for evening period

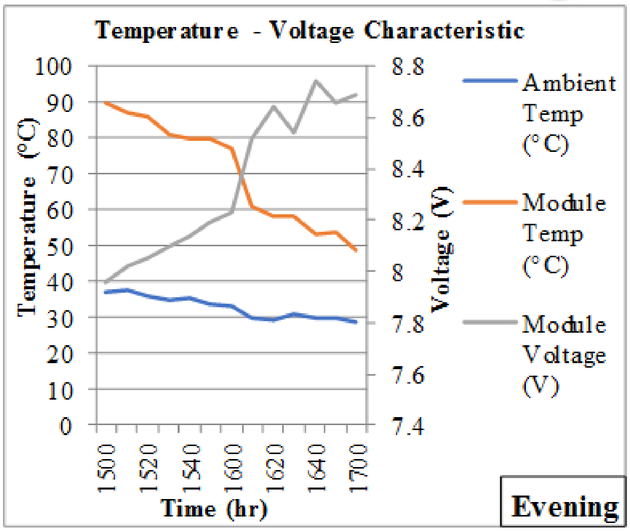

Figure 7: Uncooled module voltage and temperature time characteristic for evening period

5. Conclusion

The voltage generation of the silicon solar module has been studied for various periods of the day. It has been found that for Kaduna, the location, the worst period for module voltage generation is the afternoon. For the morning period voltage generation progressively becomes sluggish as the morning advances. In the evening period, as the intensity of the sun hence ambient and module temperatures decrease, the module voltage generation is enhanced. In all cases, the cooled module voltage generation is higher than the corresponding uncooled module.

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Table 1: Cooled and uncooled module data for morning period

Time (hr)	Ambient Temp (°C)	Uncooled Module		Cooled Module	
		Module Temp (°C)	Module Voltage (V)	Module Temp (°C)	Module Voltage (V)
0900	26	30	9.07	27	10.11
0910	26.3	35	9.07	28	10.14
0920	26.8	36	8.86	28	10.12
0930	28.8	57	8.61	45	10.12
0940	29.2	64	8.58	50	10
0950	30	70	8.51	53	9.91
1000	30	72	8.44	56	9.83
1010	31	76	8.35	57	9.8
1020	31	78	8.3	59	9.78
1030	30.5	78	8.26	61	9.77

1040	30.5	79	8.23	62	9.75
1050	31	78	8.21	65	9.66
1100	31	80	8.17	65	9.69
1110	31.8	82	8.12	65	9.69
1120	32	82	8.1	68	9.59
1130	32	85	8.05	69	9.58
1140	32.2	86	8	67	9.6
1150	33	88	7.95	69	9.54

Table 1: Cooled and uncooled module data for noon period**Error! Not a valid link.**

Table 1: Cooled and uncooled module data for evening period

Time (hr)	Ambient Temp (°C)	Uncooled Module		Cooled Module	
		Module Temp (°C)	Module Voltage (V)	Module Temp (°C)	Module Voltage (V)
1500	37.2	90	7.96	62	9.68
1510	37.5	87	8.02	59	9.73
1520	36.2	86	8.05	58	9.76
1530	35	81	8.1	57	9.77
1540	35.5	80	8.14	55	9.81
1550	34	80	8.19	53	9.83
1600	33	77	8.23	51	9.84
1610	29.8	61	8.52	46	9.94
1620	29.5	58	8.64	43	9.98
1630	31.2	58	8.54	44	10
1640	30	53	8.74	39	10.2
1650	29.8	54	8.66	34	10.5
1700	29	49	8.69	32	10.6