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ANALYTICAL MODEL FOR BLOCKING ULTRAVIOLET RADIATION ON PHOTOVOLTAIC MODULE

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A photovoltaic (PV) system uses sunlight to produce electrical energy. The ultraviolet (UV) part of sunlight has a large amount of energy that ultimately causes a decrease in the PV module's life due to degradation of the encapsulant, increases cell temperature, and ultimately reduced the PV module's efficiency. This research proposes an analytical model/framework to reduce the adverse effects of UV radiation by blocking its incidence on PV modules using UV filters. For verification of the model, experimental results are also included in this paper. In the experiments, PV modules are saved from UV radiations by placing a transparent acrylic sheet over them, along with a coating of commercially available varnish. In this way, the PV module only receives visible and IR radiations. The results show a 4.6 % reduction in cell temperature by blocking UV radiations. So due to this less exposure to UV radiations on the PV module, the panel's life is increased along with the reduction in each cell's temperature. This research work is very helpful in increasing the life and performance of PV modules.

1. INTRODUCTION

After the energy crises, the environmental issues (emission of carbon by greater use of fossil fuel produce greenhouse effect which causes global warming) have become a major problem [1]. To resolve the problem of energy crises as well as to mitigate environmental pollution, there are alternate or renewable energy resources [2,3] and now more emphasis is on re-engineering, *i.e.*, converting existing systems into more feasible and efficient forms. In this context, photovoltaic (PV) systems are gaining the interest of researchers and becoming a competitive solution in various ways [4–6]. Due to the photovoltaic effect, the solar spectrum directly converts into dc electricity through the photovoltaic cell. According to the relation $E = hc/\lambda$, among three components of the solar spectrum, *i.e.*, ultraviolet (UV), visible, and infrared (IR), only visible radiation majorly takes part to make the electrons jump from the valence band to the conduction band without dissipating energy as heat, although infrared (IR) due to long-wavelength do not take much part while shorter wavelength, *i.e.* ultraviolet has a high amount of energy, some amount of photon energy use to drive a current while other dissipate as heat that degrades PV module and also creates an adverse effect on efficiency.

As temperature and efficiency are inversely proportional to each other in PV modules, therefore, UV is harmful and creates adverse effects on the efficiency and life of PV modules [7]. By increasing temperature, open-circuit voltage reduces that causing a decrease in efficiency [8]. The polymeric encapsulant of crystalline silicon solar cell degrades due to more exposure to UV radiation which causes a decrease in power [9,10]. Due to the aging of the encapsulant, the transmittance reduces by 2-5 % [11].

Different methods have been adopted to overcome heat loss, as it increases solar cells' temperature. This causes a change in the current, but a major loss in voltage [12].

In one of the approaches, published in 2013, the researchers presented a method to improve the performance of PV panels by water cooling, when temperature increases [13]. A cooling system was developed to cool down the PV panels to their normal operating temperature, *i.e.*, 35 °C.

In another paper, research work was presented regarding the assessment of long-lasting deterioration of modules and identifying defects that may possibly occur by the visual inspection (VI) method. PV modules' average annual power degradation rate is about 1.5 %. The V-I curve helps in discovering several reasons for failures in PV modules like burn marks, delamination, and cracking however discoloration of encapsulant was the leading mode of degradation [14].

In [15], a solar cell cover was introduced which consists of a substrate that transmits the solar region through which the solar cell not only responds but also suppresses low order reflection by using the multi-layer infrared reflecting coating.

In another work, the encapsulant material and other devices were discussed which consists of a high molecular weight polymeric material, a curing agent, an inorganic compound, and a coupling agent. Optional elements include adhesion-promoting agents, colorants, antioxidants, and UV absorbers due to which it is more beneficial to block moisture entrance to the PV module [16].

Furthermore, research work revealed that UV radiation decomposes ethylene-vinyl acetate (EVA) encapsulant that leading to surface corrosion rate [17]. This corrosion is demonstrated in the research work by using the yellowness index (YI) that shows major absorption of irradiation and leads to the high operating temperature of the PV modules, which in response, speeds up the deterioration process, and lowers the efficiency of PV modules [18]. In this regard, scientists have been working on encapsulants having better antioxidants and ultraviolet (UV) absorbers that overcome these problems [19,20] and do not turn yellow over the lifetime of a module [21,22], but most PV modules available / installed facing same issue of degradation due to UV radiation.

Of the above-discussed papers, none provide an easy and low-cost solution to save PV modules of all types mainly for already installed systems from ultraviolet radiations. In this research work, this problem is being addressed and a simple & cheap solution is being presented. This solution can be used on PV modules, installed in any part of the world. A very small part of this analytical model has been published [23].

This paper is divided into seven sections. The strategy to block UV radiation is discussed in section 2, while the analytical framework is presented in section 3. The analytical and experimental results are presented and discussed in sections 4 and 5 respectively while their comparison with each

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other and published work is presented in section 6. All the conclusions are summarized in section 7.

2. BLOCKING OF ULTRAVIOLET (UV) RADIATIONS

The mechanism used for blocking UV radiations is being discussed in this section. Figure 1 shows the blocking strategy of UV radiations presented in this paper. In this paper, a simple solution to reduce the degradation of PV modules due to UV radiation exposure is presented. PV modules are being saved from UV radiations by placing a transparent acrylic sheet over it, coated with a translucent coating of varnish (GENC) as it absorbs UV radiations. In this way, the PV module only receives visible and infrared (IR) radiations.

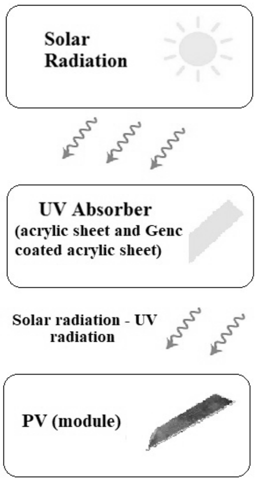

Fig. 1 – Block diagram of UV cancelation on PV module.

UV radiations are being blocked with the help of an acrylic sheet, varnish (GENC) coated acrylic sheet, and various parameters like current, voltage, and light intensity, *etc*. are determined. To know the effect of the sheet, all parameters are calculated and measured without placing any sheet. The aim of this research work is to analyze the performance of PV modules via ultraviolet cancellation.

The experimental setup is comprised of a PV module (20 W), solar meter, UV meter, acrylic sheet (3 mm thickness), varnish (GENC), variable PV module stand, and inclination angle measuring device that is important to check the angle of inclination of the module for irradiance on a particular site.

The measurements are taken in three steps. In the first step, the PV module's output is measured, while in the second part, an acrylic sheet of 3mm thickness and (4 ft. x 4 ft.) size is placed over the PV module and the output is measured. Similarly, the output is again measured in the third step by placing a UV blocker (GENC) coated acrylic sheet over the PV module. All these steps are being processed simultaneously.

3. ANALYTICAL FRAMEWORK

This research is focused on reducing the cell temperature by shielding UV radiations [24] as the energy of UV radiations is dissipated as heat and affects the performance of the PV module rather than inducing power. This objective can be achieved by using different UV stabilizers and filters. UV filters are chemical compounds that either absorb or reflect UV radiations to preserve materials [25].

In this section, an analytical model for calculating the PV module's output after blocking UV radiations is presented. In Figure 2, the analytical framework is illustrated. The framework requires the PV module's specifications at STC (standard test conditions), NOCT (nominal operating cell temperature), and solar data that can be taken from NREL (National Renewable Energy Laboratory) website [26] the countable data is the temperature (T) and global radiation which is the sum of direct and diffuse radiation (G). The ultraviolet radiation part (UV_R) is subtracted from total irradiance (G), *i.e.*, equals to irradiance without UV radiations (G_{WUV}), and is being used in the equations taken from [27].

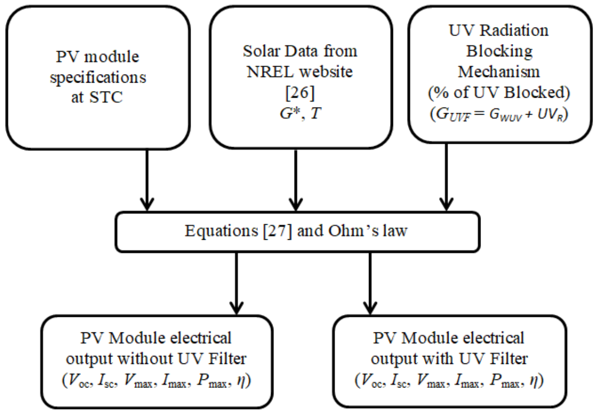

Fig. 2 – Framework for measuring the electrical output of PV module after blocking UV radiations.

*Albedo part is not included in G.

The equations of the PV Full Characteristics model [27] using datasheet values at NOCT and STC for calculations of PV module electrical output without UV filters such as short circuit current (I_{sc}) and open-circuit voltage (V_{oc}) under varying conditions of global irradiance (G) and ambient temperature (T) that taken from NREL data

$$I_{SC}(G,T) = I_{SC} \times \frac{G}{G_{STC}}\left[1+\delta I_{SC}\left(T-T_{STC}\right)\right], \quad (1)$$

where G_{STC} is irradiance and T_{STC} is the temperature at the STC, I_{SC} is the short circuit current, δI_{SC} is the temperature coefficient at short circuit current available in the datasheet of the 20 W PV module

$$V_{OC}(G,T) = V_{OC}\left[1+\delta V_{OC}^{G}\left(\ln(G)-\ln(G_{STC})\right)\right]\cdot \cdot\left[1+\delta V_{OC}^{T}\left(T-T_{STC}\right)\right], \quad (2)$$

where V_{OC} is the open-circuit voltage, δV_{OC}^{T} is the temperature coefficient at open-circuit voltage, and δV_{OC}^{G} is the irradiance correction coefficient that is calculated by putting the values from the data sheet in the given equation as,

$$\delta V_{OC}^{G} = \frac{\dfrac{V_{OC}(G,T)}{V_{OC}\left(1+\delta V_{OC}^{T}\left(T-T_{STC}\right)\right)}-1}{\ln(G)-\ln(G_{STC})}. \quad (3)$$

Now eq. (1) and (2) for UV blocking analytical work are used by replacing G with G_{UVF}, *i.e.*, the solar irradiance after UV filtration in realistic grounds in given eq. (4) and (5)

$$I_{SC}(G,T) = I_{SC} \times \frac{G_{UVF}}{G_{STC}}\left[1+\delta I_{SC}\left(T-T_{STC}\right)\right], \quad (4)$$

$$V_{OC}(G,T) = V_{OC}\left[1+\delta V_{OC}^{G}\left(\ln(GUVF)-\ln(G_{STC})\right)\right]\times \times\left[1+\delta V_{OC}^{T}\left(T-T_{STC}\right)\right]. \quad (5)$$

G_{UVF} is simply calculated by irradiance balance equation, *i.e.*, generated for the analytical calculation of global irradiance after UV filtration,

$$G_{UVF} = G_{WUV} + UV_R, \tag{6}$$

where G_{WUV} is the irradiance without a single part of UV radiations calculated G_{UV} is total UV radiation present in global irradiance, *i.e.*, 5 % to 10 % [26], subtracted from G global irradiance,

$$G_{WUV} = G - G_{UV}, \tag{7}$$

Although it is not possible to block UV radiation completely, therefore some part is still passing the UV filter which is represented as UV_R, *i.e.*, the remaining part of UV radiation after the UV blocking filter.

$$UV_R = G_{UV} - (UV_B)(G_{UV}), \tag{8}$$

where UV_B is a blocked part of UV radiation by a UV blocking sheet.

The calculation of output power is done by using the maximum Power equation [7] by putting values of short circuit current (I_{sc}) and open-circuit voltage (V_{oc}) under varying conditions of global irradiance,

$$P_{\max} = FF \times V_{OC}(G,T) \times I_{SC}(G,T), \tag{9}$$

where FF is the fill factor of the PV module [7],

$$FF = \frac{I_{mp} \cdot V_{mp}}{I_{SC} \cdot V_{SC}}. \tag{10}$$

To calculate cell temperature (T_{cell}) of PV module [7] without UV filter, the general equation is used as,

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20^{\circ}}{0.8}\right) G, \tag{11}$$

where T_{amb} is ambient temperature and NOCT is nominal operating cell temperature.

For UV blocking, this equation can be transformed by replacing G with G_{UVF},

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20^{\circ}}{0.8}\right) G_{UVF}, \tag{12}$$

where the temperature is in °C and G_{UVF} (irradiance) is in kW/m^2 after UV filtration.

The efficiency of the PV module is given by,

$$\eta = \frac{P_{\max}}{G_{UVF} A}, \tag{13}$$

where G_{UVF} can be replaced by G for calculations of PV module (*i.e.*, without UV filter).

4. ANALYTICAL RESULTS

The results of PV modules with and without UV filters/absorbers are discussed in this section. The results are calculated using the equations presented in section 3. Each graph presented in this section comprises three plots; first, when there is nothing placed between sunlight and PV module, second, after placing a transparent acrylic sheet and third, when GENC (commercially available UV absorber) coated acrylic sheet is placed between sunlight and PV module. With these three plots in each graph, it is easy to observe the behavior of various parameters with and without UV radiations.

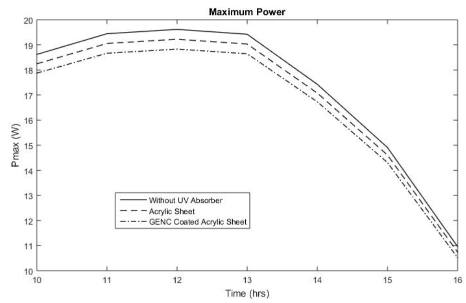

Fig. 3 – Maximum with and without UV absorbers, for one day.

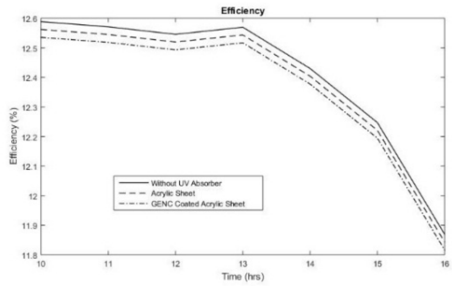

Fig. 4 – Efficiency with and without UV absorbers, for one day.

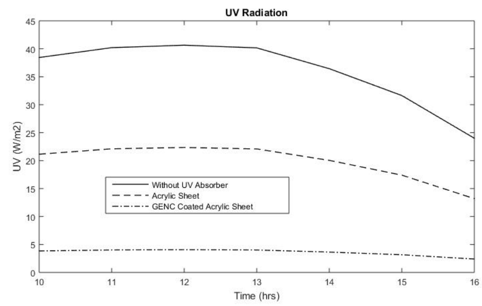

Fig. 5 – UV radiation with and without UV absorbers, for one day.

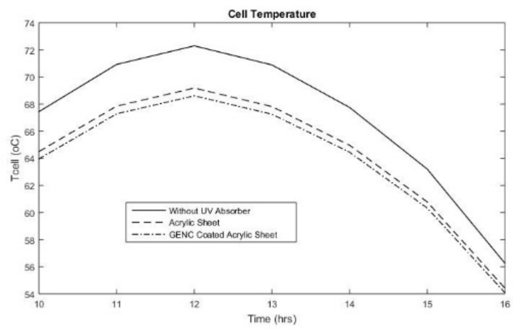

Fig. 6 – Cell temperature with and without UV absorbers, for one day.

Figure 3 shows the graph of output power (P_{max}). This graph shows a reduction in power by about 4 % as it is directly proportional to irradiance [7]. Power is decreased due to filtration of UV radiation as its 36 % of energy contributes to the production of electrical power [29].

In Fig. 4, a maximum reduction of about 0.4 % in the efficiency of the solar panel is observed due to the use of UV filters.

Figure 5 is the graph between UV radiation and time, with and without using a UV absorber. The graph shows 90 % blocking of UV radiation on PV module by using GENC coated acrylic sheet that reduces 4.6 % cell temperature, as shown in Fig. 6.

5. EXPERIMENTAL RESULTS AND DISCUSSION

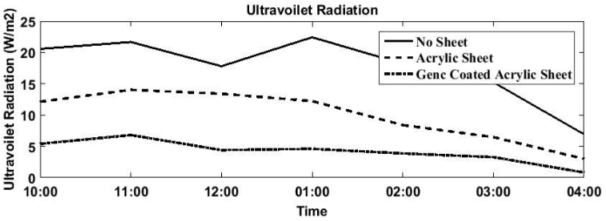

Fig. 7 – Ultraviolet (UV) radiations for no sheet, acrylic sheet and GENC coated acrylic sheet.

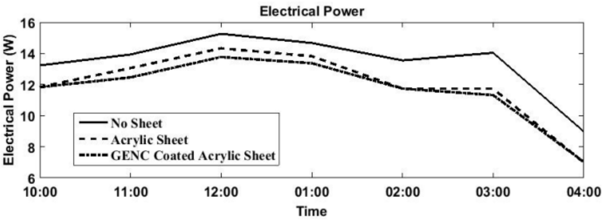

Fig. 8 – Electrical power for PV module with no sheet, acrylic sheet and GENC coated acrylic sheet.

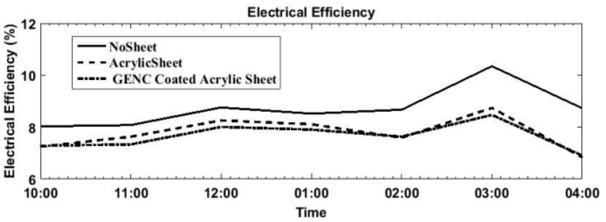

Fig. 9 – Electrical efficiency versus time plot for PV module with no sheet, acrylic sheet, and GENC coated acrylic sheet.

The experimental results are presented and discussed in this section. Each result is shown for three different scenarios which are highlighted in the previous section.

From Fig. 7, it is quite clear that without using any sheet, the PV module is exposed to more UV radiation, which reduces 43.3 % (average) due to the use of acrylic sheets and 76.24 % due to the use of GENC coated acrylic sheets. These experimental measurements of UV radiations are being done using a commercially available UV meter.

The electrical power and efficiency of the PV module for already defined three scenarios are shown in Fig. 8 and 9 respectively. It is noticed in both these graphs (Fig. 8 and 9) that the electrical power and efficiency of an unblocked PV module is always a little higher than its power, the life of the PV module will increase due to its counterparts. The average electrical power of UV blocked PV module is 11.93 W and 11.64 W using acrylic sheet and GENC coated acrylic sheet respectively, while 13.38 W is the average power of unblocked PV module.

Similarly, the electrical efficiency of UV blocked PV module is 7.78 % and 7.65 % using acrylic sheets and GENC coated acrylic sheets respectively, while that of unblocked PV modules is 8.73 % with the compromise of efficiency reduction in exposure of UV radiations on the module. It must be noted that on average 76 % of UV radiations are being blocked in this experiment. This less exposure to UV radiations will certainly contribute to maintaining PV module performance. All the experimental results are based on one-day measurements, taken in Karachi (Pakistan) and the irradiance data is taken from National Renewable Energy Laboratory (NREL) USA's website [26].

6. RESULTS COMPARISON

In this section, the comparison of analytical and experimental results is discussed to verify the analytical framework. Comparisons of analytical and experimental results of PV module for three different scenarios are being summarized in Table 1 which shows that UV radiations decrease with the use of acrylic sheets and GENC coated acrylic sheets, using both analytical and experimental approaches. Therefore, this decreases in UV radiations over the PV module not only increases the PV module's life by decreasing the aging of the encapsulant [11] but also reduces cell temperature.

Overall results are found to be the same, although there is a difference between the values due to environmental effect is not considered in an analytical framework. The measurements are closed to each other which supports the statement regarding the verification of the framework. Hence it verifies that due to the use of UV filters, the power and efficiency of PV modules will reduce.

In addition to analytical and experimental results for the support of the framework, Table 2 is also presented in this paper which shows a comparison of results obtained from the analytical work of this paper with published work [30].

Although the analytical work of this paper is done on a PV module with an acrylic sheet and GENC coated acrylic sheet as two different UV blocking sheets, in [30], published work is done on a single solar cell with two different UV filters that block UV radiations in the range of 320nm and 385nm wavelength at which their percentage transmittance is at 50% of its maximum value [30], but still the trend of reduction in open circuit voltage, maximum power and efficiency are same due to use of UV filters.

Table 1

Comparison of average values of analytical results with experimental measurements.

	Analytical Results			**Experimental Work**			**Difference between Analytical and Experimental results**		
	No sheet	**Acrylic sheet**	**GENC coated with acrylic sheet**	**No sheet**	**Acrylic sheet**	**GENC coated with acrylic sheet**	**No Sheet**	**Acrylic sheet**	**GENC coated with acrylic sheet**
I_{SC} **(A)**	1.07	1.05	1.03	1.07	0.96	0.93	0.00	0.09	0.1
V_{OC} **(V)**	21.16	21.12	21.07	19.75	19.66	19.53	1.41	1.46	1.54
I_{max}**(A)**	0.93	0.91	0.90	0.85	0.76	0.74	0.08	0.15	0.16
V_{max} **(V)**	18.45	18.41	18.37	15.84	15.81	15.75	2.61	2.6	2.62
P_{max}**(W)**	17.20	16.85	16.51	13.38	11.93	11.65	3.82	4.92	4.86
Efficiency (%)	12.40	12.38	12.35	8.73	8.28	7.65	3.67	4.1	4.7
UV radiation (W/m^2)	35.93	19.76	3.59	17.55	9.95	4.17	18.38	9.81	0.58

Table 2

Comparison of average values of analytical results with published results.

	Crystalline Solar Panel [This paper]			**Dye-sensitized Solar Cell [28]**		
	No Sheet	**Acrylic sheet**	**GENC coated with acrylic sheet**	**N719-unfiltered**	**N719-λ320**	**N719-λ385**
V_{OC} **(V)**	21.16	21.12	21.07	0.731 (±0.006)	0.718 (±0.006)	0.720 (±0.004)
P_{max} **(m W)**	17200	16850	16510	3.62 (±0.02)	3.16 (±0.01)	3.14 (±0.01)
Efficiency (%)	17.20	16.85	16.51	4.01 (±0.02)	3.50 (±0.01)	3.47 (±0.01)

7. CONCLUSIONS

Researchers have been working to sustain the market of power generation with renewables. Photovoltaic solar panel, which is a renewable technology, is a competitive solution. UV radiation blocking is one of the topics of research, as UV exposure chemically decomposes the encapsulant and increases the cell temperature. Therefore, in this research work, a simple analytical framework for blocking UV radiations to address both problems is presented. To achieve this task, UV blocker coating (GENC, a commercially available varnish) is being done on a transparent acrylic sheet, placed over the PV module and the measurements are noted. The research is being done using both analytical and experimental approaches and the results are found in good agreement.

UV radiation is blocked 90 % (according to the analytical approach) while 76.24 % (according to experimental results). Due to this blocking, the cell temperature is reduced by 4.6 % by using a UV filter, *i.e*., GENC coated acrylic sheet.

Due to this cancellation of UV radiations, there is a compromise of 4 % output power and 0.4 % efficiency reduction according to analytical results.

The reduction in output power and efficiency looks like a loss, but it is not a failure as the performance of solar panels is being maintained by controlling the cell temperature and preserving deterioration of encapsulant which is due to UV radiation's incidence. This analytical framework contributes to maintaining the performance of the PV module.

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