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On the performance of a polycrystalline PV panel under different impulse voltages and temperatures

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Abstract—***Lightning events are one of the factors that affect performance of a solar power system either by direct or indirect strikes. When lightning strikes directly to a panel, it can affect function and life cycle of the panel. Therefore, considering the electrical performance characteristics such as open-circuit voltage, short-circuit current, and maximum power of the solar panels under high voltage conditions is an important issue. In this paper, the effect of impulse voltage on the change of electrical behaviour of a polycrystalline solar panel is studied. The experimental platform is tested by a lightning impulse generated over a range of 100 kV to 300 kV. The results revealed that as the lightning impulse voltage is increased, the maximum power output gradually decreases. The performance of percentage difference from normal between 100 kV to 300 kV increased to 10.02 % for the maximum power output and the graph showed an increasing non-linear trend. After testing with lightning impulse voltages, the electrical performance of the solar panel under different thermal conditions (temperature) was evaluated in the range of 25 °C to 70 °C and the results are discussed accordingly. When the different temperatures were applied, efficiency of the polycrystalline panel continuously degraded. The percentage difference of the maximum power between samples of 100 kV to 300 kV at 70 °C increased from 2.09 % to 7.11 %.***

Keywords-Lightning impulse voltage, polycrystalline, photovoltaic (PV), temperature, thermal

I. INTRODUCTION

Lightning is an event that transfers charge between a cloud and the earth [1]. As stated in [2, 3], Malaysia faces more than 70 % of power outages due to lightning, and this has led Malaysia to become well known as the "*Crown of Lightning*" in the world since it is located at 2º 30' N and 112º 30' E. Hence, such lightning may cause severe damage, for example to electrical/communication networks and systems, data losses and so on.

Being a tropical country, Malaysia enjoys high possibility of generating energy from the sun that could at least partially supply Malaysia's ever increasing energy demand [4]. Basically, a photovoltaic (PV) panel is mostly known as a device for generating electricity by utilising solar cells to convert the sun's energy into a flow of electrons [5]. Due to this advantage, development of PV systems is rapidly progressing. However, PV panels are fully exposed to natural weather conditions, including various different unpleasant situations. One of the natural conditions is a lightning strike. As researchers have discovered, lightning can cause harm to a structure itself and also to its occupants/contents, including possible failure of a national service or utility organisation as stated in [6].

In addition, there is a high chance of a lightning strike on the PV panel itself, especially in a solar PV farm. Since most of the PV panels/arrays are installed along the rooftop or in outdoor locations, a lightning strike may damage the electronic elements and also the PV panels. The chances of a strike by lightning directly or indirectly are very high [7]. Such a strike can affect function and life cycle of the panels which directly cause panel breakdown or failure [4, 8].

Previous studies have shown that PV panels are degraded by various mechanical, chemical, electrical and thermal stresses. Research work have been conducted in related to the impact of a lightning impulse voltage on various types of electrical degradation such as heat treatment [9] and lightning impulse voltage, with repeated impulse stresses of relatively low peak voltages (15 V, 30 V, and 90 V) [10, 11] etc. By referring to [12], simulation of a direct lightning strike onto the PV panels has been made in laboratories by applying a high magnitude lightning impulse current to PV panels. The outcome indicated that efficiency of the PV panels would be diminished and the panels may physically be damaged by the injection of a high lightning impulse voltage/current.

Other than the direct lightning impulse voltage effect, several recent research approaches have been undertaken with regard to the electrical degradation of PV panels. For example, irradiance, dust, temperature, aging effect, mounting structure, shading such as buildings, trees, clouds, etc., and weather conditions such as rain, snow, wind, etc. [13-19]. As stated in [20, 21], temperature plays a dominant role in the behaviour of PV panels. According to recent research, a normal PV panel tested with high temperatures in the range 25 °C to 70 °C revealed that the performance of the panel was adversely affected by the high temperature [23-25], which led to degraded panel efficiency. Yet, as far the present researchers are aware, in that respect no prior research has thoroughly discussed the effect of temperature on solar panels that have been struck by a lightning impulse voltage.

In this paper, an experiment using lightning impulse voltage was conducted to study degradation of efficiency to PV modules, includes effect of increasing the temperature.

II. POLYCRYSTALLINE PANEL

The panel type studied is a 50 W polycrystalline panel with dimensions of 670 x 550 x 30 mm and a weight of 5.0 kg as presented in Figure 1. The electrical characteristics of this panel are tabulated in Table I.

Figure 1: Polycrystalline PV panel

Table I: Electrical characteristics of the Polycrystalline PV Panel

Parameters	Values
Max Power, P_{max}	50 W
Max Power Voltage, V_{max}	18 V
Max Power Current, I_{max}	2.78 A
Open Circuit Voltage, V_{oc}	21.80 V
Short Circuit Current, I_{sc}	2.97 A

III. EXPERIMENTAL SETUP

Alternatively, depicted that the testing is divided in two parts, namely a lightning impulse voltage test and P, I and V tests. There are six PV panels which a panel selected as a based and other five panels were chosen for lightning impulse voltage test within range of 100 kV to 300 kV. After that, all panels were then taken for P, I and V test. The P, I and V tests are required in order to identify efficiency of the panel after being strike by a lightning impulse voltage and after being put under high temperature.

A. Lightning Impulse Voltage Tests

A generated standard lightning impulse voltage at 1.2/50 µs positive polarity was applied to a rod using an impulse voltage generator. The lightning impulse voltage was applied to surface of the solar panel. The impulse voltage selected was from 100 kV to 300 kV. The experimental setup is shown in Figure 2.

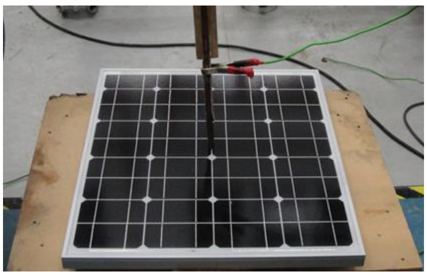

Figure 2: Experimental setup

Figure 3 presents the discharge arc after the lightning impulse voltage has struck the panel.

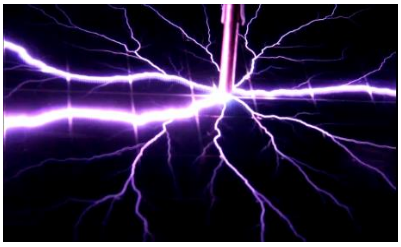

Figure 3: Discharge arc

B. P, I, and V Characteristics Tests

Figure 4 presents a diagram of the measurement of power, current and voltage characteristics using the test box as a replacement for intense sunlight. In this case, the test box consisted of 49 lamps (50 W halogen bulb, 220~240 V) and the size of the box was 0.8 x 0.8 x 1.0 m. The characteristics of the I-V data were evaluated by using a solar analyser.

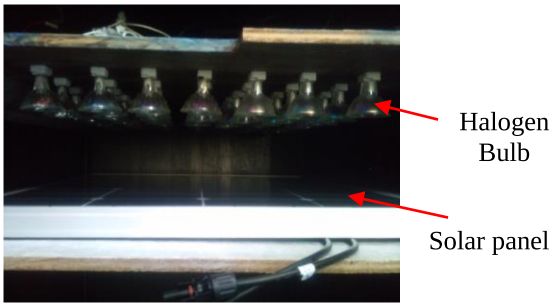

Figure 4: The panel was tested in a test box

Figure 5 illustrates how the panel was tested and the measurement of the data that was collected in the temperature range of 25 °C to 70 °C by using a thermal imaging device.

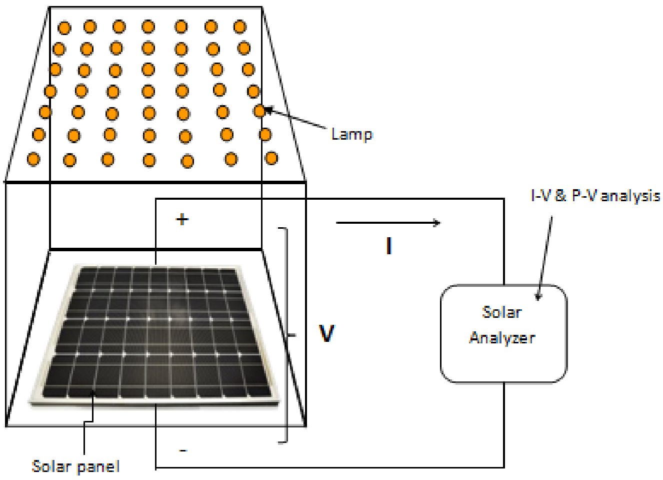

Figure 5: Schematic diagram of measurement of I-V characteristics

IV. RESULTS AND DISCUSSION

Table II presents performance obtained by comparing the data before and after the panel was struck by various lightning impulse voltages. The sample panel was tested under different lightning impulse voltages from 100 kV to 300 kV. Three parameters were recorded during the experiment.

Table II: Data from testing the solar panel sample under different impulse voltages

Parameters	Base	After				
		100 kV	150 kV	200 kV	250 kV	300 kV
V_{oc}, V	21.64	21.50	21.31	21.26	21.24	20.35
I_{sc}, A	1.32	1.35	1.36	1.31	1.29	1.34
P_{max}, W	20.86	20.70	20.56	20.28	19.40	18.77

Note 1: Before = Data of solar panel before being struck by lightning impulse voltage
Note 2: After = Data of solar panel after being struck by lightning impulse voltage
Note 3: V_{oc} = Open-Circuit Voltage
Note 4: I_{sc} = Short-Circuit Current
Note 5: P_{max} = Maximum Power Output

When the impulse voltages were applied, the maximum power output gradually reduces as shown in Figure 6. This power drop indicates that the electrical characteristics of the tested sample have changed.

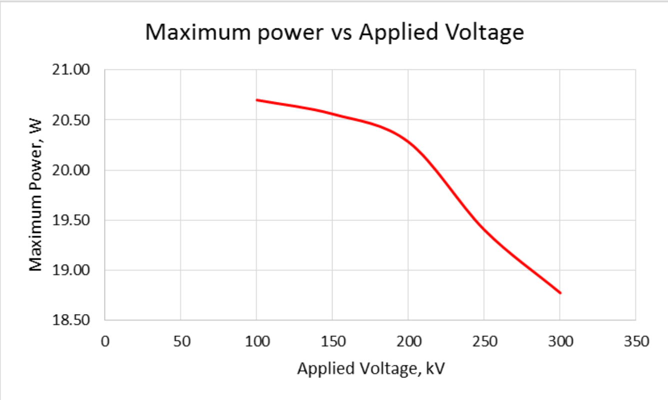

Figure 6: The relation between maximum power output and different applied impulse voltages

Table III illustrates percentage differences of the electrical parameters under different lightning impulse voltages. The percentage difference was calculated using a reference based on the data from the panel before being struck by the lightning impulse voltages. As stated in IEC 61215, the degradation of maximum output power shall not surpass 5 % of the value measured before the test [22]. In this case, after the panel was struck by 300 kV, the reduction percentage of the open-circuit voltage increased to 5.96 % from 0.65 % as well as the maximum power output which increased to 10.02 % from 0.77 % by 100 kV to 300 kV. This percentage change exceeds the maximum 5 % allowed as stated in the IEC standard.

Since the change has exceeded 5 %, performance of the panel is gradually degraded. Therefore, as the lightning impulse voltage is increased, it can worsen the degradation which means both the series resistance increases and the shunt resistance decreases respectively. In other words, the electrical performance is affected as the series resistance increases.

Table III: Percentage difference of each electrical parameter under different impulse voltages

Parameters	% Difference				
	100 kV	150 kV	200 kV	250 kV	300 kV
V_{oc}, V	0.65	1.53	1.76	1.85	5.96
I_{sc}. A	1.89	3.03	0.76	1.97	1.14
P_{max}, W	0.77	1.44	2.78	7.00	10.02

Table IV: Percentage difference of each electrical parameter under different impulse voltages with respect to the original panel results

$V_{impulse, kV}$	Temp. °C	V_{ov}, V	I_{sc}, A	P_{max}, W
100	25	21.5	1.35	21.53
	40	20.82	1.38	21.01
	50	20.30	1.39	20.44
	60	19.75	1.39	19.96
	70	19.16	1.40	19.14
150	25	21.31	1.28	20.56
	40	20.75	1.28	20.60
	50	20.19	1.30	20.07
	60	19.67	1.30	19.57
	70	19.10	1.31	18.83
200	25	21.26	1.28	20.28
	40	20.73	1.29	19.51
	50	20.13	1.31	19.11
	60	19.64	1.31	18.78
	70	18.94	1.31	18.30
250	25	21.24	1.39	19.97
	40	20.72	1.40	19.30
	50	20.10	1.41	18.94
	60	19.65	1.42	18.67
	70	18.92	1.42	18.25
300	25	21.20	1.39	19.71
	40	20.68	1.41	19.16
	50	20.09	1.41	18.88
	60	19.51	1.42	18.55
	70	18.76	1.43	18.16

Figure 7a and Figure 7b illustrate the non-linear trend of the open-circuit voltage and maximum power subjected to the applied voltages (100 kV to 300 kV) by considering the variation of temperature (25 °C to 70 °C). In this case, after the panel was struck by the lightning impulse voltages, the panel was tested under different temperatures to observe effect on the performance of the panel. From this work, the most affected parameter by increasing the temperature was found to be the open-circuit voltage, V_{oc} because of the temperature dependence of I_o as shown in Figure 7a.

$$I_0 = qA\frac{Dn_i^2}{LN_D} \quad (1)$$

where q is the electronic charge, D is the diffusivity of the minority carrier given for silicon, *Si*, L is the diffusion length of the minority carrier, N_D the doping, and n_i is the intrinsic carrier concentration given for *Si*.

According to Equation (1), the temperature sensitivity of a solar panel depends on the open-circuit voltage of the solar cell. As the temperature is increased, the open-circuit voltage is gradually degraded, which can worsen the performance of the solar panel. Meanwhile, the short-circuit current, I_{sc} is gradually increased as the temperature increases. Since the band gap energy, E_G is decreased, the electron pairs can be created as the photons have enough energy.

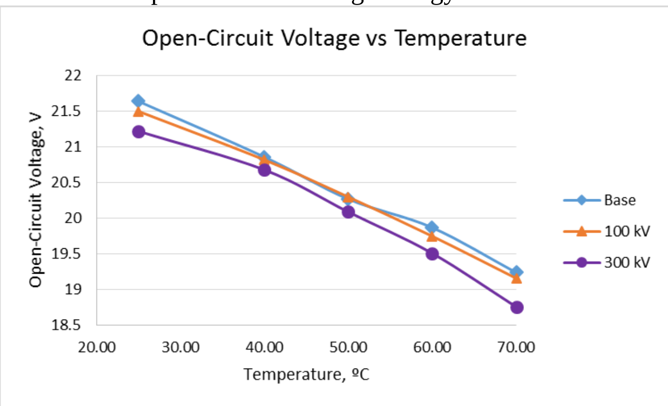

Figure 7a: The relation between open-circuit voltage and different temperatures

Figure 7b shows that the maximum power output decreases as the temperature increases. By considering this effect, it shows that the efficiency of the solar panel is degraded with increasing temperature.

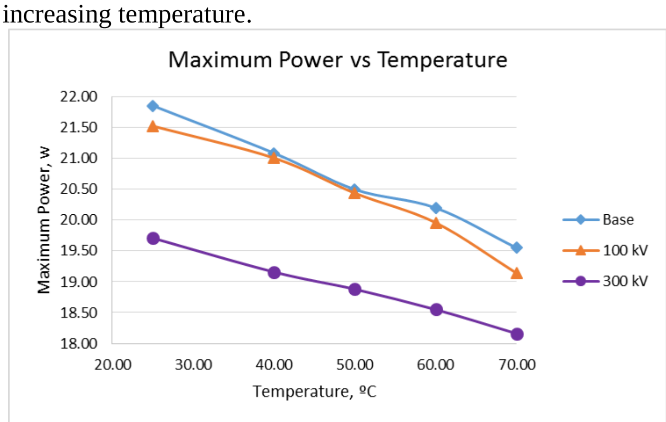

Figure 7b: The relation between maximum power and different temperatures

Table V illustrates the percentage difference for different samples corresponding to different temperatures. In the range 25 °C to 70 °C, as the temperature increases, the open-circuit voltage and maximum power output for the five different impulse voltages decreases. For example, at 45 °C, the percentage difference for the open-circuit voltage increased from 0.87 % (100 kV) to 1.98 % (300 kV). Similarly, the maximum power increased from 0.57 % (100 kV) to 8.55 % (300 kV). It can be seen that the efficiency of the panel when struck by lightning impulse voltages degrades steadily under high temperature.

The following are the details of the calculation:
If the reference temperature is 25 °C, then

$$\Delta\,\% = 100 * \left(\frac{P_{theta} - P_{ref}}{P_{ref}}\right) \tag{2}$$

where; Δ% is the percentage difference, P_{theta} is the value of P_{max} at a certain temperature and P_{ref} is the value of P_{max} at the reference temperature.

$$\Delta\,\% = 100 * \left(\frac{V_{theta} - V_{ref}}{V_{ref}}\right) \tag{3}$$

where; V_{theta} is the Value of V_{max} at a certain temperature and V_{ref} is the Value of V_{max} at the reference temperature.

$$\Delta\,\% = 100 * \left(\frac{I_{theta} - I_{ref}}{I_{ref}}\right) \tag{4}$$

where; I_{theta} is the Value of I_{sc} at a certain temperature and I_{ref} is the Value of I_{max} at the reference temperature.

Table V: Percentage differences of samples with electrical parameters corresponding to different temperature

Temp., °C (±)	% Difference														
	P_1			P_2			P_3			P_4			P_5		
	V_{oc}, V	I_{sc}, A	P_{max}, W	V_{oc}, V	I_{sc}, A	P_{max}, W	V_{oc}, V	I_{sc}, A	P_{max}, W	V_{oc}, V	I_{sc}, A	P_{max}, W	V_{oc}, V	I_{sc}, A	P_{max}, W
25.00	0.65	2.12	1.51	1.53	3.18	5.95	1.76	3.18	7.23	1.85	5.14	8.65	1.94	5.14	9.84
30.00	0.61	3.84	0.28	0.79	3.53	4.78	1.07	3.53	7.58	1.12	3.99	8.20	2.10	4.66	8.24
35.00	0.10	1.87	0.47	0.14	4.34	1.75	0.62	3.89	7.36	0.89	4.11	7.74	1.33	4.34	7.97
40.00	0.19	2.83	0.38	0.53	4.92	2.32	0.62	3.80	7.49	0.67	3.95	8.49	0.86	4.92	9.15
45.00	0.87	3.43	0.57	1.16	3.43	3.10	1.35	2.99	7.55	1.64	4.93	8.26	1.98	5.08	8.55
50.00	0.15	2.82	0.29	0.40	3.64	2.10	0.69	2.97	6.78	0.84	4.68	7.61	0.89	4.68	7.90
55.00	0.79	3.19	0.79	1.19	3.56	2.70	1.24	3.26	6.78	1.49	4.82	7.72	2.28	4.97	7.91
60.00	0.60	3.19	1.19	1.01	3.78	3.12	1.16	3.33	7.03	1.11	4.96	7.57	1.81	5.26	8.17
65.00	0.10	2.88	0.60	0.51	4.06	2.76	0.72	3.32	6.73	0.87	4.72	7.28	1.33	5.17	8.04
70.00	0.42	3.24	2.09	0.73	3.83	3.68	1.56	3.69	6.39	1.66	4.42	6.65	2.50	5.16	7.11

*P_1 to P_5 are the solar panel that strike by lightning impulse voltage from 100 kV to 300 kV

Based on these results, this study found that it is really important to consider points of view from both the technical and economic sides. Due to exposure to a lightning impulse of 300 kV on the solar PV panel, its efficiency showed 10.02 % degradation in electrical performance. The panel was then exposed to high temperature up to 70 °C. The results revealed that the maximum power output of the panel continuously degraded and exceeded 5 % difference from the default performance of the panel. Due to this problem, the developer/industry could possibly encounter losses either in terms of technical or economic issues. If the lightning and temperature problems arise in the field, the power generated would be reduced and may lead directly to a loss in investment. Since solar power is a reliable and independent source of energy that can save society billions and even trillions in capital, the developer/industry should be able to propose several proper forms of lightning protection and planning for installation locations/sites to avoid excessive heat.

V. CONCLUSION

The effect of a lightning impulse voltage on the performance of a polycrystalline panel under different thermal conditions was studied in this paper. Based on the results, a normal PV panel was struck by a lightning impulse voltage of five different voltages (100 kV to 300 kV). The study found that by conducting this experiment, the PV electrical performance was gradually degraded. The maximum power output dropped up to 10.02 % under a 300 kV lightning impulse. Hence it can be said that the higher the voltage stress, the degradation becomes more severe. Subsequently, temperature testing was conducted on the struck solar panel to see the effect of temperature on the electrical characteristics of the polycrystalline panel. Temperature plays a major part as one of the factors that affects the performance of the poly-crystalline solar panel. The results show that the degradation is more severe if the panel is put under high temperature stress. Consequently, this would affect the level of power generated as well as causing economic issues which should be borne in mind by developers and industry when selecting and siting solar panels.

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