

Evaluating DC Voltage Temperature Coefficient of a Multicrystalline Module in Actual Environmental Conditions of Western Rajasthan, India

Shalini Garg
 Government Polytechnic College
 Jodhpur, India

Arun J. B.
 Government Polytechnic College
 Ajmer, India

ABSTRACT

Solar irradiance and cell temperature are the two most important parameters governing the efficiency of PV power plant. This paper presents simultaneous impact of cell temperature and the irradiance falling on the plane of solar panels- POA (Plane of Array Irradiance) on the dc voltage (V_{dc}) of a multicrystalline Photovoltaic (PV) module, one of the most important parameter governing dc power and hence efficiency of (PV) power plant. In contrast to existing literature which specify negative temperature coefficient for V_{dc} above 25°C cell temperature, analysis in actual environmental conditions of Western Rajasthan for a grid connected multicrystalline PV power plant shows that V_{dc} has about -0.431%/°C temperature coefficient for cell temperature greater than 49°C and not 25°C as evaluated in laboratory. Moreover, voltage for cell temperature in the range of 49-60°C is far greater than voltage at 25-45°C. Further at very high cell temperature of about 49°C dc voltage (V_{dc}) reaches a point of saturation attaining 85% of its maximum rated value. It decreases slightly by about 4% as cell temperature increases from 49°C to 60°C but as soon as sun begins to descent, cell temperature starts reducing and V_{dc} starts increasing, maintaining nearly constant value in the range of 80-85% of its maximum rated value for about 6-8 hours. If cell temperature is less than about 45°C, neither V_{dc} reaches point of saturation nor does it attain constant value. Thus, high cell temperature has overall positive effect on dc voltage of a multicrystalline grid connected PV power plant. Western Rajasthan being blessed with high temperature and high insolation for 6-7 hours in a day for about eight months has the capability of high energy yield as dc power is directly proportional to dc voltage.

General Terms

Solar Irradiance, DC output voltage, Grid connected PV power plant

Keywords

Multicrystalline; high cell temperature; temperature coefficient; Plane of Array Irradiance (POA); Western Rajasthan.

1. INTRODUCTION

PV modules are rated at STC conditions that is at, Irradiance-1000W/m²; Module Temperature-25°C; Air Mass-1.5; NOCT (Nominal Operating Cell Temperature) 47°C; Operating Temperature -40°C to + 85°C. Literature and research papers all show negative effect of cell temperature above 25°C [1,2]. The temperature coefficient for both voltage and power is negative and is different for different types of cells. The temperature coefficient of V_{oc} (open circuit voltage)

as specified by the manufacturer for the module used in the analysis is -0.353%/°K for cell temperature greater than 25°C or 298°K as shown in table 1. This means that at cell temperature 30 °C, V_{oc} will be 37.67[1-0.00353*5] that is 37.005V instead of 37.67V as specified at 25°C.

In Western Rajasthan, high ambient temperature about 30-40°C persists for about eight months [3]. This paper illustrates comprehensive study of real field data to analyse the effect of high cell temperature and POA on the dc voltage of a grid connected multicrystalline module and to estimate temperature coefficient for multicrystalline module in real field conditions which is far different from laboratory conditions. The work done is extension of my previous two papers [4, 5]. In previous paper [4] dc voltage was analysed with respect to ambient temperature and GHI (Global Horizontal Irradiance) but results show that V_{dc} has better correlation with cell temperature and POA. The results are significant and consistent with the previous results. The parameters of the module used in the analysis are specified in table 1.

Table 1. The specifications of the multicrystalline PV module at 5 MW grid Connected Power Plant

S. No	Electrical Characteristics	Values
1.	Maximum power P_{mpp}/P_{max}	247.39W
2.	Voltage at P_{max} , V_{mpp}	30.64V
3.	Current at P_{max} , I_{mpp}	8.07 A
4.	Open circuit voltage V_{oc}	37.67 V
5.	Short circuit current I_{sc}	8.26 A
6.	Temperature coefficient of P_{max}	-0.447 %/°K
7.	Temperature coefficient of V_{oc}	-0.353 %/°K
8.	Temperature coefficient of I_{sc}	0.104 %/°K
9.	Power Tolerance	-0 / + 5 W
10.	Fuse rating	15 A
11.	Maximum System Voltage	1000 V
12.	Maximum array voltage	735.36 V (24*30.64)
13.	Maximum array current	161.4 A (8.07*20)
14.	Maximum array power	118.687 KW (735.36*161.4)

2. METHODOLOGY

Based on the real field data, temperature coefficient has been evaluated for extremely high cell temperature which exists during month of May to July, vide data from May 2016 to July 2016 of a 5 MW grid connected multicrystalline PV power plant located at Ramgarh, in district Jaisalmer of Western Rajasthan. To compare the dc voltage at various temperature graphs corresponding to different temperatures have been compiled on a single graph and detail view of December 2015 have also been included, considering overall one-year data over the period of September 2015-August 2016.

2.1 The analysis of dc voltage is based on the average reading of five array with maximum rated dc voltage being equal to 735.36V.

2.2 Simultaneous effect of POA and cell temperature are visualised on the true scale, by diving the entire analyses into two parts-

- With increasing POA as sun rises from about 7:15 to 1:00pm.
- With decreasing POA, as sun begins to decent from about 1:00pm to 5:00pm.

Distinct effects are seen with increasing POA and decreasing POA. VDC-U, AMB-U and CELL-U are the curves for V_{dc} , ambient temperature and cell temperature respectively with increasing POA while, VDC-D, AMB-D, CELL-D are the curves for V_{dc} , ambient temperature and cell temperature respectively with decreasing POA. The short forms are followed by the related date for example VDC-D 13-05-16 means dc voltage with decreasing POA for 13th of May 2016.

2.3 To evaluate temperature coefficient for V_{dc} following assumptions are made-

- Let ΔX represent time duration that is $\Delta X = X_2 - X_1$ where X_1 is the time when V_{dc} attains maximum value (around 10:00am) and X_2 is the time when POA is maximum ~ 1:00pm.
- Let ΔV , ΔPOA , ΔT_c , represent change in V_{dc} , POA and cell temperature respectively with increasing POA in time duration ΔX .
 - $\Delta V = V_2 - V_1$; $V_1 = V_{dc}$ at time X_1 ; $V_2 = V_{dc}$ at time X_2 ;
 - $\Delta POA = POA_2 - POA_1$; ; $POA_1 = POA$ at time X_1 ; $POA_2 = POA$ at time X_2 ;
 - $\Delta T_c = T_{c2} - T_{c1}$; T_{c1} is cell temperature at time X_1 ; T_{c2} is cell temperature at X_2
- Let V_r represent V_{dc} in % with respect to maximum rated dc voltage;
 - $V_r = (V_{dc} / V_{rated}) * 100$.
- Let ΔV_u , represent % change in V_{dc} , with respect to their maximum rated value in the time interval ($X_2 - X_1$) when POA is increasing continuously.
 - $\Delta V_u = \{ \Delta V / \text{maximum rated dc voltage of the array} \} * 100$.
- Let V_a represent Temperature coefficient in %/ $^{\circ}C$;
 - $V_a = (\Delta V_u / \Delta T_c)$

2.4 Weather monitoring station, pyranometer, and SCADA (Supervisory Control and Data Acquisition) is used to record and store various data.

2.5 The irradiance considered is the irradiance incident on the plane of the array- POA

3. EXPERIMENTAL DATA ANALYSIS

3.1 Effect of high cell temperature on V_{dc}

The effect of high cell temperature on V_{dc} has been analysed by considering three different dates of the month having very high temperature for long duration. The time with corresponding POA over the interval when V_{dc} is reducing is marked in figure 1.

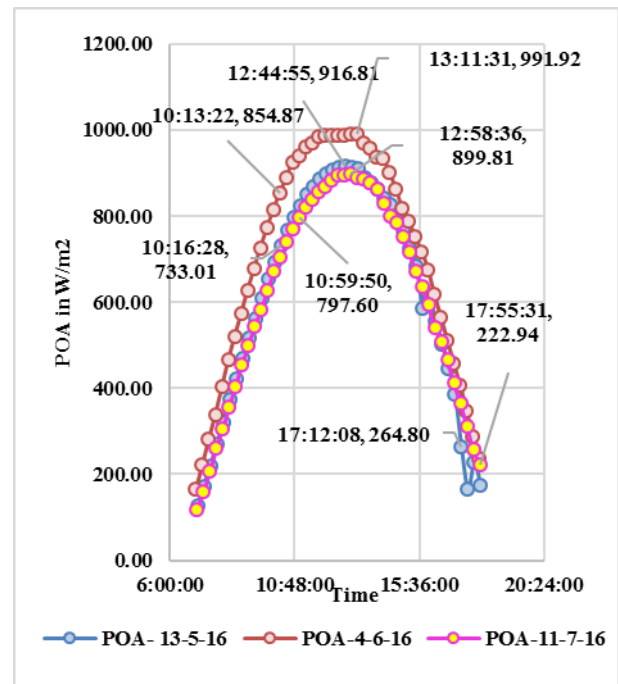


Figure 1- Variation of POA in W/m^2 with time for 13-5-16; 4-6-16; 11-7-16

3.1.1 Analysis for 13th of May 2016

Starting from the wake up voltage as soon as light falls on module, V_{dc} (VDC-13-5-16) drops rapidly as Sun starts rising [6]. This is followed by rapid increase in V_{dc} with increasing POA until ambient temperature is less than 38 $^{\circ}C$ and cell temperature is less than 49 $^{\circ}C$. At this point it attains maximum value nearly 85% of its maximum rated value. Thereafter V_{dc} starts reducing with increasing POA and increasing ambient temperature but as soon as POA start reducing, V_{dc} (VDC-D-13-5-16) starts increasing gradually although ambient temperature (AMB-D-13-5-16) continues to increase as depicted in figure 2. The reason for this is clear from figure 3, which shows that as soon as POA starts decreasing, cell temperature also begins to drop gradually, the result is gradual increase in V_{dc} . Thus, it is evident from figure 2 and 3 that it is the cell temperature which is governing the dc voltage and not the ambient temperature. For all further analysis only cell temperature is considered.

V_{dc} remains constant from the time when POA is 733.01 W/m^2 to when POA drops to 264.80 W/m^2 that is from 10:15 to 17:15 for about six hours as shown in figure 1 and 3.

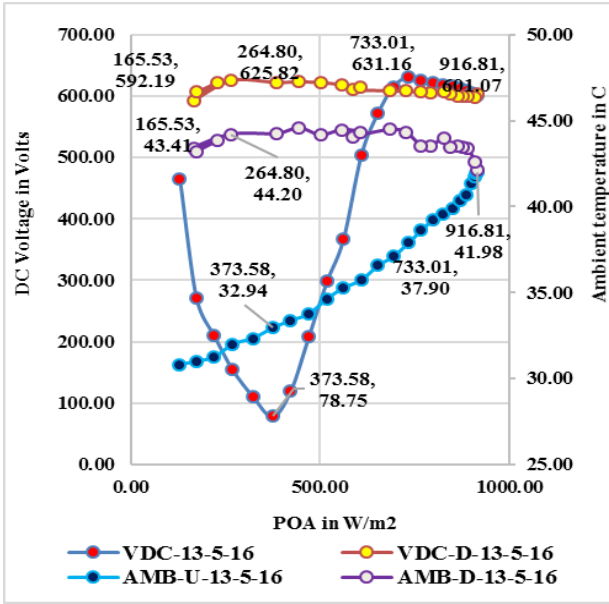


Figure 2- Variation of V_{dc} and ambient temperature with POA for 13-05-16

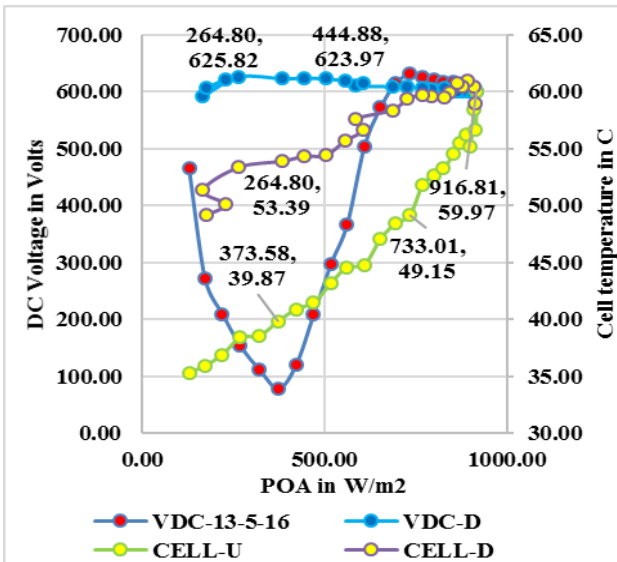


Figure 3- Variation of V_{dc} and cell temperature with POA-13th May 2016.

3.1.2 Analysis for 4th June and 11th July

The results are further verified by considering data for 4th June and 11th July 2016. Dates have been chosen randomly for display otherwise results are almost same for all dates for the month of May, June and July. The graph in figure 4 clearly shows that V_{dc} reduces slightly with increasing POA (VDC-U) as soon as it attains 85% of its maximum rated value but again increases with decreasing POA (VDC-D) that is from 596.04V to 627.88V for 4th June and from 613.57V to 630.21V for 11th July, maintaining nearly constant value for more than 7 to 8 hours.

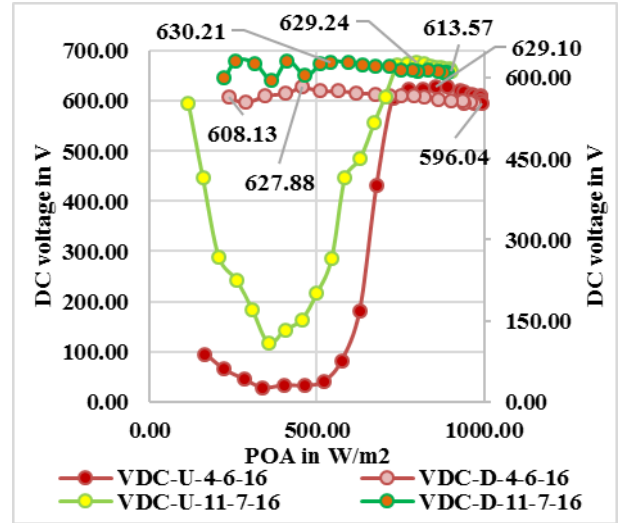


Figure 4- Variation of V_{dc} and cell temperature for 4th June and 11th July with POA

3.1.3 Evaluation of temperature coefficient

Detailed view of figure 4 only for the duration when V_{dc} is decreasing is shown in figure 5 showing that V_{dc} decreases linearly with linear increase in cell temperature with increasing POA for cell temperature greater than 49°C.

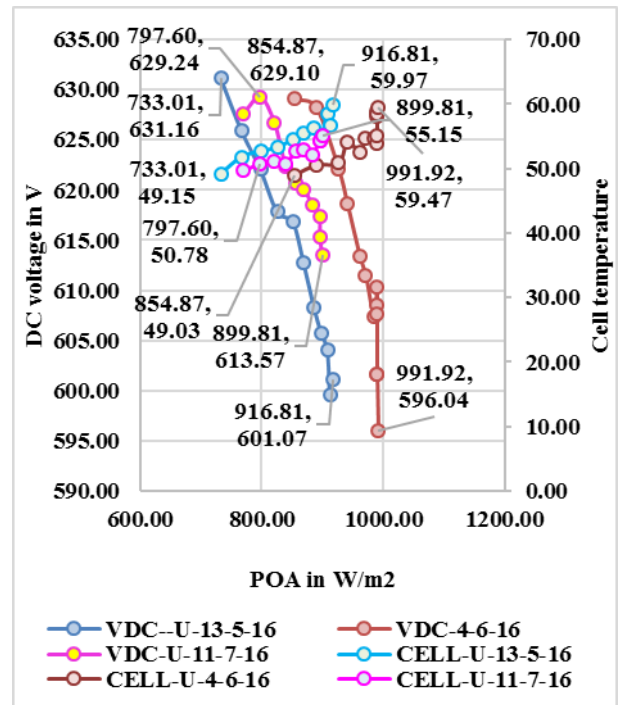


Figure 5- Graph showing detail view of decreasing V_{dc} with increasing cell temperature.

In particular –

- For 13th May- V_{dc} decreases linearly from 631.16V to 601.07V as cell temperature increases linearly from 49.15°C to 59.97°C.
- 4th June - V_{dc} decreases linearly from 629.10V to 596.04V as cell temperature increases linearly from 49.03°C to 59.47°C.
- 11th July - V_{dc} drops from 629.24V to 613.57V as cell temperature increases from 50.78°C to 55.15°C.

The change in dc voltage with the corresponding change in cell temperature is evaluated in table 2. The temperature coefficient is also calculated for real time data as V_{dc} decreases linearly with linear increase in cell temperature. Temperature coefficient, $V_{\alpha} = (\Delta V_u / \Delta T_c)$ for –

- 13th May- $\Delta V_u = -\{(631.16-601.07)/735.36\} * 100 = -4.09\%$; $\Delta T_c = (59.97 - 49.15) = 10.82\text{ }^{\circ}\text{C}$; $V_{\alpha} = -(4.09/10.82) = -0.378\%/^{\circ}\text{C}$;
- 4th June - $\Delta V_u = -\{(629.10-596.04)/735.36\} * 100 = -4.49\%$; $\Delta T_c = (59.47 - 49.03) = 10.44\text{ }^{\circ}\text{C}$; $V_{\alpha} = -(4.49/10.44) = -0.43\%/^{\circ}\text{C}$
- 11th July - $\Delta V_u = -\{(629.24-613.57)/735.36\} * 100 = -2.13\%$; $\Delta T_c = (55.15-50.78) = 4.37\text{ }^{\circ}\text{C}$; $V_{\alpha} = -(2.13/4.37) = -0.487\%/^{\circ}\text{C}$
- Average $V_{\alpha} = (V_{\alpha M} + V_{\alpha j} + V_{\alpha d})/3 = 0.431\%/^{\circ}\text{C}$

Where $V_{\alpha M}$, $V_{\alpha j}$, $V_{\alpha d}$ are the temperature coefficient for specific dates in the month of May, June and July.

Similarly, ΔPOA_a , ΔT_{ca} , ΔV_a , ΔV_{ua} correspond to the average value of ΔPOA , ΔT_c , ΔV , ΔV_u respectively.

- $\Delta POA_a = (\Delta POA_M + \Delta POA_j + \Delta POA_d)/3$
- $\Delta T_{ca} = (\Delta T_{cM} + \Delta T_{cj} + \Delta T_{cd})/3$
- $\Delta V_a = (\Delta V_M + \Delta V_j + \Delta V_d)/3$
- $\Delta V_{ua} = (\Delta V_{uM} + \Delta V_{uj} + \Delta V_{ud})/3$

Table 2- Evaluation of ΔV_u

Date	Time interval	POA in W/m ²	Cell temperature in ^o C	V_{dc} in volts	V_r in %	V_{α} in %/ ^o C
13-5-16	$X_1 = 10:16:28$	$POA_1=733.01$	$T_{c1} = 49.15$	$V_1= 631.16$	85.83	-0.378
	$X_2 = 12:45$	$POA_2=916.81$	$T_{c2} = 59.97$	$V_2= 601.07$	81.73	
	$\Delta X=X_2-X_1 = 2:30\text{hrs}$	$\Delta POA_M = 183.8$	$\Delta T_{cM} = 10.82$	$\Delta V_M = -30.09$	$\Delta V_{uM} = -4.09$	
4-6-16	$X_1 = 10:13:22$	$POA_1=854.87$	$T_{c1} = 49.03$	$V_1= 629.10$	85.56	-0.43
	$X_2 = 13:11:31$	$POA_2= 991.92$	$T_{c2} = 59.47$	$V_2= 596.04$	81.05	
	$\Delta X=X_2-X_1 = 3:00\text{hrs}$	$\Delta POA_j = 137.05$	$\Delta T_{cj} = +10.44$	$\Delta V_j = -33.06$	$\Delta V_{uj} = -4.49$	
11-7-16	$X_1 = 10:59:50$	$POA_1= 797.60$	$T_{c1} = 50.78$	$V_1= 629.24$	85.56	-0.487
	$X_2 = 12:58:36$	$POA_2= 899.81$	$T_{c2} = 55.15$	$V_2= 613.57$	83.36	
	$\Delta X=X_2-X_1 = 2:00\text{hrs}$	$\Delta POA_d = 102.21$	$\Delta T_{cd} = + 4.37$	$\Delta V_d = -15.67$	$\Delta V_{ud} = -2.13$	
Average		$\Delta POA_a = +141.07$	$\Delta T_{ca} = + 8.94$	$\Delta V_a = -26.27$	$\Delta V_{ua} = -3.56$	-0.431

3.2 Effect of comparatively lower cell temperature

To compare effect of high and low cell temperature graphs corresponding to relatively different temperature for the month of October, December, February and April have been compiled in figure 6. In the month of December, November and January the maximum cell temperature is less than 45 ^oC, the result is that V_{dc} does not reach point of saturation and hence does not attain constant value as shown only for the month of December in figure 6. For the month when cell temperature is low, duration for which V_{dc} remains constant reduces as is evident for the month of February in figure 6. As temperature increases both the value of dc voltage and duration for which it remains constant increases correspondingly as is evident from the figure 6 by the gradually increased duration for the month of February, October and April respectively clearly showing overall positive effect of high cell temperature despite slight negative temperature coefficient above 49^oC.

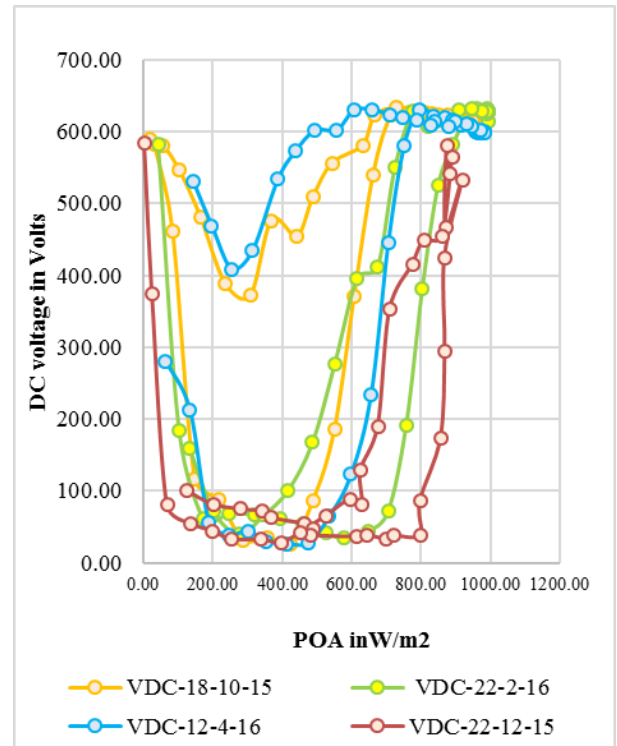


Figure 6- Variation of dc voltage for specific days- October (18th), December (22nd), February (22nd) and April (12th)

3.3 Effect of extremely low temperature

Effect of very low cell temperature in the range of 20-41 ^oC is explained vide figure 7

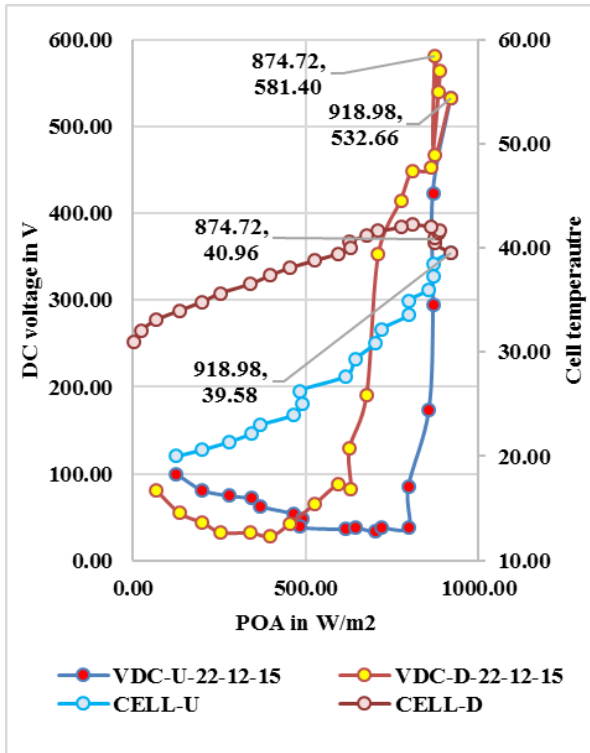


Figure 7- Variation of V_{dc} and cell temperature with POA for 22-12-2015

V_{dc} in the range of 60-75% of its maximum rated value is obtained for very short duration of about two hours. It can be observed that maximum V_{dc} in the month of December is only 581.40V that too only once at cell temperature 41.49°C, POA 874.72W/m², while at POA 918.98W/m², cell temperature 39.5°C, V_{dc} is only 532.66V, clearly showing higher dc voltage at higher cell temperature. Comparing it with month of June much higher dc voltage 629.24V is obtained at cell temperature 50.78 °C and 613.57V at cell temperature 55.15°C. Thus, in contrast to existing literature which shows dc voltage decreases with increase in cell temperature above 25 °C, the analysis of real field data for different temperatures especially for extreme temperatures clearly show positive effect of high cell temperature on a multicrystalline PV module.

4. RESULT

The analysis for three different random days of May, June and July has been shown, although the result is same for all days of these months, except for few days when data is not available either due to grid failure or some other problem. For the month when cell temperature is below 45°C, V_{dc} does not reach saturation and constant value is not maintained. The temperature coefficient is calculated on the basis that there is linear decrease in V_{dc} with linear increase in cell temperature for three different days and the average value of three different days is shown in table 2. With reference to 13th May, as shown in figure 5 and table 2, one can clearly see that V_{dc} decreases linearly from 631.16V to 601.07V as cell temperature increases linearly from 49.15°C to 59.97°C. The corresponding percentage reduction in V_{dc} with respect to maximum rated voltage is $\{(631.16-601.07)/735.36\} * 100 = 4.09\%$; the corresponding increase in cell temperature is $59.97 - 49.15 = 10.82$ °C; the resulting temperature coefficient is $-4.09/10.82 = -0.378\%/^{\circ}\text{C}$ as shown in table 2. Similarly,

temperature coefficient for 4th June and 11th July are $-0.43\%/^{\circ}\text{C}$ and $-0.487\%/^{\circ}\text{C}$ respectively. The average temperature coefficient of three days is $(-0.378+ 0.43 +0.487)/3 = -0.431\%/^{\circ}\text{C}$ for cell temperature greater than 49°C in contrast to 25°C cited in literature. Further environmental conditions vary from place to place and is different in different seasons even at the same place. In Western Rajasthan in summer season(April-July) the cell temperature is as high as 50.78°C even when POA is only 797.60W/m² and reaches about 60°C for POA equal to 992W/m², while in the month of December the cell temperature is only 39.58°C for POA equal to 918.98W/m². It is observed that V_{dc} attains point of saturation only at high temperature. The point of saturation for dc voltage is the point at which V_{dc} attains 85% of its maximum rated value and thereafter maintains nearly constant value within 80-85% even though POA drops to as low as 250W/m². Further V_{dc} at cell temperature 39.58 °C, POA equal to 918.98W/m² is only 532.6V, whereas much higher V_{dc} (629.24V) is obtained at higher cell temperature of 50.78°C, POA 797.60W/m². Slight negative temperature coefficient is observed for cell temperature greater than 49°C, but still V_{dc} even at 60°C cell temperature is far greater than V_{dc} at 25°C showing overall positive effect of high temperature.

5. CONCLUSION

The negative temperature coefficient for V_{dc} calculated for the real field data of a grid connected multicrystalline PV power plant of Western Rajasthan is about $-0.431\%/^{\circ}\text{C}$ for cell temperature greater than 49°C in contrast to 25°C mentioned in literature. Another noteworthy feature is that with decrease in POA, cell temperature also starts reducing, the result is that V_{dc} start increasing, maintaining nearly high constant value in the range of 80-85% of its maximum rated value. DC voltage obtained at high cell temperature 49-60°C is much greater than voltage at 25-40 °C even at lower irradiance, showing overall high cell temperature has positive impact on a multicrystalline module.

Thus, this paper besides evaluating DC voltage temperature coefficient of a multicrystalline module in real field conditions, brings forward a vital fact that PV plant should be operated at cell temperature greater than 45°C to attain dc output voltage in the range of 80-85% of its maximum rated value. As to dc voltage has positive effect at high cell temperature and current has positive temperature coefficient, operating a multicrystalline power plant at high POA and high cell temperature will give higher efficiency. Western Rajasthan has high cell temperature and high irradiance for about 7 hours for more than eight months, high dc voltage (80-85%) for about $(7*8*30 = 1680)$ hours in a year is obtained provided proper grid evacuation is ensured. Thus, Western Rajasthan has the capability to become world leader in the field of solar energy. As further work the temperature coefficient needs to be re-evaluated considering average of all possible values over a period of at least one or five years and effect of high cell temperature on the power output needs to be analysed. Also, analysis for different types of cell in different environmental conditions needs to be done.

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