Effect of Different Dust Accumulation on the Performance of PV Module in Egypt.

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***Abstract*—Accumulation of different dust from the outdoor environment on the panels of solar photovoltaic (PV) system is natural. In Egypt, there are different dust types depending on the environment and location. The objective of this paper is to study the effects of different artificial dust accumulation, included in different regions of Egypt, on the performance of solar PV panels. Experiments were conducted using different artificial dust particles that are uniformly distributed on the surface of PV module. The performance of the used PV module is measured by subjecting it to a constant-power light source. Experimental results showed that the accumulation of dust on the surface of PV module can reduce its efficiency by up to 40% especially in cement-rich regions.**

***Index terms* - PV module, artificial dust, PV performance.**

I. Introduction

In Egypt, solar PV panels are normally mounted on roofs of premises and wide areas. There are many types of solar PV cells available, which are mainly monocrystalline silicon cells, multi crystalline silicon cells, amorphous silicon cells and alternative compound thin-film solar cells. [1].

Energy produced by a PV module deployed outdoors depends greatly on PV materials and solar insolation [2]. Over time, the electrical energy output will decrease, commonly due to causes such as humidity, thermal cycling, ultra-violet radiation, and moisture ingress [3] that lead to some permanent degradation, namely corrosion, discoloration, delamination, and breakage and cracking cells [4]. Besides these internal factors, one environmental factor that significantly reduces the energy produced by a PV module temporarily is dust [3]. The PV performance could be recovered to its maximum capacity by cleaning activities performed manually, automatically and naturally [5].

Deposited dust on a PV module's cover glass diminishes the illumination by absorbing and scattering sun light received by the solar cells [6]. The accumulation of dust on a PV module's surface is different from location to location and depends on the environmental conditions of ambient temperature and humidity, rainfall and wind velocity [7]. Therefore, PV performance degradation caused by dust is not uniform for every region of the world. Adinoyi and Said [8] (2013) found that dust reduces the power output of PV modules by 50% for panels exposed for approximately six months without cleaning in the eastern part of Saudi Arabia. Kalogirou et al.(2013) [8] revealed a 6–13% reduction in power output due to dust recorded in three seasons (spring, winter and summer) in Cyprus. Zorrilla-Casanova et al. (2011)[9] reported that daily energy losses caused by dust in the south of Spain averaged around 4.4% for a year and could increase to more than 20% in dry conditions. Elminir et al. 2006 [10] in their intensive experiments in Egypt found that the energy yield of a PV module decreased about 17.4% per month for south-facing panels at a tilt angle of 45^o. In addition to location, dust accumulation is affected by the PV's tilt angle [8]. Elminir et al. (2006) [10] in their experiments in Egypt reported that the difference of transmittance reduction for tilt angle of 0^o (dust accumulation maximum) and 90^o (dust accumulation minimum) is 21.3%. PV module performance tends to degrade as the amount of dust impinged on its surface increases [11]. In comparing the electrical parameters of two identical pairs of PV modules, it is found that a 1.5% reduction of efficiency was recorded by the accumulation of dust with a density of 0.4 mg/cm^2. Jiang et al. (2011) [10] in an experiment featuring three different PV cell technologies such as monocrystalline silicon (mc-Si), polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) observed that the efficiency of the modules decreases from 0% to 26% as dust deposition increased from 0 to 22 g/m^2.

In addition to dust density, PV performance is also dictated by the properties of dust. Kaldellis et al. (2011) [11] examined the effect of pollutants comprising red soil, limestone and carbonaceous fly-ash particles on module performance. The study revealed that red soil particles contributed the highest reduction followed by limestone and carbon-base ash. Furthermore, Appels et al. (2013) [6] reported that finer dust particles play a more significant role in decreasing power output than larger particles. Different PV technologies respond differently to the adverse effect caused by dust. Ndiaye et al. (2013) [11] compared the electrical output parameters of crystalline PV modules that had been exposed without cleaning for a year in Senegal. The result revealed a more severe power reduction for mc-Si modules (77.75%) than pc-Si modules (18.02%). Moreover, a spectral analysis performed by Qasem et al. (2012) [12] to investigate the effect of dust on PV technologies concluded that dust has a more significant effect on the performance of those PV modules that have a wider spectral response e.g. a-Si. Very little seems to be known about the effect of dust on performance in a long-term study.

This paper introduces an experimental study that evaluates the effects of artificial dust accumulation on the performance of one PV module in different location in Egypt.

II. The PV Model

The PV arrays are built up with series and/or parallel connected combinations of solar cells. A solar cell is usually represented by the equivalent circuit given in Fig.1. Therefore, for an array of $n_s \times n_p$ (i.e., cells in series by panels in parallel) the current equation is [14]

$$I_{PV} = n_p I_{LG} - n_p I_{os}\left[\exp\left(G\left(\frac{V_{PV}+I_{PV}R_s}{n_s}\right)\right)-1\right]-\frac{V_{PV}+I_{PV}R_s}{R_{sh}} \quad (1)$$

Where,

$$G = \frac{q}{A_i\, TK} \quad (2)$$

$$I_{os} = I_{or}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_{G\circ}}{B_i\, K}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right] \quad (3)$$

$$I_{LG} = [I_{sc} + K_{Isc}(T_c - 28)] \times \frac{Rad}{1000} \quad (4)$$

$$I_{PV} = n_p I_{cell} \quad (5)$$

$$V_{PV} = n_s V_{cell} \quad (6)$$

$$R_s = R_{scell}\frac{n_s}{n_p} \quad (7)$$

$$R_{sh} = R_{shcell}\frac{n_s}{n_p} \quad (8)$$

The array temperature T_c is given, approximately, by the relation

$$T_c = T_{air} + 0.3 \times Rad\% \quad (9)$$

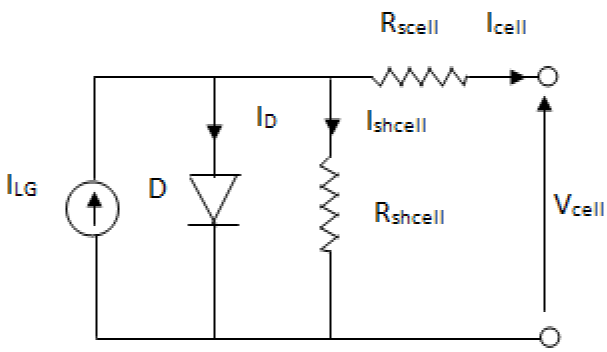
All the symbols in Eqs. (1) – (9) can be defined as

I_{PV} = PV array output current, A
V_{PV} = PV array output voltage, V
n_s = number of cells connected in series
n_p = number of panels connected in parallel
I_{LG} = light-generated current, A
I_{or} = reverse saturation current at
$A_i = B_i$ = ideality factors (= 1.92)
K = Boltzmann's constant (= 1.38×10^{-23} joule/^{o}K)
q = electronic charge (= 1.602×10^{-19} coulomb)
T_r = reference temperature (= 301 ^{o}K)
I_{os} = cell reverse saturation current, A
T_c = cell temperature, ^{o}C
T = cell temperature, ^{o}K
K_{Isc} = short-circuit current temperature coefficient (= 0.0017 A/^{o}C)
Rad = cell illumination, W/m^2 (1000 W/m^2 ≡ 100 % illumination)
I_{sc} = cell short-circuit current
E_{Go} = band gap for silicon (= 1.11 ev)
T_{air} = ambient temperature,^{o}C
R_s = PV array series resistance, Ω
R_{sh} = PV array shunt resistance, Ω
I_{cell} = cell output current, A
V_{cell} = cell output voltage, V
R_{scell} = cell series resistance
R_{shcell} = cell shunt resistance, Ω

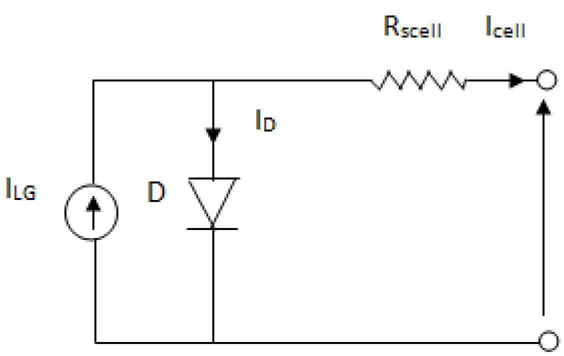
Since the shunt resistance R_{sh} is much greater than the series resistance R_s, the last term in Eq. (3) becomes very small with respect to the other terms. Therefore, the last term will be neglected as it will not cause a large error in the PV array model; hence, Eq. (3) can now be modified to the form

$$I_{PV} = n_p I_{LG} - n_p I_{os}\left[\exp\left(G\left(\frac{V_{PV}+I_{PV}R_s}{n_s}\right)\right)-1\right] \quad (10)$$

Eq. (10) can be represented (for one cell) by the simplified equivalent circuit shown in Fig. 1.



(a) Actual cell model



(b) Simplified cell model

Figure 1. Equivalent circuit models of a PV cell.

A. PV Parameters **[14]**

There are some important parameters that can characterize the PV performance. One of these parameters is the short–circuit current I_{SC} which is simply the generated current Ios. A second parameter is the open-circuit voltage V_{OC} which is obtained by setting I=0 in Eq. (10)

$$V_{OC} = \frac{n_S}{G_o}.\ln\left((1+\frac{I_{LG}}{Ios}) \right) \tag{11}$$

No power is generated under short or open circuit. The maximum power Pmp produced by the device is reached at a point on the characteristics where the product I by V is maximum value. This is shown graphically in Fig. 2, where the position of the MPP represents the largest area of the rectangle. While, the third characterized parameter is the fill-factor FF that is defined as

$$FF = \frac{V_{mp} I_{mp}}{V_{OC} I_{SC}} \tag{12}$$

Where, Vmp and Imp are the voltage and current at maximum power point.

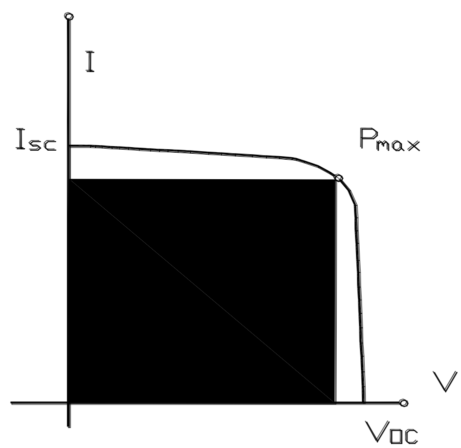


Figure 2. The I-V characteristics of a solar cell with the maximum power point.

The PV module efficiency η is calculated as following equation

$$\eta = \frac{P_{max}}{A_m Rad} \tag{13}$$

Where A_m is the area of module in m^2.

III. Dust Degradation Factor

Accumulations of dust on the surface of PV module glazing reduce strongly the optical transmissivity of the module. Consequently, a corresponding degradation in the module's performance became apparent. Therefore, in order to evaluate for this degradation, the dust degradation factor

International Journal of Advanced Information Science and Technology (IJAIST) ISSN: 2319:2682
Vol.4, No.12, December 2015 DOI:10.15693/ijaist/2015.v4i12.4-11

(DDF) should be estimated for all the PV performance parameters as [15]

$$\%DDF = 100\left[\frac{Fpvc - Fpvd}{Fpvc}\right] \quad (14)$$

Where F_{pvc} is the measured PV parameter for cleaned glazing and F_{pvd} is the measured PV parameter for dirty glazing.

IV. Experimental System

A. System setup

Fig. 3 shows the experimental setup that can be used to study the effects of artificial dust accumulation on the performance of PV modules. Typically, the electrical system is composed of one PV module and a series-connected variable resistance load. The used PV module ARCO SOLAR M25 type that can give 6 Wp at standard test conditions (i.e., 1000 W/m^2 and 25^{o}C). This module contains 9 cells amorphous silicon cells each of 10 cm^2 area connected in series and has a small dimensions of 30cm*55cm*0.02cm; to ensure a uniform distribution of light on its surface. Also, this module is located horizontally to guarantee the uniformity of the distributed dust on its surface.

The experimental system contains, also, a halogen lamp, that is fixed directly overhead of the PV module to simulate the incident solar radiation. This halogen lamp is fixed at a constant distance from the module, such that it can give a constant module's surface temperature of 25^{o}C and a fixed incident radiation of 1000 W/m^2 on the surface of the module. Noting, here, that fixing the module's temperature at 25^{o}C may require some cooling for the module from its rare side; to maintain the uniformity of the distributed dust over the front surface of the PV module. In addition, a digital solar power meter (SPM-1116 SD) is utilized, in the setup, to measure the level of the incident solar radiation on the module and the module surface temperature.

Also, two mustimeters are used in the electrical system to measure the PV voltage and current. Therefore, this setup is able to measure the I-V chartertistics of the considered PV module, and hence it is able to study the effect of dust accumulation on its surface. Noting, here, that this setup was carried out indoor in the Lab to avoid the adverse effects of wind speed, humidity, and rain on the uniformity of the distributed dust on the PV surface. Also, the indoor system enables us to control the desired incident insolation and temperature of the module surface.

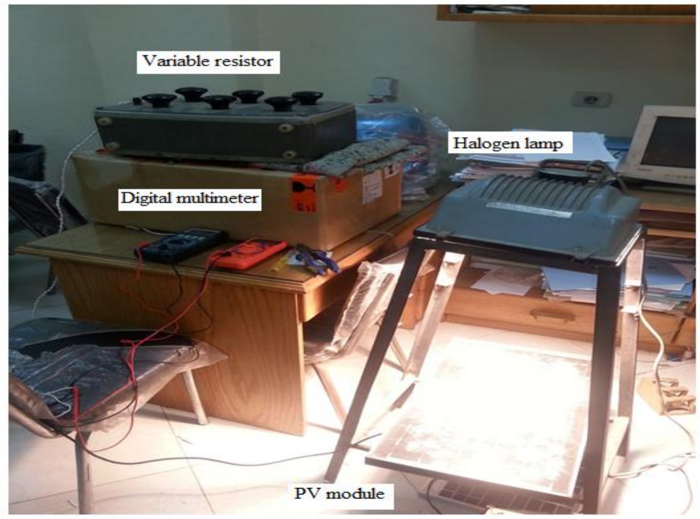


Figure 3. Experimental setup of the considered system.

B. Measuring procedure

Experimental were conducted by applying a four artificial dust types on the front glazing surface of the utilized PV module, such that each dust type is tested individually. The utilized dust types are normal dust, sand, cement, and limestone, and these types are considered in this work to simulate natural dust accumulation on the surfaces of PV modules located in different locations in Egypt.

Same test were performed, also, on a clean PV module; to study the effect of regular cleaning process on the performance of the considered module.

Before starting the experiments, nearly equal samples of the considered dust types were prepared separately, to measure the individual dust weight by using a high-accuracy digital microbalance in a clean container. Such that each sample weight is adjusted at 50 gm; so as to give the same dust distribution density for the four dust types of 0.3 gm/cm^2.

The flow diagram of the procedures conducted in every test to measure the effects of certain type of dust accumulation on the performance of the considered PV module is illustrated in Fig.4.

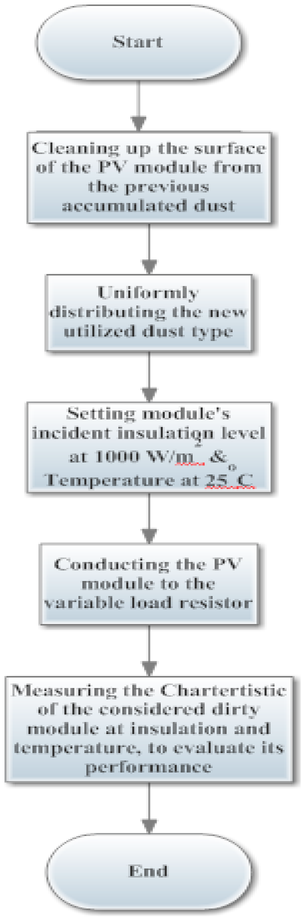


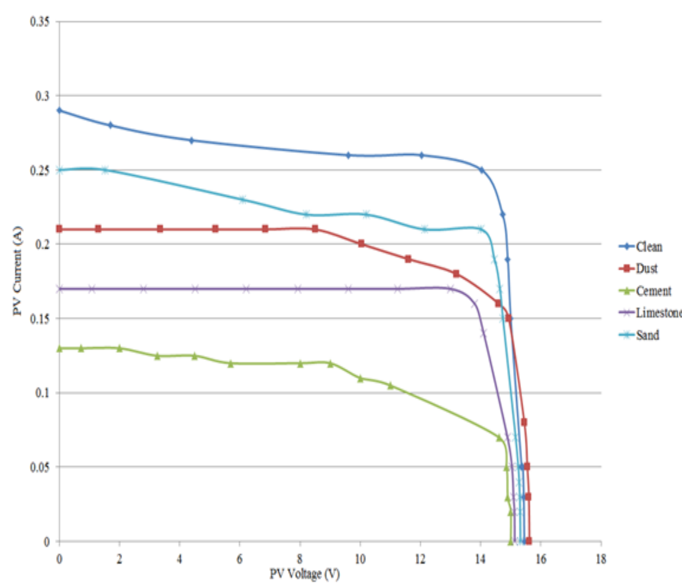
Figure 4. Flow diagram of measuring the performance of the dirty PV module.

V. Results

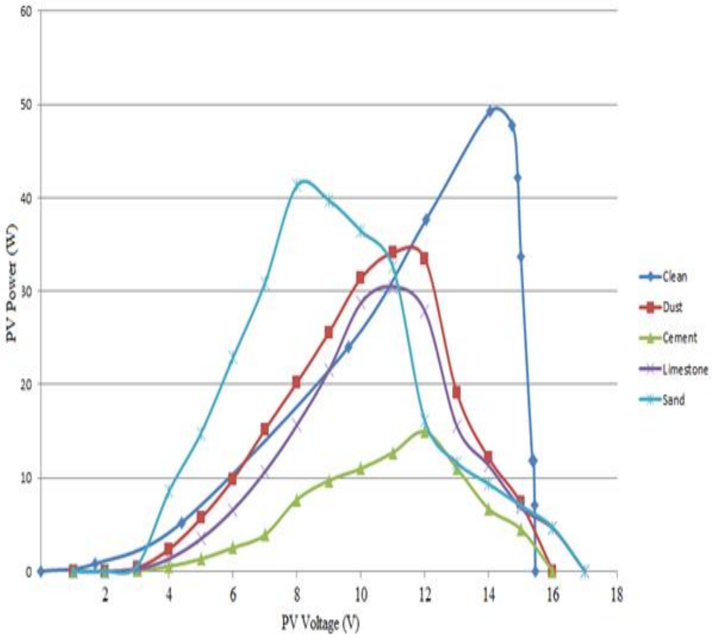
The I-V and the P-V Chartertistics of the considered PV module, using all types artificial dust accumulation, were measured by the experimental setup system indicated in the previous section. These Chartertistics are shown in Figs. 5 (a) & (b), respectively. Thus, by inspecting these figures, it can be indicated that the best I-V and P-V Chartertistics are of the clean module, while the worst ones are of the module which is covered with cement.

Table 1 shows a comparison among the performance parameters of the used module for the different cases of artificial dust accumulation on the PV module surfaces and the clean one. Therefore, these parameters indicate that clean PV module is of the highest performance and the degradation in module's performance starts to increase successively from sand to dust to limestone and finally to cement. And this can be explained by referring to the fact that the smaller the particle size for a fixed deposition density, the greater would be the reduction in solar intensity captured by the solar PV module.

This was probably due to the greater ability of finer particles to minimize inter-particle gaps and thus obscuring the light path more that for larger particles.



(a) I-V Chartertistics



b) P-V Chartertistics.

Figure 5. PV Chartertistics of the PV module using different dust accumulation types.

Table 1. PV Module parameters in different cases.

Layer	I_{sc} (A)	DDF_{Isc} (%)	V_{oc} (V)	DDF_{Voc} (%)	P_{max} Watt	DDF_{Pmax} (%)	µ %	DDFµ (%)	FF %	DDF_{FF} (%)
clean	0.29	0	15.45	0	3.5	0	58	0	79	0
dust	0.21	27.6	15.62	-1.1	2.375	32	39.6	31.7	72	8.8
Cement	0.13	55.1	15	2.9	1.15	67	19.2	66.8	59	25.3
limestone	0.17	41.3	15.13	2	2.21	36.8	36.8	36.5	85	-7.5
sand	0.25	13.7	15.32	0.8	2.94	16	49	15.5	76	3.7

VI. CONCLUSION

Natural dust accumulation on the surface of PV modules often degrades their performance, and the degree of degradation may differ depending upon the environment conditions from season to season and from location to location.

The effect of artificial dust accumulation on the performance of one PV module is studied for different sites in Egypt. The performance parameters of the considered PV module is theoretically analyzed, at first, and then evaluated from the experimentally measured module Chartertistics. The Chartertistics of the considered module, at the desired solar insolation and temperature, are measured by sitting up on experimental system, which can measure I-V & P-V Chartertistics of the PV module for different types of dust accumulation.

Experimental results illustrate that all the performance parameters of the dust accumulated PV modules are degraded relative to that of the clean module. Also, the results indicate that the highest-case performance is recorded for the clean module, and the worst-case performance is recorded for the Cement-dust accumulation.

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International Journal of Advanced Information Science and Technology (IJAIST) ISSN: 2319:2682
Vol.4, No.12, December 2015 DOI:10.15693/ijaist/2015.v4i12.4-11

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The biography of Prof. Nafeh was included in the 23rd, 24th, and 25th Editions of Who’s Who in the World for the years 2006, 2007, and 2008, respectively. Also, his biography was included in the First Edition of Who’s Who of Emerging Leaders for the year 2006, and in 9th and 10th Edition of Who’s Who in Science and Engineering for the years 2006 and 2007, respectively. Moreover, he was awarded the Honorary Doctorate of Engineering from the Yorker International University in June 2007. In addition, he was selected by the International Biographical Center (IBC) of England to be a member of the IBC Leading Engineers of the World 2009. Finally, he won the State Encouragement Prize for Engineering Sciences for the year 2010.