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Dust effect on optical transmittance of photovoltaic module glazing in a desert region

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Abstract

The energy strategy of Algeria is based on the acceleration of the development of solar energy. The strategic choice is motivated by the availability of a huge potential in solar energy. This energy is the major focus of the energetic program where the photovoltaic (PV) solar systems constitute an essential part. The photovoltaic energy fully meets the needs of facilities in remote desert areas where connection to the grid is too expensive. However, the southern Algerian regions are generally characterized by frequent sandstorms. This natural phenomenon causes the dust accumulation on PV modules. Consequently, this may reduce the efficiency of PV array. The objective of this research is to study the effects of the dirt accumulation on the optical transmittance of a PV array glazing in desert regions of Algeria. Firstly, we have validated our model of irradiance on tilted plane, which was the result of Hottel model improvement for Algerian sites. Secondly, the experiments have been conducted on the effect of the dust particle accumulation on the PV modules glazing. The tests were performed with the PVPM2540C in natural conditions to determine the current/voltage characteristics and see the resulting efficiency. It was found in this study, that the dust accumulation on the PV generator glazing surface tilted at 32° can significantly decrease the irradiance transmittance during the day by an average between 0 % and 8 % after an exposure period of several months.

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Keywords: Desert region, PV module, irradiance incidence, dust effect, glazing optical transmittance;

1. Introduction

The Algerian desert presents over 80 % of the country area. This is considered as one of the regions in the world that receive a great portion of solar radiation, especially in summer time with an average of 3000 sunshine hours per year [1]. One of the most promising applications of solar energy in Algeria would be PV system. This is the direct conversion of sunlight to electricity. It is an attractive alternative to conventional sources of electricity for many reasons. In this sense, the insertion of a PV system has an impact on economy and environment of country.

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The Algerian energy strategy recommends an increase of renewable energies contribution. The government plans to launch several solar photovoltaic projects with a total capacity of 800 MWp by year 2020 [1]. However, sandstorm, low frequency and intensity of rain in Algerian desert region provoke the dust accumulation on PV modules and affect their performance. When foreign particles fall on PV modules, they interfere with illumination quality by both absorbing and scattering light, which consequently cause degradation in the efficiency of PV modules. This study can be of great importance to PV solar system designers in Algeria and all other countries with similar weather conditions of sandstorms.

H.C. Hottel has presented a model for estimating the direct solar radiation transmitted through clear atmosphere [2]. In Egypt, A.T.T. Hussein has developed a mathematical model to estimate the hourly global solar radiation using the Hottel parameters of atmospheric transmittance [3]. This model provides predictions in good agreement with the measured data for three locations in Egypt. Nevertheless, in another study the dust accumulated on the PV module surface decreases the transmittance of irradiance and consequently decreases the useful energy received by the PV modules. To investigate the effect of dust on the transparent cover of solar sensor, Elminir et al. [4] in Egypt performed measurements using several sensors and concluded that dirt accumulated on glass inclined of an angle of 0° at 90° from horizontal causes a reduction in the corresponding transmittance by approximately 52,54 at 12,38%, respectively. The tilt angle is one of the most important factors that determine the performance of PV panels. In an experiment carried out in Roorkee by Grag [5] discovered that gather dust on a glass plate tilted at 45° decreases transmittance by an average of 8% after an exposure period of 10 days. Hegazy [6] studied dust deposition on glass plate with different tilt angles as well as measured the transmittance of the plate under different weather conditions. It was found that degradation in solar transmittance depends on the tilt angle. Also, the work by Sayigh & al [7] of dust deposition on a tilted glass plate located in Kuwait city were found to reduce the transmittance of the plate from 64% to 17% for tilt angles ranging from 0° to 60° respectively after 38 days of exposure to the environment. J. Cano [8] has studied the effect of tilt angle of PV modules on deposition of soiling in Arizona State. This study shows that during the period of January through March 2011 there was an average loss due to soiling of approximately 2.02 % for 0° tilt angle. Modules at tilt angles 23° and 33° also have some irradiance losses but do not come close to the module at 0° tilt angle. Tilt angle 23° has approximately 1.05 % monthly irradiance loss, and 33° tilt angle has an irradiance loss of approximately 0.96 %. The soiling effect is present at any tilt angle, but the magnitude is evident, the flatter the solar module is placed the more energy it will lose. Zorrilla-Casanova & al. [9] are worked on the measurements of radiation losses produced by the accumulation of dust. The experiment has been carried out at the roof of the PV Laboratory of the University of Malaga (36.7°N, 4.5°W, 50 m) in the south of Spain. Their results show that the mean of the daily energy loss along a year caused by dust deposited on the surface of the PV module is around 4.4 %. In long periods without rain, daily energy losses can be higher than 20%. In addition, the irradiance losses are not constant throughout the day and are strongly dependent on the sunlight incident angle. When has studied as a function of solar time, the irradiance losses are symmetric with respect noon, where they reach the minimum value. The authors have also proposed a simple theoretical model that, taking into account the percentage of dirty surface and the diffuse/direct radiation ratio, accounts for the qualitative behavior of the irradiance losses during the day.

Al-Hasan [10] investigated the effect of the amount of accumulated dust on the efficiency of a PV module in the Kuwait climate (latitude 30°). A linear relation has been proposed to correlate the degradation in efficiency to the amount of sand dust accumulated on the module surface. This relation can help PV system designers to reliably predict the effect of sand dust accumulation on PV module efficiency under real environmental conditions. Another study has been carried out by H. Jiang & al. [11], to investigate the output degradation of different types of PV modules with different surface materials caused by airborne dust pollution experimentally. It is a series of experiments under controlled conditions were designed and conducted. The results indicated that dust pollution has a significant impact on PV module output. With dust deposition density increasing from 0 to 22 g·m-2, the corresponding reduction of PV output efficiency grew from 0 to 26 %. The reduction of efficiency has a linear relationship with the dust deposition density, and the difference caused by cell types was not obvious. Recently, A. Ndiaye & al. [12] investigated the effect of dust on the performance of PV modules. This work has highlighted the impact of dust on the current-voltage and power-voltage characteristics of PV modules with the advent of the mismatch effect. The maximum power (P_{max}), the maximum current (I_{max}), the short-circuit current (I_{sc}) and the fill factor are the most affected performance characteristics by the dust deposits on the PV modules surface. P_{max} output losses can be from 18 to 78 % respectively for the polycrystalline module (pc-Si) and mono-crystalline module (mc-Si). I_{max} loss can vary from 23 to 80% for respectively pc-Si and mc-Si modules. However, the maximum voltage output (V_{max}) and the open-circuit voltage (V_{oc}) are not affected by dust accumulation for both technologies studied.

In this paper, an experimental validation of our improved model of solar irradiance on tilted surface was presented for desert area in Algeria. Then we show the effect of dust on optical transmission of glazing of a PV module by measurements of power losses produced by PV generator. The experiment has been carried out at the roof of the PV Laboratory of the Applied Research Unit on Renewable Energies in the south of Algeria (32°29'N, 3°40'E, 450 m). The unit is located close of an industrial area surrounded by an open desert space. A national road with heavy traffic flow is very close to the unit. At the time of the measurements, a mine of rock not very far from the unit is in full activity, which has increased the amount of dust particles present in atmospheric air.

2. System modelling

In this part, models of irradiance on tilted surface and photovoltaic module are presented.

2.1. Irradiance model on tilted surface

The global irradiance on a tilted surface G(β) is calculated by a sum of diffuses D(β), reflected R(β) and direct irradiance B(β) (Eq. 1) [13].

$$G(\beta) = D(\beta) + R(\beta) + B(\beta) \tag{1}$$

Where, β is the tilt angle of PV module. The direct component on a tilted surface B(β) (Eq. 2) is obtained versus the incidence angle θ_s, zenith angle θ_z and direct irradiance on the horizontal plane B(0) (Eq. 3) by using the Hottel correlations [14].

$$B(\beta) = \frac{B(0) \cdot \cos\theta_s}{\cos\theta_z} \tag{2}$$

$$B(0) = T_b \cdot G_e \cdot \sin(h_s) \tag{3}$$

T_b is the coefficient of atmospheric transmission of direct irradiance. This parameter is given by the Eq. 4.

$$T_b = A_0 + A_1 \cdot exp\left[-\frac{k}{\cos(\theta_z)}\right] \tag{4}$$

The parameters A0, A1 and k are presented respectively by the Eq. 5, Eq. 6 and Eq. 7 [2].

$$A_0 = r_0 \cdot (0{,}4237 - 0{,}0821 \cdot (6 - Alt)^2) \tag{5}$$

$$A_1 = r_1 \cdot (0{,}5055 + 0{,}00595 \cdot (6{,}5 - Alt)^2) \tag{6}$$

$$k = r_k \cdot (0{,}2711 + 0{,}01858 \cdot (2{,}5 - Alt)^2) \tag{7}$$

Where, r_0, r_1 and r_k are the correction factors of direct irradiance for different climates, and Alt is the altitude of site. The diffuse component on a tilted surface D(β) is obtained by using the model of Liu and Jordan (Eq. 8) [13].

$$D(\beta) = D(0) \cdot \left(\frac{1 + \cos(\beta)}{2}\right) \tag{8}$$

With D(0) is the diffuse irradiance on the horizontal plane. The reflected irradiance on a tilted surface R(β) is given by Eq. 9 [13].

$$R(\beta)=\frac{1}{2}\rho\ G(0)(1-\cos(\beta)) \tag{9}$$

Where G(0) is the global irradiance on the horizontal plane given by Eq. 10. And ρ is the reflectivity of the ground. In the absence of specific information, the value of ρ used is 0,2 for ordinary ground or covered with grass [13].

$$G(0) = D(0) + B(0) \tag{10}$$

2.2. Improved mode

Our improved model is based on the changing of the sign of the second part of parameter k (Eq. 7). So, this equation is presented as follows (Eq. 11) [14].

$$k = r_k \cdot (0{,}2711 - 0{,}01858 \cdot (2{,}5 - Alt)^2) \tag{11}$$

2.3. PV module model

The model of PV module requires the standard condition parameters relative to short-circuit current (I_{SC0}), open circuit voltage (V_{OC0}), (I_{max0}) and (V_{max0}) are respectively the current and the voltage at the maximum power point and the cell number in serial/parallel (N_S / N_P) as well as solar irradiation (G_a) and the surrounding temperature (T_a) [15]. Therefore, the module current I according to the tension V can be described in arbitrary functioning conditions as follow (Eq. 12).

$$I = I_{SC}\left[1-\exp\left(\frac{V-V_{OC}+R_S . I}{N_S . V_t^c}\right)\right] \tag{12}$$

With V_t^c and R_S are respectively the cell thermal voltage (Eq. 13) and the module series resistance (Eq. 14).

$$V_t^c = \frac{mkT^c}{e} \tag{13}$$

$$R_s = \frac{N_S}{N_P} R_s^c \tag{14}$$

Where, m is the ideality factor, equal 1,2 for the mono-crystalline and 1,3 for polycrystalline silicon [16]. The advantage of this model is that it can be established by using the data given by manufacturer [16].

2.4. Evaluation criteria of dust accumulation on glazing

Accumulations of dust on the surface of photovoltaic module glazing reduce strongly the optical transmission of irradiance. In order to study this phenomenon, PV power values sensed by the clean and the dirty modules throughout the day are compared. In this case, relative power losses are calculated as (Eq. 15) [9].

$$PL_{pv} = 100 \cdot \left(\frac{P_{pvc} - P_{pvd}}{P_{pvc}}\right) \tag{15}$$

Where P_{pvc} is the measured power for cleaned glazing and P_{pvd} is the measured power for dirty glazing.

2.5. Model Programming in Matlab

The simulation program was developed in Matlab. This program contains the models of the PV module and the irradiance on tilted surface. The simulation was performed with geographical data of desert site. The step time of this simulation was five minutes depending on data acquisition process.

3. Experimentation description

3.1. Application site

This study focuses in desert region, at 600 km south of the capital Algiers. This region takes profit from a climate that is arid. Indeed, it is ranked in the third climatic zone [17]. This region is characterized by exceptional sunlight. The database of global solar radiation measured on a tilted plane to the latitude of place is available, in addition to temperature. These parameters are recorded on a daily basis, with an interval of five minutes. During the year, the daily solar radiations have values between 2330 and 8155 (Wh/m²) with a minimum temperature of 3 °C in winter and a maximum temperature greater than 45 °C in summer [18].

3.2. Data acquisition

A data acquisition system was installed in order to ensure the data collection of the various climatic parameters. For irradiation measurement, a CM11 Pyranometer type with a sensitivity equal to $4{,}57 \cdot 10^{-6}$ V/W m^{-2} was used. The experimental I-V characteristics of PV generator were measured by the PVPM2540C.

3.3. PV generator description

Figure 1 displays the photovoltaic generator installed in roof of PV laboratory. It includes 31 mono-crystalline PV modules (22 × Isofoton-50 + 9 × Isofoton-100) with total modules area of 14,98 m². The generator power output at STC (1000 W/m², 25°C) was 2 kW_p.

Fig. 1. Photovoltaic generator of 2 kW_p installed on roof

The modules are tilted 32° from horizontal plane and oriented to south. This slope was chosen according to the optimization done for different fixed slopes, each one during a whole year (Fig. 2).

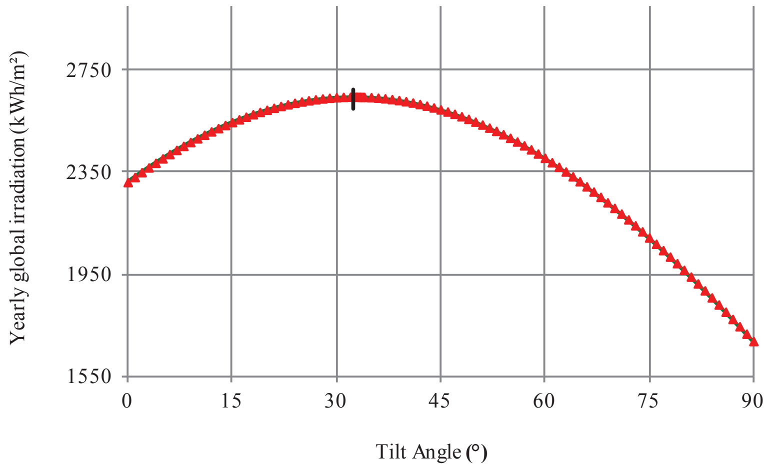

Fig. 2. Yearly global irradiation calculated versus several slopes [12]

4. Results and discussion

4.1. Experimental validation of solar irradiance on tilted surface

The solar irradiation on tilted surface is calculated using the models above with new parameters correction of Hottel correlations. Figure 3 presents the simulation results obtained assuming that the solar irradiance reached the maximal value of 1070 W/m² in March. Comparing the results, we can see that all the used equations gave very good results. The figure shows also that the simulated solar irradiance followed the same trends as that measured one but with some variations in the peak values. The simulated data sometimes higher or almost equal the measured variable. In general, the models gave the good approximation and have the smallest relative errors especially between springs and summer seasons (Table 1).

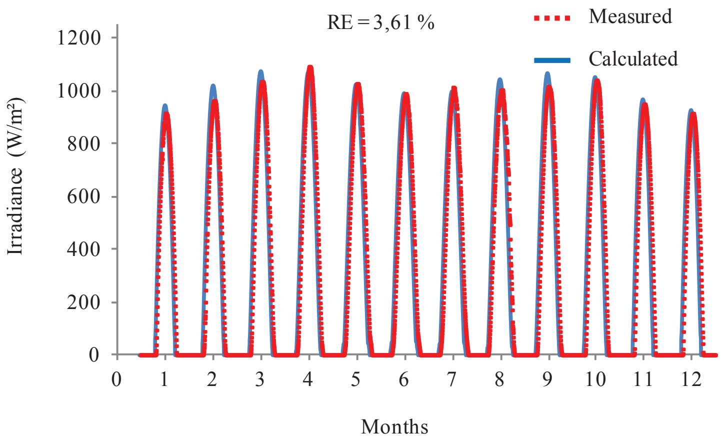

Fig. 3. Daily cycles of predicted and measured solar irradiance for application site

Table 1. Relative errors between a measured and calculated irradiance for different months

Months	01	02	03	04	05	06	07	08	09	10	11	12
Relative errors (%)	5,27	6,19	2,71	3,13	2,43	2,79	2,88	4,46	3,66	1,96	3,52	4,09

The predicted solar irradiance from simulation model was plotted versus the measured as shown in Fig. 4. High correlation coefficient between the predicted and measured values was observed.

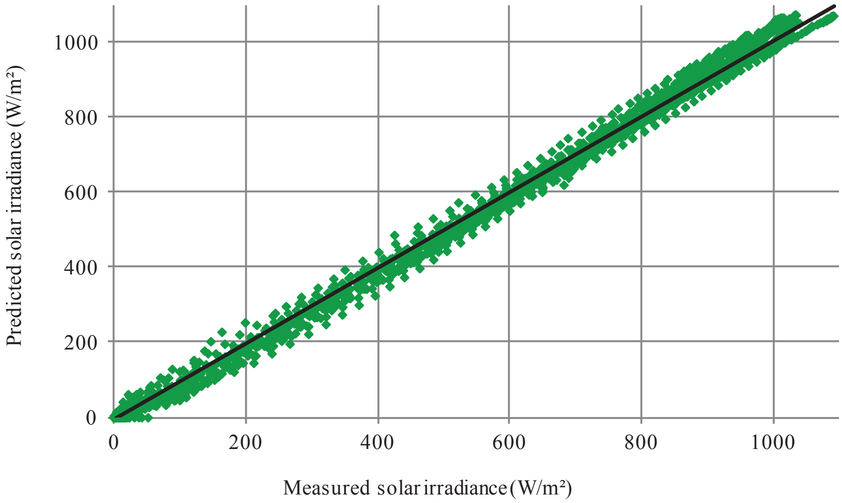

Fig. 4. Comparison between predicted and measured solar irradiance

The model give an accurate prediction of the solar irradiance with determination coefficient of 99,79 %. Fig. 5 represents the differences between the calculated and the measured values of the solar irradiance. It can be observed that the maximum difference is 73,65 W/m² in January.

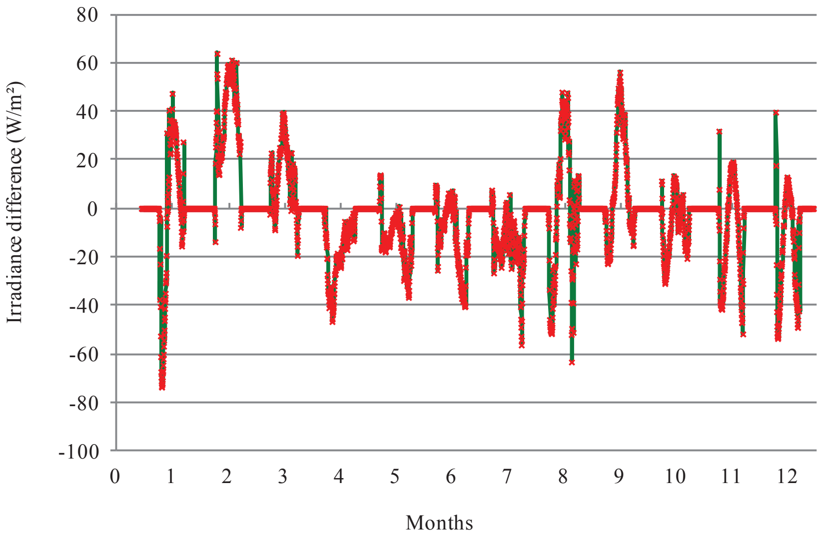

Fig. 5. Difference between predicted and measured solar irradiance

4.2. Dust effect on PV generator production

The experimental I-V characteristics of part of PV generator with and without dust on glazing surface are illustrated in Fig. 6. This figure shows the effect of dust on the short circuit current. Figure 7 shows the disparity between the experimental power curves of PV generator with and without dust on glazing surface. The relative losses of electrical parameters I_{sc} and P_p between the experimental curves with and without dust on PV modules glazing surface are shown in Table 2.

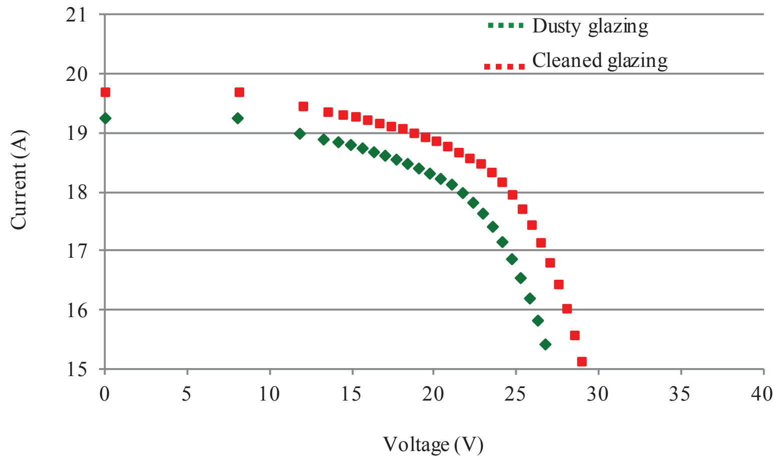

Fig. 6. Example of experimental I-V with and without dust at 10h00 AM

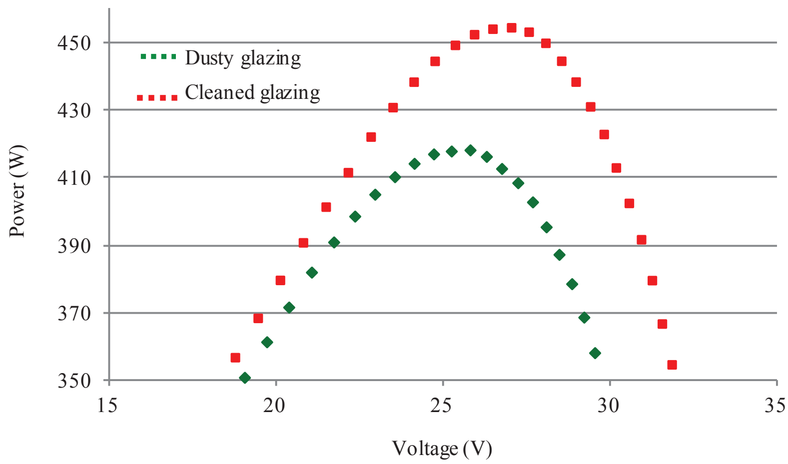

Fig. 7. Difference between predicted and measured solar irradiance

Table 2. Electrical parameters with relative gaps at 10h00 AM

Parameters	I_{sc} (A)	V_{oc} (V)	P_p (W)
Dusty PV modules glazing	19,25	34,75	418,22
Cleaned PV modules glazing	19,69	36,28	454,5
Relative gaps (%)	2,23	-	7,98

Figure 8 shows the experimental I-V characteristics of dusty and cleaned PV generator glazing for a cell temperature 65 °C and irradiance of 934 W/m² at 01h00 PM. It was found that the effect of dust is almost negligible at noon.

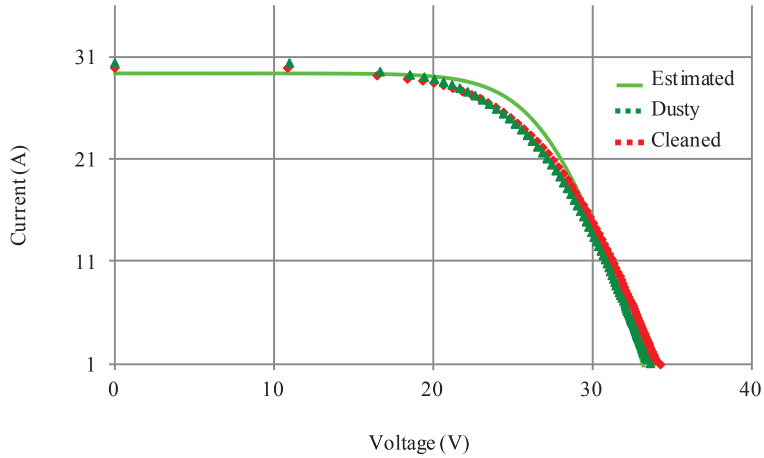

Fig. 8. Example of experimental I-V with and without dust at 01h00 PM

4.3. Dust effect on optical transmittance of PV module glazing

Daily evolution of energy losses due to dust effect on glazing optical transmittance of PV generator at 18/07/2010 is illustrated in Fig. 9. This is a clear sky summer day, more than two months after the last rains; as consequence, dust level deposited on the PV generator glazing surface causing an average daily loss of 4,4 %. These energy losses represent the fraction of irradiance that the photovoltaic generator will not receive. When PV modules are clean, the energy losses are approximately constant during the day. As dust is deposited on the PV module glazing, the behavior of the losses is not constant throughout the day in clear sky days, becoming dependent on the optical transmittance of glazing with dust.

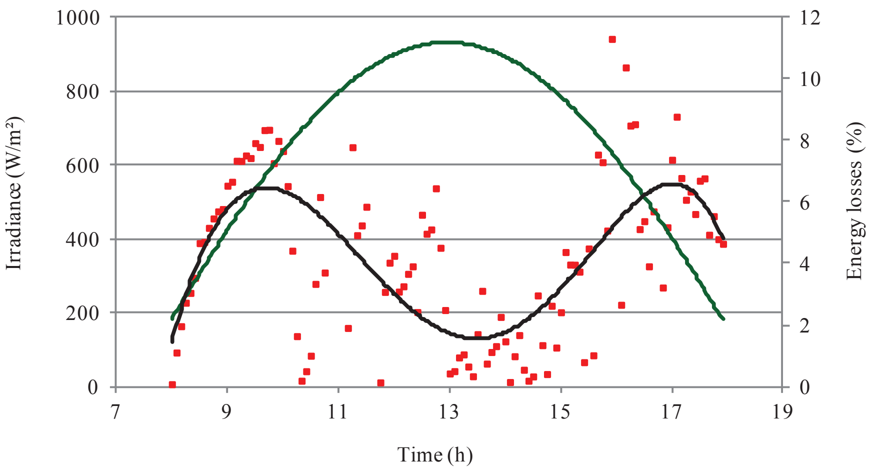

Fig. 9. Daily evolution of energy losses at 18/07/2010

The trend curve that describes the dependence of energy losses with the optical transmittance has a very specific shape (Fig. 9). It was found that this phenomenon is due to the refractive index n_2 of dust material (Fig. 10). The optical transmittance of PV modules glazing has a maximum around solar noon, and then decreases with the elevation of the incidence angle θ_s up to a minimum value (Fig. 10), and then increases for larger values of incidence angle.

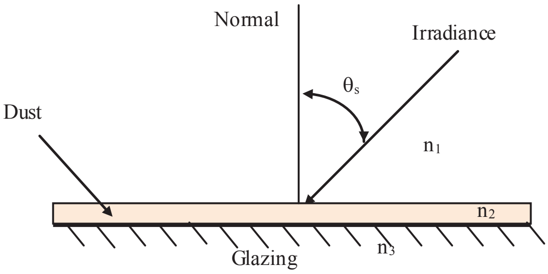

Fig. 10. Irradiance incidence illustration

5. Conclusion

Firstly, in this study we have improved the Hottel model of solar irradiation on tilted plane with a new correction of parameters. Our model has been experimentally validated for several months in Algerian desert sites. Secondly, we have shown in general the effect of dust on optical transmittance of photovoltaic modules glazing. This effect causes the output energy losses of photovoltaic generator. The results about the dust effect on electrical parameters of PV generator have been presented. The relative losses of parameters I_{sc} and P_p are respectively of 2,23% and 7,98% at 10h00 AM. The results of the dust effect on optical transmittance of glazing have been presented at through the energy losses of PV generator along the day of 18/07/2010. The variation of these energy losses during the day depend of the optical transmittance due to the incidence angle of irradiance on tilted plane and refractive index of dust material.

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