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Empirical Analysis of Performance Efficiency of Monocrystalline Silicon Solar Photovoltaic Module Based on Ambient Temperature and Wind Speed

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Abstract: This paper presents an empirical analysis and evaluation of performance efficiency of monocrystalline silicon solar photovoltaic (PV) based on ambient temperature and wind speed. The evaluative analysis was carried out within a range of process parameters: efficiency, 12.23-13.74 (%); ambient temperature, 24.1-35.8(°C) and wind speed, 1.7-3.2 (m/s). The empirical model; $\eta = 0.072\vartheta + 0.3651\beta + 9.6892$ predicts the PV performance efficiency as sum of two linear parts involving the ambient temperature and wind speed. The validity of the model was rooted on the core model expression $\eta - K =$ Ꜧ$\vartheta + N\beta$ where both sides of the expression are correspondingly almost equal. The standard error incurred in predicting the model-based PV efficiency relative to the actual results was 0.25%. Evaluations from generated results reveal that the PV performance efficiency per unit ambient temperature and wind speed as obtained from the actual and model-predicted results are 0.1291 & 0.1188%/ °C and 1.01 & 0.94 % (s/m) respectively. Deviational analysis of model-predicted results (with respect to actual results) indicates a maximum < 2.23%. This translated into over 97% operational confidence levels for the derived model and 0.97 dependency coefficient of the PV efficiency on ambient temperature and wind speed. The correlation coefficients between values of PV efficiency and ambient temperature &wind speed from model-predicted results were all > 98%. This is an increment from experimental results of previous work; 96 and 68% for ambient temperature & wind speed respectively.

Key words: Empirical model - Performance efficiency - PV module - Solar energy - Ambient temperature - Wind speed

INTRODUCTION

The global demand for energy is ever increasing. This has put much pressure on the exploration conventional energy sources, and also raised the need for research and development towards exploring alternative sources in a sustainable manner.

Sun`s energy is the cleanest and most abundant source of energy which could indirectly come to us as wind energy. The wind energy could also translate to electrical energy.

Recently, the operational principle of photovoltaic devices has been well understood leading to a very significant increase in the power conversion efficiencies of such devices. The power output of solar cells varies with temperature changes. Based on the foregoing, research [1] has shown that the desired PV module efficiency can be achieved by altering the ambient temperature around the PV module.

The basic characteristics of PV system and the associated environmental issues have been found [2] to significantly affect the performance of the system. The results of this work indicate that ambient temperature is an environmental issue which plays very important role in the photovoltaic conversion process. It has been revealed [3] that when solar modules are used in different localities for domestic purposes, the performance of the modules varies significantly with environmental issues such as ambient temperature and wind energy prevailing in the particular location where the modules are subjected. Results of investigation [4] carried out to evaluate the photovoltaic output performance shows that it varies with atmospheric factors. The results indicate that energy production by the solar cells changes at any

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instant due changes in the intensity of solar energy radiation at any instant. Based on the foregoing, the research submitted that power delivered by the PV systems at any instant is dependent on weather condition.

Studies [5] have shown that the efficiency of the module is also dependent on the environmental parameters. A similar study [6] has shown that meteorological data such as solar radiation, ambient temperature, relative humidity, and wind speed are not only dependable, but accepted as variables for renewable energy sources.

Studies [7] on different types of modules under varying levels of solar radiation at different climates of different regions have been taken into account. Scientists [8] have reported that the results of investigation on the performance efficiency of the PV system can only be accurate when the environmental parameters prevailing at the location of experiment are strictly considered rather than just the specification from the manufacturer.

Some researchers [9,10] have investigated the effects of ambient temperature and wind speed on the performance analysis of a monocrystalline silicon solar photovoltaic module. The research work was carried out by monitoring the variation of module efficiency with ambient temperature and wind speed. The results of statistical analyses on the research output indicates that the correlation coefficient between PV efficiencies and ambient temperature & wind speed are 96%and 68%respectively, considering confidence level of 95%.The result also shows a strong positive linear relationship between module efficiency and ambient temperature and a moderate positive linear relationship between module efficiency and wind speed. The research concluded that generation of output power will be negatively affected for any deviation from the standard test condition (STC).

The present work is an attempt to derive an empirical model which will evaluate the performance efficiency of monocrystalline silicon solar photovoltaic module based on the environmental issues such as ambient temperature and wind speed.

MATERIALS AND METHODS

The experiment was carried out with solar photovoltaic module no. 03018119, manufactured by M/S Tata BP Solar India Ltd., India. A digital multimeter (M3900) was used to measure the short circuit current and open circuit voltage. Digital thermometer (MS2101) was used to check the ambient temperature, anemometer to measure wind speed, and TENMARS TM -207 solar power meter to measure the intensity of the solar radiation. Details of the experiments are as stated in the previous work [10].

RESULTS AND DISCUSSION

Table 1: Variation of performance efficiency η, of solar photovoltaic module, with ambient temperature ϑ, and wind speed β for the period Dec. 2012-April 2013[10]

(η)	(ϑ)	(β)
12.23	24.1	1.7
11.50	21.2	1.2
11.77	22.4	1.6
13.56	35.0	4.3
13.74	35.8	3.2

Computational analysis of the actual results shown in Table 1, gave rise to Table 2 which indicate that;

$$\eta - K = ƀ\vartheta + N\beta \quad (1)$$

Introducing the values of K, ƀ and N into equation (1) reduces it to;

$$\eta - 9.6892 = 0.072\vartheta + 0.3651\beta \quad (2)$$

$$\eta = 0.072\vartheta + 0.3651\beta + 9.6892 \quad (3)$$

where
K = 9.6892, ƀ = 0.07 and, N = 0.3651 are all; equalizing constant (determined using C-NIKBRAN [11])

(η) = Performance efficiency of PV module (%)
(ϑ) = Ambient temperature (°C)
(β) = Wind speed (m/s)

Boundary and Initial Conditions: Consider a monocrystalline silicon photovoltaic module exposed to solar energy in the presence of atmospheric gases. The performance of the PV module is assumed to be affected by any repulsive dissolved gases. The considered ranges of the performance efficiency, ambient temperature and wind speed are 12.23- 13.74 (%), 24.1-35.8 (^{0}C) and 1.7-3.2 (m/s) respectively.

Table 2: Variation of η - 9.6892= 0.072ϑ+ 0.3651β

η - 9.6892	0.072ϑ + 0.3651β
2.5408	2.3559
1.8108	1.9645
2.0808	2.1970
3.8708	4.0899
4.0508	3.7459

Model Validity: The validity of the model; $\eta = 0.072\vartheta + 0.3651\beta + 9.6892$is strongly rooted on the core model equation (2) where both sides of the equation are correspondingly almost equal. Table 2 also agrees with equation (2) following the values of η – 9.6892and 0.072ϑ+ 0.3651β evaluated from the actual results in Table 1. Furthermore, the derived model was validated by comparing the efficiency predicted by the model and that obtained from the experiment. This was done using various analytical techniques which includes statistical, graphical and deviational analyses.

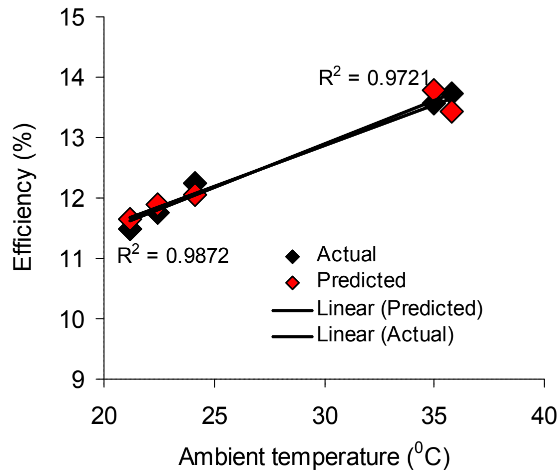

Fig.1: Coefficient of determination between PV efficiency and ambient temperature as obtained from actual and model-predicted results

Computational Analysis: PV performance efficiencies per unit ambient temperature/ wind speed.

The PV performance efficiencies per unit ambient temperature $\eta_{\vartheta}(\%)/^0C$ was calculated from the equation;

$$\eta_{\vartheta} = \eta / \vartheta \tag{4}$$

Re-written as;

$$\eta_{\vartheta} = \Delta \eta / \Delta \vartheta \tag{5}$$

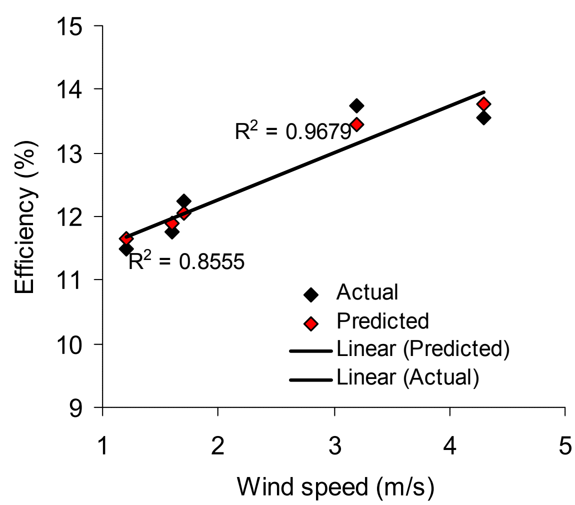

Fig. 2: Coefficient of determination between PV efficiency and wind speed as obtained from actual and model-predicted results

Equation (5) is detailed as;

$$\eta_{\vartheta} = \eta_2 - \eta_1 / \vartheta_2 - \vartheta_1 \tag{6}$$

where

η_{ϑ} = Change in the performance efficiencies η_2, η_1 at ambient temperatures ϑ_2, ϑ_1.

Considering the points (24.1, 12.23) & (35.8, 13.74) and (24.1,12.0451) & (35.8,13.4351) as shown in Fig. 3, designating them as (ϑ_1, η_1) & (ϑ_2, η_2) and then substituting them into equation (6), gives the slopes: 0.1291 and 0.118 %/°C as PV efficiencies per unit ambient temperature as obtained from the actual and model-predicted results respectively. Similarly, on considering the points (1.7, 12.23) & (3.2,13.74) and (1.7,12.0451) & (3.2, 13.4351) as shown in Fig. 4, designating them as (β_1, η_1) & (β_2, η_2) and also substituting them into equation (6), gives the slopes: 1.01 and 0.94 %/ (s/m) as PV efficiencies per unit wind speed as obtained from the actual and model-predicted results respectively.

Statistical Analysis

Correlation: The correlation coefficient between PV efficiency and ambient temperature & wind speed were evaluated (using Microsoft Excel Version 2003) from the coefficients of determination R^2 (shown in Figs. 1 and 2) of the actual and model-predicted results respectively using equation (7).

The evaluated correlation coefficients are 0.9936 and 0.9860 & 0.9249 and 0.9838 respectively. Based on the model-predicted results, the correlation coefficients were all > 98%. This is an increment from experimental results of previous work [10]; 96 and 68% for ambient temperature & wind speed respectively.

$$R = \sqrt{R^2} \tag{7}$$

Standard Error (STEYX): The standard error incurred in predicting the model-based PV efficiency relative to values of the actual results is 0.25%. The standard error was evaluated using Microsoft Excel version 2003.

Graphical Analysis: The validity of the derived model was further verified by plotting values of the actual, besides the model-predicted results using Microsoft Excel (version 2003) to evaluate the trend of both results. Comparative analysis of Figs. 3 and 4 indicate very close alignment of curves which depicted significantly similar trend of data point's distribution for the actual and derived model-predicted PV efficiency. This shows proximate agreement between both results.

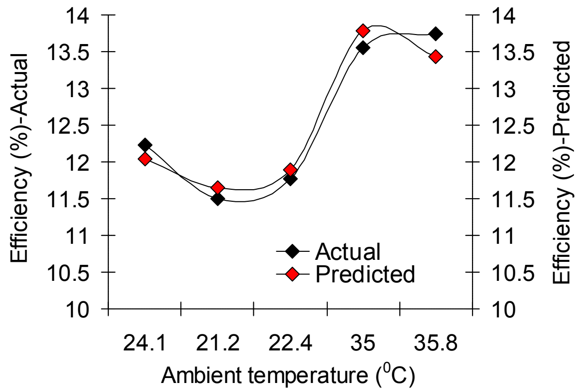

Fig. 3: Variation of PV efficiencies with ambient temperature as obtained from actual and model-predicted results

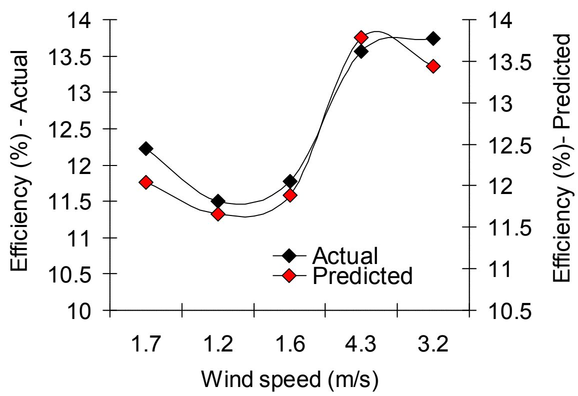

Fig. 4: Variation of PV efficiencies with wind speed as obtained from actual and model-predicted results

Deviational Analysis: Critical analysis of the PV efficiencies obtained from the actual and model-predicted results shows deviation from the actual by model-predicted results. This was attributed to the fact that the effects of the surface properties of the monocrystalline silicon which played vital roles during the PV exposure to the solar energy were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted PV efficiency to those of the corresponding experimental values.

The deviation Dv, of model-predicted PV efficiency from the corresponding actual result was given by;

$$Dv = \left(\frac{\eta_P - \eta_E}{\eta_E}\right) \times 100 \quad (8)$$

where

η_E and η_P are PV performance efficiencies evaluated from actual and model-predicted respectively.

Fig. 5 shows that maximum deviation of model-predicted PV efficiency from the actual results was less than 2.3%. This translates into over 97% model operational confidence. The figure shows that the least and highest deviations of model-predicted results (from actual results) are 0.99 and-2.22%.

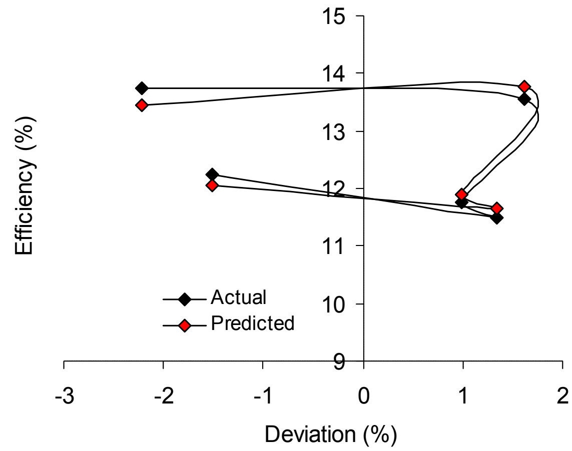

Fig. 5: Deviation of model–predicted results from actual values

These deviations correspond to model-predicted PV efficiencies: 11.8862 and 13.4351(%); ambient temperatures: 22.4 and 35.8(°C) and wind speeds: 1.6 and 3.2 (m/s) respectively.

Correction factor, Cf to the model-predicted results was given by;

$$Cf = -\left(\frac{\eta_P - \eta_E}{\eta_E}\right) \times 100 \quad (9)$$

Critical analysis of Fig. 5 and Fig. 6 show that the evaluated correction factors are negative of the deviation as shown in equations (8) and (9).

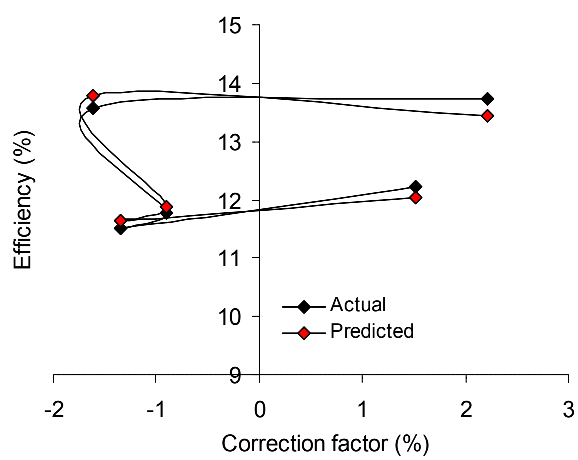

Fig. 6: Correction factor to model–predicted results

The correction factor took care of the negligence of operational contributions of the effects of surface properties of the monocrystalline silicon which actually affected the PV performance efficiency. Introduction of the corresponding values of Cf from equation (9) into the model gives exactly the corresponding actual PV efficiency. Fig. 6 indicates that the maximum correction factor to the model-predicted PV efficiency was less than 2.23%. The figure shows that the least and highest correction factors to the model-predicted results (from actual results) are -0.99 and 2.22%. These correction factors also correspond to model-predicted PV efficiencies: 11.8862 and 13.4351(%); ambient temperatures: 22.4 and 35.8 (°C) and wind speeds: 1.6 and 3.2 (m/s) respectively.

It is pertinent to state that the negative and positive signs preceding numerals in reporting deviation and correction factors merely indicate deficit and surplus respectively. The actual deviation or correction factor is just the numeral.

CONCLUSION

Empirical analysis and evaluation of performance efficiency of monocrystalline silicon solar photovoltaic (PV) based on ambient temperature and wind speed was carried out. The empirical model; $\eta = 0.072\vartheta + 0.3651\beta + 9.6892$ predicts the PV performance efficiency as sum of two linear parts involving the ambient temperature and wind speed. The validity of the model was rooted on the core model expression η - K =Ђϑ+ Nβ where both sides of the expression are correspondingly almost equal. The standard error incurred in predicting the model-based PV efficiency relative to the actual results was 0.25%. The PV performance efficiency per unit ambient temperature and wind speed as obtained from the actual and model-predicted results were 0.1291 & 0.1188%/°C and 1.01 & 0.94% (s/m) respectively. Deviational analysis of model-predicted results (with respect to actual results) indicates a maximum <2.23%. This translated into over 97% operational confidence levels for the derived model and 0.97 dependency coefficient of the PV efficiency on ambient temperature and wind speed. The correlation coefficients between values of PV efficiency and ambient temperature & wind speed from model-predicted results were all > 98%. This is an increment from experimental results of previous work; 96 and 68% for ambient temperature & wind speed respectively.

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