Design and Performance Analysis of Reflectors Attached to Commercial PV Module

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Abstract- The hybrid (PV/T) solar water systems are commercially unviable because of its low concentration ratio, less combined PV/T efficiency, non-standardization of PV heat exchanger surface and long payback period. The simplest and cost effective technique to increase PV/T efficiency is to boost solar radiation on surface of PV module. This can be done by attaching flat reflectors to sides of commercial PV module. This paper provides design and performance analysis of commercial silicon based PV module with reflectors for Mumbai latitude ($\varphi=19.12^0$). The flat reflectors made of anodized Aluminum sheet were attached to shorter sides of PV module at North-South direction. For different tilts of module and reflector orientations, photovoltaic power, efficiency and highest working temperature of modified module are discussed and analyzed. The modified PV module at 25^0 tilt and 24^0 reflector orientation with vertical surface of module could able to generate PV power and efficiency of 161 W and 13.8% respectively. This results shows that modified module produced 15% more PV power than one-sun concentration of PV module. During the experiments the modified module was found heated with maximum operating temperature of 66 ^{0}C.

Keywords- Low concentration ratio, silicon based PV module, flat reflectors, anodized Aluminum sheet, PV output power, one-sun concentration.

1. Introduction

The solar Photovoltaic (CPV) cell material contributes about 50 % to 60% of total cost of commercial PV module. The Photovoltaic modules cost has been started declining since last few years. As on today cost of mono crystalline PV module is as high as 100 Rs/Watt to 130 Rs/Watt. The significant measures are required to be undertaken to reduce PV power generation cost by reducing utilization of cell material to widespread and commercializes the PV technology in near future. The number of techniques incorporated by many PV module manufacturing companies such as use of thinner wafer, thin-film solar cell technologies and concentrator techniques are found helpful in reduced PV material consumption/watt of generated output power.

In PV concentrator technology optical reflectors would replace costly PV cell area by cheaper reflector material such as glass mirror, aluminum sheets or foils, acrylic mirror sheets etc. Percentage area of solar cell incorporated in PV module is reduced by the value of concentration ratio as compared to one-sun concentration. The idea to use solar PV concentrator with modules is simple but it is difficult to get high level of concentration ratio. The elevated concentration ratio put stringent constraints on solar PV cell's heat dissipation capacity and sun tracking system. However it is possible to use low concentration optics with commercial PV modules in static mode to eliminate continuous tracking of module. Based on this concept, flat reflector is an attractive selection to reduce price of photovoltaic output power. Flat reflectors are static concentrators, where solar intensity is boosted by fitting reflectors to sides of commercial flat plate PV module.

A simple review was conducted on research, development and selection of various PV absorber designs, materials and use of concentrators for higher energy output of hybrid solar systems [1].Overall system performance of PV module could be improved by applying these augmentation techniques to existing simple hybrid PV/T solar systems.

A critical review was carried on enhancement in system performance of a hybrid PV/T water collector system for various heat absorbing fluids and configurations of heat exchanger with different materials [2]. Spiral flow heat exchanger with copper material fitted with reflectors could produce highest combined power PV/T efficiency compared to simple hybrid solar water system and this system could be commercially viable in future.

V-trough photovoltaic (PV) concentrator systems along with conventional 1-sun concentration PV module were designed and fabricated to evaluate the PV electricity cost ($/W) reduction [3]. V-trough concentrator system with 2-sun concentration was able to generate 44% more output power as compared to 1-sun concentration for passively cooled PV modules. The cost/unit watt of electricity generated from PV module was reduced by 24% from 7.72 to 5.88 $/W by using V-trough concentrator system as compared to 1-sun concentration PV module.

Different experiments were performed on sheet and tube heat exchanger PV/T water collector system by attaching flat concentrators to sides of PV module [4]. Two flat Aluminum concentrators had been mounted at sides of PV module at an angle 10^0 and 56^0 to the vertical plane of PV/T water collector. Aluminum sheet concentrators could develop PV energy of 8.6% and thermal energy of 39 % more than simple PV module. Aluminum foil concentrators could increase PV energy of 17.1% and thermal energy of 55 % more than conventional PV module.

Various formulas were derived analytically for geometrical concentration ratios and irradiance distribution at the base of flat-sided linear trough configuration [5]. Different results were presented graphically for optimum configuration which requires minimum material to achieve optimum concentration ratios. The realistic concentration ratios were obtained in a range of 1.5 to 4 depending on geometry and coefficient of reflection.

An extensive study on water cooled PV/T solar systems was conducted at the University of Patras and University of Rome respectively with glazed and flat reflectors [6]. Tube heat exchanger with metallic sheet was placed at PV module back surface and cold water circulating through it was heated by absorbing heat from bottom side of module. The energy output for all PV/T systems were calculated at system operating temperatures of 25^0C, 35^0C and 45^0C respectively. For University of Patras, annual solar input collected on PV plane was 1644.7kWh/m^{2}y. Simple PV Module without glazing generated electricity of 183kWh/m^{2}y with efficiency of 11.12 %. Different experiments were performed on hybrid PV/T system with & without glazing, and with & without reflectors at system operating temperatures at 25 ^{0}C, 35 ^{0}C and 45 ^{0}C respectively. Finally PV/T system with glazed and flat reflectors at system operation at 25^0C generated highest annual electrical energy of 167.98kWh/m^{2}y with electrical efficiency of 10.21% and highest annual thermal energy of 831.75kWh/m^{2}y with thermal efficiency of 50.57 % as compared to other operating temperatures.

The low concentration solar energy configurations was investigated and studied to know effect of concentrator geometry on PV electrical output [7]. The flat diffuse reflectors provided a uniform distribution of solar radiation on PV surface. The linear Fresnel lenses were used to achieve additional solar control of interior spaces. The compound parabolic collector (CPC) with reflectors was effectively combined with PV strips as flat solar thermal absorbers. The absorbed solar radiation increased the cell temperature and reduced PV efficiency. Several modes were applied for efficient and cost effective heat extraction and most appropriate one was selected according to required application.

Different types of reflectors were fixed to sides of simple PV module [8]. By this configuration the energy produced by solar module was improved significantly. Different experiments were performed on aluminum; stainless steel and chrome film reflectors to determine type of reflectors more efficient in practical and do not produce excess waste heat. The final results showed that, chrome reflectors produce a 27.65% additional PV power output against aluminum foil and a 34.05% enhance in PV power output against stainless steel reflectors.

The combine photovoltaic systems with V-trough cavities was identified as an attractive option to reduce the prices of the PV electrical energy [9]. The V-trough cavities were simple to manufacture and can be used with conventional (1-sun) solar cells. The main design requirements of V-trough cavities were uniform illumination on the plane of the PV module, minimum cost of energy and heat dissipation by natural passive means.

Two moderate concentrations were designed and developed for east-west aligned non-tracking, infinitely long, trough-like solar energy collectors [10]. They were namely one-and two-facet plane side-wall configurations. At solstice a 9° acceptance angle was necessary for minimum eight hours of collection at optimum performance. Under this constraint the practical concentration ratios were obtained limited to 2 and 2.6 for the one and two-facet designs respectively.

An intellectual solar tracker and diffused reflector enhanced systems were designed and developed to compare the power output of standing alone systems which could achieved higher power output to reduce the number of PV panels and there costs[11]. For this study, experimental readings were taken from the panel, sun tracker and the panel with diffuse reflectors aligned at 23.50^0 with horizontal. It was concluded that the power output of the panel with reflectors was higher from 11 am till 2 pm, while the panel with tracking was higher at other times.

An auxiliary mirror drive mechanism was designed and developed to track the sun and reflect the rays on to stationary PV arrays [12]. This mechanism had a five bar spherical linkage used for solar tracking and two degrees of freedom for tracking the sun along its azimuth and altitude. The final results showed that output power from the PV panel was increased by 22% with the use of tracking reflector.

This research provides design and development of Aluminum flat reflectors and its performance analysis on commercial PV module for different module tilts and reflector orientations for Mumbai latitude. By mounting reflectors to sides of module, augmentation of radiation on surface of module was takes place. This modified system was able to produce more PV power, at the same time increasing its operating temperature. The working voltage and current generated by module was drastically increased without effect of high temperature on it. This was happened as experiments were performed during winter season. If same experiments would have been perform during summer season, voltage produce by module could have been decreased drastically because of increase in module temperature. The reflectivity of Aluminum reflectors was found high and illumination was homogeneous on entire module surface. The percentage increase in PV power and effect of raise in temperatures on performance of PV module are discussed and analyzed.

2. Experimental

2.1. Commercial PV module with stand

A commercial PV module of 180 watts of capacity was used to determine effect of reflectors on its performance for latitude of Mumbai. The electrical specifications of the module are given in table1 at standard test conditions (STC). The manual tracking was done to track PV module to South direction at different slopes during experimental work at different time of a day. The commercial PV module fixed on stand is placed on roof of institute's main building at I.C.T. Mumbai as shown in figure1.

Table1. Electrical data of the PV module

Module type	Tata Bp Mono Crystalline
Power (W)	180
I_{SC} (A)	5.4
V_{OC} (V)	44.8
I_{MP} (A)	4.99
V_{MP} (V)	36.6
FF	0.75
η_{mod} (%)	14.5
Module L (m)	1.58
Module W(m)	0.79
PV module area (m^2)	1.25

2.2. Design and Fabrication of Aluminum Flat Reflectors

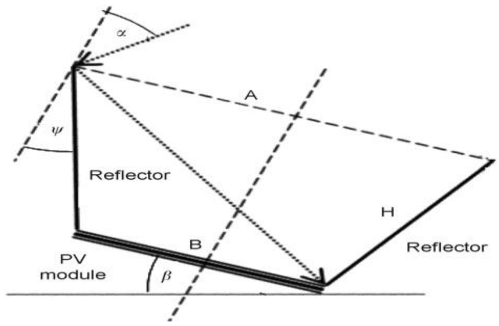
The commercial PV module is used to generate photovoltaic power and efficiency as per manufactures specifications at standard test conditions (STC). The STC conditions defined by manufactures are solar radiation of 1000 W/m^2, highest module working temperature of 25 ^{0}C and wind velocity of 1 m/sec. In actual practice STC conditions are invalid for latitude of Mumbai.

The peak PV power generated by any PV module will depend on local climate, season of year, ambient temperature, wind velocity, latitude of location, tilt of module and solar radiation. The performance of module is strongly influenced by solar radiation falling perpendicular to its surface. The intensity of solar radiation is not constant over a day. Its value is less during morning, increases at noon and again decreases at afternoon. Due to fluctuation of solar radiation over a day, there is a variation in power produced by module at different time of a day. So PV module generates variable power as compared to rated power specified by manufactures. The various methods can be used to increase PV power of module as mentioned in introduction. In this paper cost effective method is used to increase concentration ratio by mounting flat reflectors to sides of PV module.

An anodized aluminum sheet of 0.5 mm thickness, available in market was used for fabrication of flat reflectors. The reflectivity of Aluminum sheet was measured by using Albedo meter. Anodized aluminum sheet was found to be a better reflector with reflectivity of 82%. The amount of solar radiation reflected from reflectors on module surface was strongly influenced by concentration ratio. With increased concentration ratio, power output and efficiency of module was found enhanced because of more solar radiation falling on its surface.

The concentration ratio and reflector slant height were calculated by using formulas shown in Table 2. Using this data, a pair of reflector was fabricated from Aluminum sheet with its size equal to module dimensions as per Table 1 and fitted to shorter sides of PV module [5]. The modified PV module includes simple PV module with reflectors and other measuring instruments is shown in figure 1.

Table 2. Analytical relations to calculate concentration ratio and reflector height [5]



Where: α-acceptance angle; ψ-trough angle; A-collector aperture width; B-receiver base width; H- reflector slant height; CR- concentration ratio; n-number of reflections and ρ- reflectivity of reflectors.

$CR = \dfrac{\sin[(2n+1)\psi+\alpha]}{\sin(\psi+\alpha)}$	(1)
$\dfrac{H}{B} = \dfrac{\sin[(2n+1)\psi+\alpha]-\sin(\psi+\alpha)}{2\sin(\psi+\alpha)\sin\psi}$	(2)

Fig. 1. Actual installation of flat reflectors to sides of PV module at N-S direction.

2.3. Measuring Instruments

A Dynalab Radiation Pyranometer was used to measure global and diffuse solar radiations on horizontal surface. An ACD Anemometer was used to measure wind velocity of surrounding air. Thermocouples of K-type were used to measure ambient temperature and temperatures at top and bottom side of module. A Sixteen channel temperature data logger was used to scan and record temperatures during experimental process over a day. A DC voltmeter and ammeter were used to measure voltage and current at various loading conditions. A DC load bank of 36-Volt with 180-watts capacity was used to measure voltage and current across load applied to PV module during experiments.

2.4. Experimental Observations

All experiments on simple PV module and PV module with reflectors were conducted during months of February and March-13. These experiments were performed on simple PV module for slopes of 20^0 (latitude of Mumbai), 25^0, 30^0 (specified by manufacturer) and 35^0 (latitude of Mumbai $+15^0$) to know its performance at actual test conditions. This was done to determine the optimum slope generating highest photovoltaic power and efficiency for Mumbai latitude. To determine precise performance of simple PV module, experiments were conducted between 9:30 am and 4:30 pm.

An electrical energy produced by simple PV module over a day was reliant on two key factors such as intensity of solar radiation and module temperature. Intensity of solar radiation was found fluctuating over a day and raise of module temperature was directly proportional to solar radiation. To estimate above effects practically different readings such as global and diffuse radiation on horizontal surface; wind velocity of surrounding air; voltage and current at corresponding loading conditions were recorded in 30 minutes of time interval. Thermocouples of K-type were attached to data logger to scan and record temperatures of PV module at various points in 30 second of time interval. After conducting different experiments on simple PV module for above mentioned slopes, it was found that at 25^0 tilt simple module was able to generate highest values of PV power and efficiency.

At 25^0 slopes Aluminum flat reflectors were fitted to shorter sides of PV module at North-South direction as shown in figure1. At fixed slope of 25^0 different experiments were conducted on modified PV module by changing orientations of reflectors manually from 100^0 to 135^0 (90^0+45^0) normal to PV surface with an interval of 5^0 on distinct days. This was done to determine the optimum orientation of reflectors generating highest photovoltaic power and efficiency. For selected module slope, at 24^0 orientations of reflectors with normal to module surface was able to generate highest photovoltaic power and efficiency. At 24^0 orientations of reflector, 1.8 concentration ratios calculated by using correlation for highest photovoltaic power point condition as per table 2.

3. Calculations of various Technical Parameters at ATC Conditions

The following equations and procedures were used to calculate technical parameters for simple PV module and PV module with reflectors at ATC conditions of Mumbai latitude [13, 14 and 15].

The PV module power P_{PV} (W) without reflectors for different loading can be find out by using

$$P_{PV} = V \text{ x } I \tag{1}$$

Where V and I are voltage (V) and current (A) generates by module. Beam radiation I_b (W/m^2) on horizontal surface can be given by

$$I_b = I_g - I_d \tag{2}$$

Where I_g and I_d are total and diffuse radiation measured by pyranometer on horizontal surface (W/m^2). Input solar radiation I_T on normal to PV surface (W/m^2), total solar input power I_G on normal to PV surface (W) and PV module efficiency η_{PV} (%) without reflectors are calculated by using

$$I_T = (I_b \text{ x } r_b) + (I_d \text{ x } r_d) + (I_b + I_d) \text{ x } r_r \tag{3}$$

$$I_G = I_T \text{ x } A_{PV} \tag{4}$$

$$\eta_{PV} = V \text{ x } I / I_G \tag{5}$$

Where r_b, r_b & r_r are tilt factors for beam, diffuse and reflected radiation and A_{PV} is area of PV module (m^2). Solar radiation reflected I_r from one reflected surface on PV surface (W/m^2) and input solar radiation $I_{T\ ref}$ on PV module surface by considering both reflectors (W/m^2) can be given by

$$I_r = \{[I_b \text{ x } r_b + (1-F_{C\text{-}R})I_d] \text{ x } \rho \text{ x } A_{ref} \text{ x } F_{C\text{-}R}\} / A_{PV} \tag{6}$$

$$I_{T\ ref} = (I_b \text{ x } r_b) + (I_d \text{ x } r_d) + (I_b + I_d) \text{ x } r_r + 2\text{x } I_r \tag{7}$$

Where $F_{C\text{-}R}$, ρ and A_{ref} are view factor, reflectivity (%) of reflectors and reflector area of any one reflector (m^2). The total radiation $I_{G\ ref}$ (W) on PV module surface and PV module efficiency $\eta_{PV\ ref}$ (%) by considering both reflectors are given as

$$I_{G\ ref} = I_{T\ ref} \text{ x } A_{PV} \tag{8}$$

$$\eta_{PV\ ref} = (V * I) / I_{G\ ref} \tag{9}$$

4. Results and Discussion

4.1. Performance Analysis of Commercial PV Module Attached with Flat Reflectors

After converting simple PV module to modified PV module with reflectors, performance of PV module increased drastically due to concentration effect. The modified PV module generated maximum voltage of 33.30 V at 1 pm. This increase in voltage shows contradiction to increase in module temperature to 66 ^{0}C because of boosting solar radiation. The voltage produced by a PV module is a logarithmic function of intensity of solar radiation and solar intensity is directly proportional to rise in module temperature [13]. All experiments were conducted during winter season, the highest ambient temperature recorded was of 33 ^{0}C. As an effect of concentration ratios and heating, highest module temperature recorded was of 66 ^{0}C. This highest module temperature was more than Nominal Operating Cell Temperature (NOCT) for Mono Crystalline PV module. Due to combined effect increase in voltage generation took place.

The highest operational current of 4.82 Amp was produced by modified module at 1 pm. The operational current was found improved considerably as an effect of boosting solar radiation on PV module. This happened because the current produced by a PV module is the linear function of intensity of solar radiation [13]. As a combined effect of above two working parameters, photovoltaic power and efficiency were improved to 161 W and 13.8% as shown in figure 2 and 3. For modified PV module the performance ratio was raised to 90%.

During experiments on modified module, the orientation angle of reflectors was fixed at 24^0 north south for a day mentioned1.8–sun concentration ratios. At this concentration ratio, modified module produced PV power equal or more than rated power claimed by manufacturer [3, 8]. With continuously changing angle of incidence; solar rays were not falling normal to module surface during different time of a day. With fixed reflectors, sun rays falling on it were not fully reflected on module surface. This was a common phenomenon for period of 11.30 am to 2 pm when angle of incidence was nearly normal to PV surface and reflectors reflecting all receiving rays on module surface and produced highest PV power. For other timings, missed reflections from reflectors did not hit the module surface and directly went to atmosphere. During this timings modified module performance was less than simple module. To utilize these missed reflections, reflectors were tracked from morning to evening continuously along East-West direction, producing power and efficiency equal to or more than its rated output. With higher concentration ratio, solar radiations falling on PV module surface improved. As per assumption made earlier in introduction section, illumination was homogeneous over PV module surface for whole day. But actual change in angle of incidence continuously, non-homogeneous pattern on module surface was established during morning and evening. Due to this some part of the module was heated more than other part. So the highest temperature obtained from top side was not constant at 66 ^{0}C over an entire surface of module.

Experiments carried out in summer will observe voltage generation strongly affected by rise in module temperature. Due to this effect photovoltaic power and efficiency may be declined drastically. The life of PV cell will decrease due to overheating of PV cells and components of module. Cooling of modified module will be required to enhance life of PV cell and module by placing heat exchanger at backside of module will absorb heat from module cooling it at reasonable level [4, 6, 7]. With cooling, module may produce desired output power as per claims of manufacturer and additional thermal energy will be produced in terms of hot water or air. This thermal energy may be used for low temperature applications such as solar air drying, pre heating of swimming water and domestic water heating applications. This combined system called as hybrid Photovoltaic/Thermal (PV/T) solar system converts solar energy to electricity and thermal energy from single integrated unit. The hybrid PV/T solar system will generate higher energy output per square meter than simple PV modules and could be cost effective if additional cost of thermal unit is low.

4.2. Performance Analysis Comparison of Simple PV Module and PV Module with Flat Reflectors

The Performance comparison of PV module under actual test condition with and without reflector at highest power point condition was compared for 25^0 slopes for Mumbai latitude. Simple PV module at one sun concentration ratio was able to produce 132 W at solar radiation of 965 W/m^2 at 1.30 pm. During experiments the simple PV module was heated to the highest temperature of 52.2 ^{0}C.

The modified PV module with reflectors at 1.8 sun concentration ratios was able to generate 161 W at solar radiation of 935 W/m^2 at 1 pm. During experiments the modified PV module was heated to the highest temperature of 66 ^{0}C.

The above results showed that by fitting inexpensive flat reflectors to two smaller sides of module, enhancement in PV power output and system efficiency took place. The performance of both systems in term of increased in photovoltaic power and efficiency at ATC conditions are shown in figure 2 and 3. Due to high operational temperature of modified PV module, open circuit voltage was found decreased to 37.8 V.

The above experiments were carried out and readings were recorded at every 30 min of time duration from morning to evening for both systems. The total energy generated by simple PV module per day was 0.656 kWh and PV module with reflectors was able to produce 0.707 kWh of energy per day. Finally it can be concluded that PV module with reflectors can produce 8 % more energy per day compared to simple PV module.

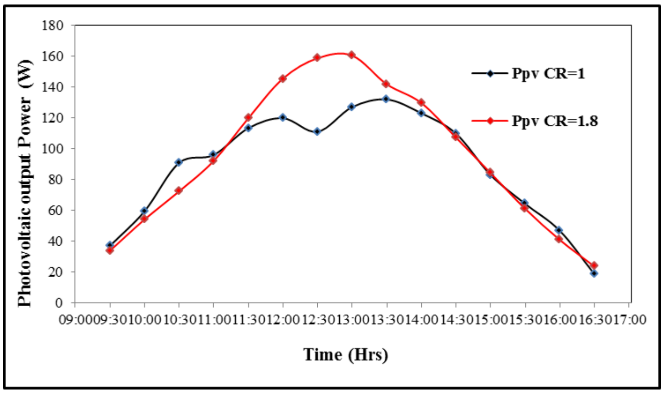


Fig. 2. Photovoltaic power produced by simple PV module and PV module with reflectors

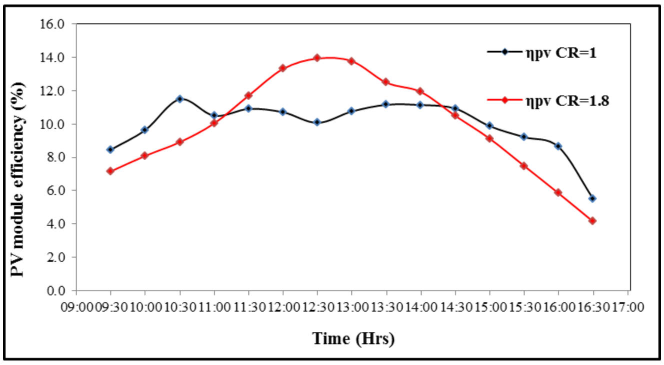


Fig. 3. Photovoltaic efficiency of simple PV module and PV module with reflectors

5. Conclusions

This research paper shows experimental recordings of performance of simple PV module and modified PV module at ATC conditions for Mumbai latitude. The modified PV module was able to produce more PV power and efficiency of 22 % and 21 % respectively as compared to simple PV module. By adding Aluminum reflectors, PV power and efficiency were enhanced significantly with small increase in the total cost of the system. The performance ratio of modified system was enhanced by 17 %.

The experiments were performed on modified system when orientation angle of reflectors was constant at 24^0 normal to module surface over a day. With continuous tracking of reflectors from morning to evening along East-west direction, PV module produces more PV power and efficiency compared to its rated power.

Modified system producing highest output voltage with reflectors was required to cool PV module by heat exchanger circulating cool water or air as its working fluid through it. This new system is called as hybrid Photovoltaic/Thermal (PV/T) system which generates electrical energy and thermal energy from one integrated system and cooling PV module at reasonable temperature level.

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