Mathematical Approach for Optimizing Heat Sink for Cooling of Solar PV Module

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Abstract: ***The temperature dependency of electrical performance of PV modules has led to an increase in research and development of adequate cooling mechanisms to lower the temperature coefficient of modules on small as well as the large scale. A significant number of cooling techniques available today are being studied and further developed for proper use in PV systems. While deciding the suitable cooling technique for system, the proper design is necessary to limit the effect of auxiliary equipment on the overall economics of the system. This paper discusses a mathematical approach for designing an optimum heat sink for maximum heat transfer from the PV module for achieving performance enhancement of solar PV module for natural convective cooling condition. A thermal analysis has been conducted in ANSYS for the obtained dimensions of heat sink.***

Keywords: Heat sink, Cooling, PV, Fins, Design

1. Introduction

In the recent years, there has been a global trend of dependence of countries for energy needs shifting from the conventional sources like coal to renewable and clean sources like solar energy, wind energy, bioenergy etc. Among the many alternate sources for clean energy sources, solar energy has outshined the other sources on its way to the top contender to replace the depleting conventional sources [1]. In order to extract power from solar energy, solar power plants are utilized. Figure 1 enlists the different classification of solar power plants.

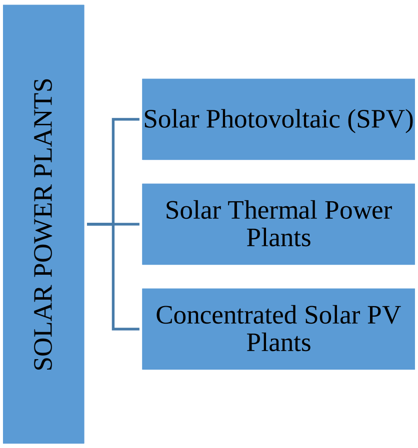

Figure 1: Different Solar Power Plants

Solar Photovoltaics technologies can further be classified into monocrystalline solar cells, multi crystalline solar cells and thin film solar cells [2]. Although solar photovoltaics has taken gigantic leaps when it comes to the advancement of technologies, certain barriers remain that dampen the effectiveness of this technology. One of the major challenges is the effect of high ambient temperatures on solar cell temperature that in turn effects the conversion efficiency of solar cell. The dependency of PV module electrical efficiency on temperature is a well-established fact. Many studies show that with every degree rise in module temperature, there is a reduction in the efficiency of PV module ranging from 0.4-0.6% for crystalline Silicon solar modules while in case of amorphous Silicon solar modules, this reduction in efficiency is about 0.05% [3]. This numerical value assigned for reduction in efficiency per degree rise in module temperature is defined as the temperature coefficient of the PV module. The temperature coefficient for every PV module is determined by the manufacturer by testing the module at the Standard Test Conditions (STC) i.e. radiation 1000 W/m^2, ambient temperature of 25^{0}C and wind speed of 1 m/s. Figure 2 shows the dependence of various output parameters [4].

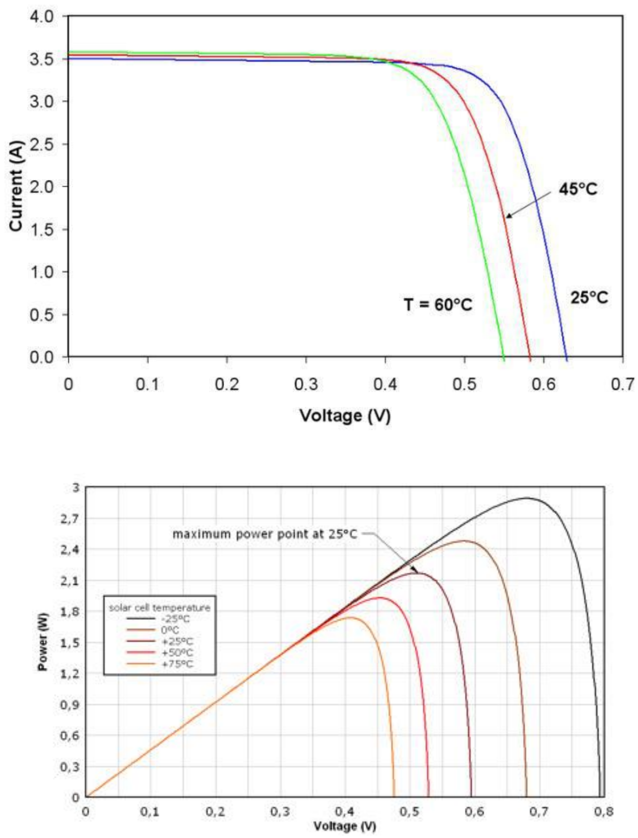

Figure 2: Dependence of Voltage and Power on module temperature

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It can be clearly observed from the above figure that as the module temperature increases over the STC temperature, the output voltage and power gradually decreases, thus leading to a fall in the electrical efficiency of the PV module. The dependency of efficiency on the temperature arises due to the dependency of the open circuit voltage (V_{OC}) on temperature which varies with temperature due to the change in the reverse saturation current (I_O) [5]. The following correlation can be used to describe the variation of open circuit voltage with temperature change:

$$\left(\frac{d(Voc)}{dt}\right) = \left(\frac{1}{T}\right)\left(Voc - \left(\frac{Eg}{q}\right)\right) \quad \text{(i)}$$

Where Eg/q is the ideal voltage that should be derived from the module. This term is always greater than V_{OC} as the real voltage is obtained after incurring certain losses. Thus an increase in temperature causes a decrease in the V_{OC}.

2. Cooling Requirements and Methodologies: A Review

The increase in module temperature over the STC limit is a major barrier in achieving the rated power from PV module. This leads to sizing problems while designing PV systems on a large scale and can cause an upward shift in the economics of the system. The rise in module temperature can also lead to several mechanical damages to the module like cracks, degradation, mismatch etc. [6]. These damages limit the life of the PV and increase the payback period, both of which are undesirable. Thus an adequate and effective cooling mechanism is required to limit the effect of high module temperatures on the conversion efficiency. Various studies have been conducted all over the world where researchers have tried to determine the effectiveness of various cooling methods. Both review works as well as experimental works have been carried out in this research area. Depending on the use of external power for cooling purposes, cooling can be further classified into active cooling and passive cooling.

Skoplaki et al. reviewed various works correlating the dependency of module temperature on their performance and list out a large number of equations that equate the temperature-performance relation [7]. The authors suggest that while rating PV modules, factors such as irradiation over an area, average ambient temperatures etc. need to be considered before deciding which correlation to use. Hasanuzzaman et al. studied the different cooling technologies available for PV systems. Their study shows that while passive cooling techniques show a temperature reduction of 6-20 ^{0}C, the active cooling systems are much more efficient with a temperature reduction of over 30^{0}C [8]. Active cooling may serve additional purposes like domestic water heating and air circulation. Sargunanathan et al. reviewed different active and passive techniques and concluded that heat pipe assisted cooling is most efficient with a reduction of 30^{0}C-40^{0}C in module temperature [9]. Nizetic et al. in their work, studied both the passive cooling techniques as well as the active cooling techniques. In case of passive cooling techniques, the authors suggest that after taking all factors like cost, environmental impact, size etc., the most effective cooling technique is air cooling while water based cooling is the most effective in reducing module temperature among various active cooling techniques with an efficiency improvement in the range of 10-15% [10-11]. Shukla et al. carried out a review work of different cooling methods of PV module and observe that PCM assisted cooling is the most effective cooling mechanism while thermoelectric cooling being the most inefficient [12].

While the aforementioned studies enlist review works, several experimental works have also been conducted to corroborate these findings. Nebbali et al. utilized the properties of pulsed air to cool the PV module. This is an active cooling method which resulted in an efficiency improvement of 71.43% [13]. Leow et al. investigated the temperature profiles of solar panel by changing wind velocities using ANSYS. Their experiment shows that as the wind speed increases, the panel temperature decreases due to increased convection [14]. Jakhrani et al. fabricated and analysed an active cooling system to enhance the performance of panel and achieved an increase of 6.7% in efficiency by making use of aluminium fins [15]. Syafiqah et al. evaluated the temperature drop of PV panel by altering the number of fans. Lowest operating temperatures were observed with maximum number of fans, with a temperature drop of 18^{0}C [16]. A recent study, with the help of simulation software, emphasises that increasing heat transfer area and increasing the convective heat transfer coefficient can lead to reduction in panel temperature. This increase in heat transfer area can be achieved using heat sinks i.e. fins. [17]. A study conducted by Sharma et al. uses fins to improve the electrical efficiency of solar panel. The authors observed an efficiency improvement of 5-6% using air cooled heat sinks [18].

These studies collectively reiterate the fact that an adequate cooling technique can enhance the efficiency of PV module while not affecting the overall economics of the system. This paper aims to mathematically, with the help of heat transfer relations, determine the optimum dimensions of heat sink to maximize the reduction in solar panel temperature.

3. Problem Identification

The previous works have made use of heat sinks to improve the performance of solar panel but have not considered the appropriate design factors of the heat sink like thickness, spacing of fins, optimum number of fins etc. A proper design can help elevate the temperature reduction effectively. While certain assumptions are necessary as it is very difficult to control all factors, the authors of this work have tried to maintain accuracy in the results. The material selected for rectangular fins is Aluminium. Although it has lower thermal conductivity compared to copper, it is relatively cheaper. The width of fins is predetermined in accordance with the width of the solar panel. The wind velocity is decided by considering an annual average of the location of study i.e. Hamirpur, India while the ambient temperature is maintained at 25^{0}C. Figure 3 shows a cross section of rectangular fins [19].

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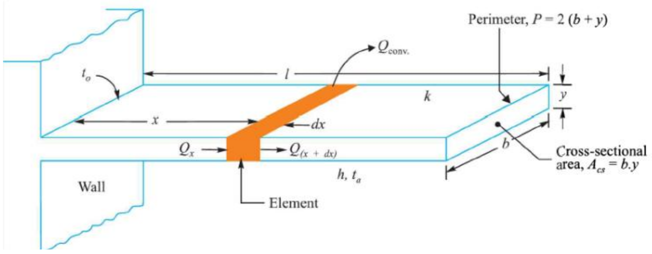

Figure 3: Cross section of rectangular fin

4. Design Methodology

The PV panel used for this study is amorphous silicon solar panel of the following specifications:

Table 1: Specifications of Panel Used in study

Manufacturer	Orb Energy
Nominal Peak Power P_{MPP}	5 W
Open Circuit Voltage V_{OC}	26.70 V
Short Circuit Current I_{SC}	410 mA
Maximum Power Voltage V_{PM}	17 V
Maximum Power Current I_{PM}	295 mA
LxB	0.405x0.345 m^2

The known parameters for determination of fin data are given below:

Average ambient wind speed (U) (calculated for the location of study from the period 30th August 2017 to 30Th August 2018)-1.8 m/s

Ambient Temperature (T_A): 25^0C

Width of Fins (b): 0.3 m.

Difference between backside panel temperature and ambient $\Delta T = 20^0$C.

Since PV modules are rated at STC radiation of 1000 W/m^2, the design for fins has also been carried out for same radiation value. The energy balance for the module can be given by equation (ii)

$$E_{in} = E_{out} + E_{LOSSES} \qquad \text{(ii)}$$

E_{IN} is the incoming solar insolation whereas E_{OUT} is the electrical output achieved from the solar PV module. The losses that are incurred include the loss of energy in the form of heat which is responsible for the rise in the PV module temperature [20]. Using equation (iii), the increased heat transfer by the use of heat sink can be determined.

$$Q_{Fin} = h * A_C * \Delta T * N_{OPT} \qquad \text{(iii)}$$

PV cell absorbs the radiation of a particular wavelength spectrum which is of the same range as the PV cell semiconductor. Remaining radiation is the loss that is depicted in equation (ii). The remaining radiation is of wavelength that is not absorbed by the PV module and results in heating of the PV module. This heat is conducted down to the backside of the module causing the backside temperature to be 20^0C-30^0C greater than the surrounding temperature. Studies indicate that the back surface temperature is a close approximation to the cell temperature; hence it is safe to design the heat sink for the back surface temperature [21].

The correlations used to determine the fin dimensions are described in table 2.

Table 2: Correlations for determining fin dimensions [22]

Reynolds Number	Re	$\left(\frac{Ub}{\nu}\right)$ Where; ν = kinematic viscosity of air at 25^0C = 1.5 x 10^{-5} m^2/s
Convective Heat Transfer Coefficient	h	$0.664 * \left(\frac{K_{air}}{b}\right) * (Pr^{0.3}) * (Re^{0.5})$ Pr- Prandtl Number =0.7 K_{AIR} = Thermal conductivity of air at 25^0C = 0.028
Volume of Fin	V_{FIN}	$V = m/\rho$ ρ= density of fin material (aluminium)= 2.707 g/cm^3
Thickness of fin	t_{FIN}	$t = \left(\left(\frac{V_{fin}}{b}\right)^{0.66}\right) * \left(\left(\frac{h}{K_{al}}\right)^{0.33}\right)$ K_{AL} = Thermal conductivity of Aluminium= 205 W/mK
Height of Fin	H_{FIN}	$H_{fin} = \left(\left(\frac{V_{fin}}{b}\right)^{0.33}\right) * \left(\left(\frac{h}{K_{al}}\right)^{-0.33}\right)$
Spacing between Fins	S_{OPT}	$S_{OPT} = 3.2 * (Pr^{-0.25}) * (Re^{-0.5}) * b$
Optimum Number of Fins	N_{OPT}	$N_{OPT} = \frac{L_{PANEL}}{S_{OPT} + t_{FIN}}$ Where L_{PANEL} = length of test PV panel

These correlations help determine the optimum size of fins that should be utilized for enhancing heat transfer from the panel thereby reducing the panel temperature thus increasing the efficiency. The above relations are derived with the assumption that the fin has a low slenderness ratio i.e. the ratio of thickness of fin to its height is less than one. Along with this, it has also been assumed that all the heat from the PV module is being distributed to the ambient through the backside of the module with no radiation or convection occurring from the remaining faces of the panel. It has also been assumed that the backside EVA layer and PVF film

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offer negligible thermal resistance to the conduction of heat to backside of PV module.

5. Results

Using the correlations mentioned in previous section and using the known data, the optimum fin dimensions for particular PV module can be deliberated. The results obtained show that for maximum heat dissipation, it is necessary that the fins to be designed be thin and closely packed. The geometry of heat sink obtained using mathematical relations are mentioned hereafter:

Fin dimensions: b x H x t = 0.3 x 0.02 x 0.00204 m^3
Spacing between adjacent fins: S_{OPT} = 0.0055 m
Optimum number of fins for panel length 0.38 m = 50

Using equation (iii), the maximum possible heat dissipated using the heat sink from backside of PV module to atmosphere amounts to 126.36 W. This heat transfer may vary at any given point in relation to the difference between the module backside and ambient temperature, thus reducing the back surface temperature of PV panel. The use of heat sink thus creates a temperature gradient in the direction of heat sink causing excess heat to flow in direction of gradient, thereby having the overall effect of reduction of PV module temperature. Using the aforementioned mathematical relations, a heat sink can be designed for optimum performance for any given PV module. The heat sink obtained is designed for the case of natural convection. The results will vary significantly if forced convection is considered. A close approximation to optimum size of heat sink for has been realised, however the best results can only be achieved after considering the weight limitations and the economics of heat sink. The efficiency of the fin can be calculated using equation (iv).

$$\eta = (\tanh(m * H_{fin}))/(m * H_{fin}) \qquad \text{(iv)}$$

The above equation shows that for the designed fin dimensions, an efficiency of 99% can be achieved. This highlights the result that for the calculated dimensions, the heat transfer will be most effective. Figure 4 and 5 showcase the temperature distributions on the test panel under given irradiation with and without heat sink respectively. The figures show that by using an optimally designed heat sink, a reduction in temperatures of the PV panel in the range of 30^0C-40^0C can be achieved. It can be observed from the figure that using a heat sink of optimum design can help in reducing the temperature of PV panel thus affecting the electrical efficiency.

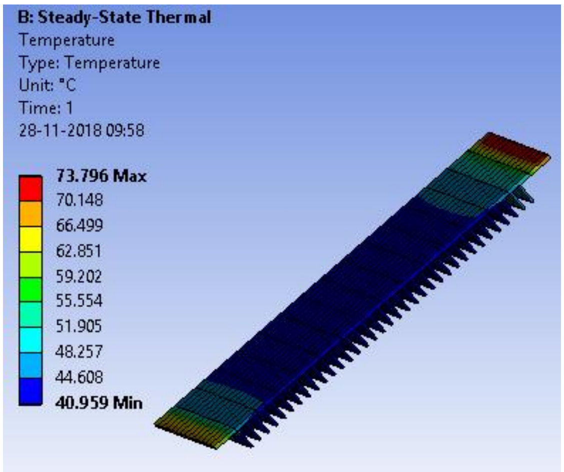

Figure 4: Temperature distribution of test panel using heat sink

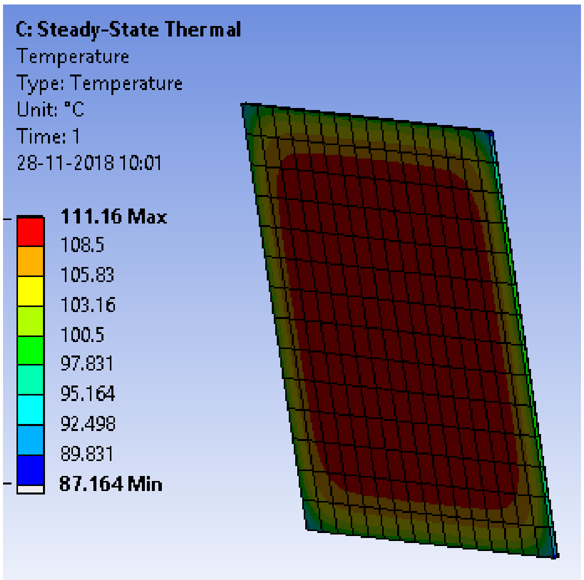

Figure 5: Temperature distribution of test panel for bare panel condition

6. Conclusion

Although promising, PV technology still faces a number of challenges in achieving maximum output. One such barrier is the effect of high ambient and module temperatures on the working of PV module. A significant number of cooling technologies have developed over the years with the purpose of maintain the PV module temperature within subscribed limits. Optimum design of these cooling systems is of utmost importance as they may determine the overall economics and efficiency of the PV system. One such technique is the use of a heat sink for natural or forced convective cooling of PV module. The design of a heat sink for PV module of known dimensions has been carried out in this work and the best possible design has been realised. The results thus obtained are further analysed using ANSYS software. The simulation work stipulates that proper designing of heat sink can help achieve maximum temperature reduction thus enhancing the electrical efficiency of PV panel. Certain assumptions are necessary to design an optimum heat sink but most accurate results can be achieved by considering the weight limitations and economics of heat sink.

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