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Research Paper

Reducing the thermal load of a photovoltaic module through an optical water filter

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ABSTRACT

This paper presents new experimental investigations to reduce the accumulation of heat in a photovoltaic module. The optical water filter is placed above the photovoltaic module used to absorb the undesired infrared spectra and converts it to heat, and also transmits the visible spectra to the photovoltaic module to produce electricity simultaneously. In this work, the temperature of the solar cells was measured at various water thickness in the filter (1–5 cm) and different distance between the filter and the photovoltaic module (1–3 cm). Results show that there is a significant effect of the water layer thickness on the temperature reduction of the solar cells (14–30.2%), while showed lower impact of the distance between the filter and the photovoltaic module (6.2–12.2%).

1. Introduction

Worldwide, using photovoltaic (PV) systems to generate clean electricity is increasing continuously where in the year 2014, 40 GW of generation capacity were added worldwide to increase the global total generation capacity to about 177 GW [1]. The reduction in manufacturing cost of the PV modules is the main factor for developing this sector [2], in addition to other advantages like ease of installation, low maintenance cost, no moving parts and noiseless, safe, and generation of clean electricity at different scales suitable for different applications [3]. On the other hand, the main disadvantage of PV modules is that the power output depends on weather conditions such as solar radiation [4,5] and ambient temperature [4,6]. Decreasing the solar radiation intensity reduces the output current of the PV, while increasing the ambient temperature leads to increasing the solar cell temperature which reduces the PV output voltage leading to reduction in the overall and PV efficiency [7]. Also, increasing the cell temperature produces higher thermal stresses and hot spots on PV module, thus reducing the working life of the PV cells.

To overcome these drawbacks of the PVs, several methods were investigated which can be categorised in three enhancement techniques. Firstly, increasing the input solar radiation to the PV module using different types of concentrators (CPV) thus increasing the PV output current [8]. However, increasing the input radiation increases the PV temperature leading to a reduction in the PV output voltage [9]. Secondly, reducing the cell temperature of the PV module by removing the accumulated heat from the cell and using this heat for thermal application (PVT). In PVT systems, a cooling fluid like water or air is passed through channels attached to the back side of the PV module to remove the accumulated heat from the solar cells, and delivered this heat for thermal applications [10–15]. The advantage of PVT systems is not only reducing the cell temperature but also producing electrical power and thermal energy simultaneously leading to savings in the energy cost [16]. However, the main limitations of the PVTs are the low temperature of the thermal energy produced, and the higher cost compared with conventional PV module [9]. Thirdly, increasing the input solar radiation technique using concentrators (CPV system) and reducing the cell temperature (PVT) simultaneously known as Concentrated Photovoltaic Thermal (CPVT) systems [17]. The CPVTs are considered a superior heat and power generation systems which reduces the drawbacks of the CPV and PVT systems [9], making CPVTs suitable for different applications [18–25].

In PV, PVT, and CPVT systems, different methods were proposed to reduce the cell temperature including collect in the wind by a conical tunnel [26], using ventilator exhaust air [27], applying phase change materials [28] and graphite [29] to cool the backside

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Nomenclature

Abbreviations

CPV	concentrating photovoltaic
CPVT	concentrating photovoltaic/thermal
CR	concentration ratio
DHW	domestic hot water
FF	Fill Factor
IR	infrared
NOCT	normal operation cell temperature
OWF	optical water filter
PV	photovoltaic
PVT	photovoltaic/thermal
STC	Standard Test Conditions
UV	ultraviolet
VIS	visible

Symbols

A	surface area of photovoltaic module (m^2)
c_p	water specific heat (J/kg K)
dT	water temperatures difference (K)
G	solar irradiance after the optical water filter (W/m^2)
G_o	solar irradiance before the optical water filter (W/m^2)
I_{pm}	current at maximum power (A)
I_{sc}	short circuit current (A)
P_{max}	power at maximum power point (W)
T	transmittance (%)
T_a	ambient temperature (C)
T_c	cell temperature (C)
V_{oc}	open circuit voltage (V)
V_{pm}	voltage at maximum power (V)

of the cells, using refrigerant (R134a) as a working fluid in heat pump cycle coupled with CPV module [30], and using water as a PV coolant [31–36].

There were many papers studied several methods for PV-water cooling. Baloch et al. [31] presented a new design of a water-thermal collector placed underneath the PV strings, and evaluated experimentally under Saudi Arabia weather conditions. Their results showed that the percentage reduction in the cell temperature of 57.8% in June and 32.7% in December compared with PV without cooling. Bahaidarah et al. [32] studied the performance of PVT water system under outdoor weather condition in Dhahran, Saudi Arabia during February. The water was pumped directly under the tedlar layer of the PV to remove the heat from the backside of the cells. Their results showed that the PV temperature reduction rate was 34%. Colmenar-Santos et al. [33] proposed to use the water canal for cooling PV modules. The Tajo-Segura canal in Spain with the environmental conditions in July was considered in the simulation. Their results showed that PV temperature reduced by 53.3%. Moradgholi et al. [34] presented a PVT system where thermosyphon heat pipe with water cooling jacket was coupled to the back side of PV module to absorb the excessive heat from the cells. Based on their results, the PV cell temperature reduced about 26%. Chandrasekar et al. [35] proposed a passive cooling system for PV module using a cotton wick with different cooling nanofluids attached on the back side of the PV module under the outdoor environment conditions in Tiruchirappalli, India during April. Their results showed that the PV temperature reduction is about 30% with wick-water cooling, 11% with wick- CuO/water nanofluid cooling, and 17% with wick-Al_2O_3/water nanofluid cooling. Nižetić et al. [36] used three techniques for water spray (front, back, and simultaneous front and backside) to cool a PV module in outdoor during summer day in Croatia. Their results showed that the percentage of PV temperature reduction for the back water spray cooling, front water spray cooling, and both sides spray cooling techniques were about 42.8%, 58.9%, and 60.7%, respectively.

The above studies showed that different methods of reducing the PV module temperature to enhance the electrical output at different weather conditions were investigated. However, some of these have higher complexity, applied only in specific locations and times, needs extra power for cooling, and some of them are costly. It can be concluded that there is a need for a PV cooling technique that can remove the heat from the cells to be used in thermal application, applied throughout year, low cost, and more practically acceptable.

2. Optical water filter: a stat of art

The main reason for the increases of the PV module temperature is that the PV cells can't convert all solar radiation to electricity and some of the radiation is converted to heat. Solar radiation consists of three types of spectra [37]: 8% of Ultraviolet UV (0.2–0.38 μm), 36% of Visible VIS (0.38–0.78 μm), and 46% of Infrared IR (0.78–2.5 μm). Silicon PV cells converts only the VIS and some of IR to electricity, and the rest of spectra is converted to waste heat. Although several cooling techniques were used which reduced the cell temperature as described above, these methods place the cells under cyclic thermal stresses due to periodic heating and cooling processes, and also cause hot spots on some cells due to non-uniformity in the cooling. These thermal stresses and hot spots in the PV module lead to reducing the power output and decreasing the working life of the module.

Thus, water can be used as a spectrum splitter for the silicon PV module where placing water layer above the solar cells can absorb the undesired infrared and convert it to heat. This heat can be used in small or large scale for thermal applications such as domestic hot water, space heating, or water desalination. Rosa-Clot et al. [38] studied the performance of PV module submerged under water. Two PV modules were submerged under 4 cm and 40 cm water depth in a pool while the third PV module placed outside the pool under direct solar radiation for comparison. The test was carried out under outdoor conditions in Pisa, Italy. Their results showed that the average electrical efficiency is increased by around 11%, at the 4 cm water depth, while the average electrical efficiency decreased by 23% at 40 cm water depth. Rosa-Clot et al. [39] proposed a polycarbonate box placed above the PV module and contained 2.5 cm depth of flowing water. The thermal and electrical performance of the system tested under outdoor weather condition in Pisa, Italy. Their results showed that the average yearly thermal, electrical, and total efficiencies are about 4.39%, 12.87%, and 17.3%, respectively. In another work, Rosa-Clot et al. [40] tested experimentally performance of the PV with the polycarbonate box and compared to the performance of conventional PV without box. The polycarbonate box placed above the PV and filled with water for a depth of about 2 cm. The two systems were tested under outdoor conditions in Enna and Pisa cities, Italy. Their results showed that the average electrical efficiency of conventional PV is 13.19%, while of the efficiency of PV with water-box is 6.77%. This reduction in the electrical efficiency is due to the radiation absorption by water and optical losses. In addition to that, they mentioned that the additional weight of the box with the water