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Cooling methodologies of photovoltaic module for enhancing electrical efficiency: A review

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ABSTRACT

Solar Photovoltaic (PV) cells can absorb up to 80% of the incident solar radiation obtained from the solar band, however, only a small amount of this absorbed incident energy is transformed into electricity depending on the conversion efficiency of the PV cells and part of remainder energy increases the temperature of PV cell. High solar radiation and ambient temperature lead to an elevated photovoltaic cell operating temperature, which affects its lifespan and power output adversely. Number of techniques have been attempted to maintain the temperature of photovoltaic cells close to their nominal operating value. In the present review various cooling techniques such as natural and forced air cooling, hydraulic cooling, heat pipe cooling, cooling with phase change materials and thermoelectric cooling of PV panels are discussed at length. It is important to note that, though cooling techniques are highly needed to regulate the PV module temperature, especially for mega installations, these should be economically viable too.

1. Introduction

The growing global demand for electricity, rising fossil fuel prices and increasing apprehensions about global warming have reenergized the idea to rapidly move towards renewable energy resources, especially during last two decades. Solar energy is the most abundant energy source available on the earth. Though technologies for converting sunlight energy to power have made a lot of progress, high capital price and low conversion proficiency are the main obstacles to the common use of these technologies. In order to increase the efficiency of solar power generation and make it a more cost-effective technology, different approaches have been attempted over the years consistently.

Photovoltaic (PV) is a method of transforming sunlight into electricity with the help of semiconductor materials that show the photovoltaic effect. Photovoltaic systems are composed of a number of solar cells to supply serviceable solar power. Power generation from solar PV is a clean and sustainable tool, which depends upon the planet's most ample and widely spread renewable energy source of the sun. Straight transformation of sunlight to electricity takes place without any moving parts or environmental releases through the process. This technology is well recognised, as photovoltaic systems have now been used for over fifty years both for stand-alone uses, and grid-connected installations. It is well known that the efficiency of photovoltaic solar cells declines with an increase in temperature. This decline is determined first of all by the drop of open- circuit cell voltage, and therefore, an efficient performance of PV cells in conditions, for example, of concentrated sunlight, needs to be cooled. Earlier theoretical studies [1–5] have shown the efficiency decrease which is expected, but the carrier transport mechanism put a significant effect on the actual temperature coefficient of the efficiency, and in different cases could differ significantly depending on the ambient conditions; the effects of recombination generally increase the efficiency deviation with temperature.

2. Temperature effect on photovoltaic cells

PV cells absorb 80% of incident solar radiation, but they do not fully convert it into electricity. The conversion efficiency depends upon the PV cell technology used. The remainder part of solar radiation increase solar cell temperature up to 40 °C above the atmospheric temperature [6]. This is due to the fact that PV cells convert a range of definite wavelength of the solar spectrum of light into electricity and the rest of the incident solar spectrum is converted into heat [7]. The conversion efficiency of single junction solar cells ranges between 6% and 25% under optimal operating conditions, which depends upon the semiconductor material used for the preparation of the solar cell [8,9].

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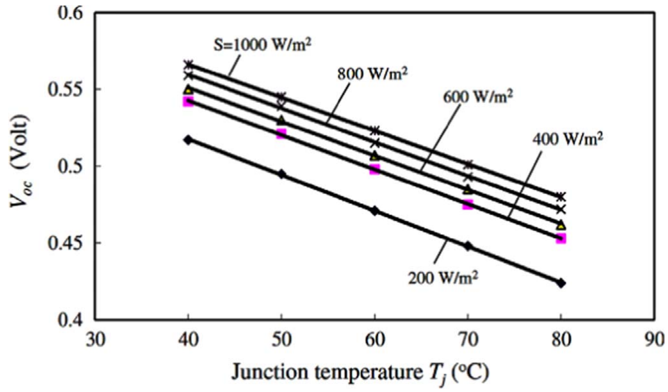

Fig. 1. Variation of open-circuit voltage with a junction temperature of PV cell [13].

Various elements affect the performance of PV modules which are installed in outdoor locations. Influences of low irradiance, dust accumulation on PV panels, and elevated operating temperatures leads to the reduction of photovoltaic conversion efficiency and technical lifetime [10,11]. The efficiency of PV cell decreases due to increase in intrinsic carrier concentrations at higher temperatures, which tend to upsurge the dark saturation current of the p–n junction [7,12]. Decrease in band-gap due to high doping also helps to upsurge the intrinsic carrier concentration [7]. The increase in dark saturation current causes the open-circuit voltage to decrease linearly which for silicon at 300 K corresponds to about −2.3 mV/°C [7]. Huang et al. [13] performed an experimental investigation to see the effect of operating temperature on the variation of open-circuit voltage with temperature (40–80 °C) at different solar radiation (200–1000 W/m^2), Fig. 1.

Fig. 2(a, b) shows the variation of power output with voltage for different temperatures. The short circuit current, increases up to some extent due to drop in the band-gap energy, Fig. 3. Andreev et al. [14] estimated an increase in the short circuit current of 0.1%/°C due to a reduction in the bandgap of the solar cell with temperature varying between 20 and 100 °C. In spite of this increase in current, the degradation of the open-circuit voltage leads to an evident decrease in the available maximum electrical power which can be better observed in the characteristic curves of PV modules at different operating temperatures in Fig. 3. For crystalline silicon PV cells, a drop in the electrical power output of about 0.2–0.5% is seen with an increase of 1 °C PV module temperature, principally due to the temperature dependence of the open-circuit voltage of the cell [15,16]. This property of PV cells is known as the temperature coefficient. According to Del Cueto [17], the decrease in efficiency due to temperature is in the range of e 1–2% for PV panel lying above a temperature span of 30 °C. Table 1 presents the temperature coefficients of various PV technologies along with their typical efficiencies [18–21].

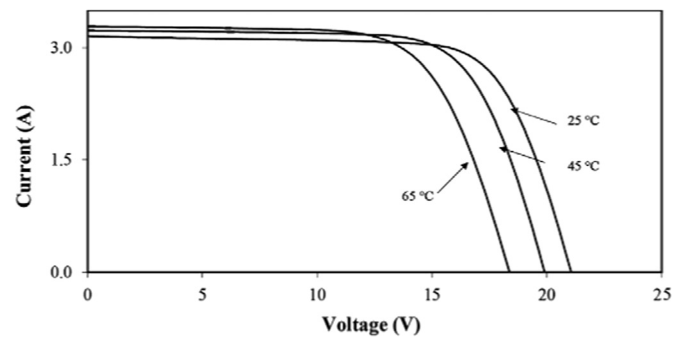

Fig. 3. Influence of temperature on PV module I–V curve [14].

Table 1
Temperature coefficients of different PV cell technologies.

T_{ref} (°C)	ηT_{ref} (%)	βref (°C^{-1})	PV technology	Refs.
25	16–24	0.0041	Mono-cSi	[20]
25	14–18	0.004	Poly-cSi	[21]
25	4–10	0.011	a-Si	[21]
25	7–12	0.0048	CIS	[17]
25	10–11	0.00035	CdTe	[17]

3. Temperature regulation systems: a review

The temperature regulation of photovoltaic panels can be achieved by several methods such as air cooling, water cooling, use of heat pipe, phase change materials and thermoelectric cooling. Some of these methodologies have been excellently reviewed by chow et al. [22] and Moradi et al. [23]. In the present study, all these available cooling methodologies (have been reviewed and the merits and drawbacks of these cooling techniques with a comparable outlook are presented Summary of the same is also given in tabular form in Table 2.

3.1. Air cooling

3.1.1. Natural air circulation

Air-cooling with a natural flow due to stack effect represents a non-expensive and simple method of PV cooling. In the natural air cooling, no extra arrangement is required for cooling PV panels. However, systems with heat extraction by natural air circulation are limited in their thermal performance due to the low density, the lower volumetric heat capacity and thermal conductivity of air and measures for heat

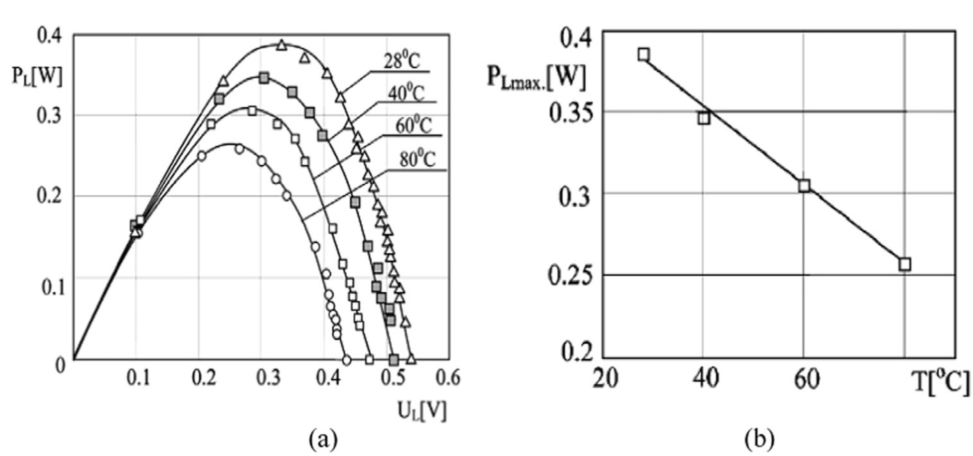

Fig. 2. The output power of single-crystalline silicon PV cells at different operating temperatures (a) temperature dependence of the maximum output power (b) [9].