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Optical filter design applied to photovoltaic modules to maximize energy production

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ABSTRACT

This paper proposes a method for evaluating and selecting the solar spectrum range to be absorbed by a photovoltaic cell to obtain a better relationship between radiation absorption for photovoltaic conversion and heating efficiency losses, in order to maximize the power generated by the cell. The methodology proposed considers the spectral response of the photovoltaic conversion technology and environmental operating conditions that affect the photovoltaic cell performance. The application of the methodology to a case study with real data from an equatorial location resulted in an optical filter that reflects wavelengths above 1000 nm. The application of this proposed filter reaches earnings between 6.8% and 1.1% in energy generated by crystalline silicon modules, depending on the reflectance of the filter.

1. Introduction

The solar spectrum is composed of a wide range of wavelengths. There are wavelengths in the solar spectrum that contribute little or nothing to electricity generation regarding photovoltaic technology. However, such spectrum frequencies contribute to increase the operating temperature of the cell and hence increase losses by heating (Radziemska, 2003; Roppolo et al., 2014).

Amorphous silicon cells are less sensitive to temperature; however, the spectral response is restricted to a small range of the solar spectrum. For this reason, they have lower efficiency than mono and polycrystalline silicon solar cells. Monocrystalline silicon solar cells are very sensitive to temperature while polycrystalline have intermediate sensitivity (Halden; Taylor et al.).

For this reason, particularly in hot regions, although polycrystalline silicon cells have lower efficiency in standard conditions than monocrystalline silicon cells, they can generate more power than monocrystalline silicon cells because they are less sensitive to temperature. Other technologies have different spectral responses and sensitivity to operational temperature.

In this article, it is proposed a methodology to design an optical filter that reflects wavelengths that heat the module without significant power generation and, thereby, reducing module temperature, increasing the whole amount of energy generated.

1.1. Wavelength range selection and solar spectrum splitting

The solar spectrum selection is an old idea, proposed in 1955 by Mojiri et al. (2013). This concept has been applied as an alternative option to multi-junction cells, in which cells with different semiconductors are ordered separately and receive the most appropriate spectrum range for promoting photovoltaic effect, improving the system efficiency as a whole.

Mojiri et al. (2013) describe a comprehensive review of the techniques applied to solar spectrum range selection to increase PV cell efficiency. It should be noted, among the findings of Mojiri, the cost of ideal optical filters is very high and needs to be balanced with the expected gain from applying this technique, because spectral splitting involves significant optical losses and, therefore, a lot of splitting shall be avoided.

Taylor et al. suggest the use of an optical filter based on nanoparticles in water suspension. This fluid is circulated in the module to filter the radiation incident on the cell and is heated for hybrid solar photovoltaic/thermal applications.

Roppolo et al. (2014) proposed a coating that reflects radiation with a wavelength greater than 1200 nm. The temperature of the modules tested with this coating was less than the temperature of the modules without it. However, the efficiency of the cell was smaller than without the coating, due to increased reflection of the useful radiation.

Russo et al. (2014) evaluate the theoretical effectiveness of using four types of cells (InGaP2, GaAs, Si, and GaSb), and the separation of the solar spectrum for each cell receives the radiation range that would

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provide maximum efficiency for electricity production. This study concludes that ideal filters could reach an efficiency of 41.65% in experimental cells. The study does not consider the concentration of radiation and suggests it as a matter for later studies.

Imenes et al. (2006) propose that an optical filter splits the range from 700 nm to 1100 nm to direct it to photovoltaic generators and that the remaining radiation be directed to the absorber in an Australian solar thermal power plant.

Sebastian and Pattabi (1992) and Sebastian and Sivaramakrishnan (1991) investigated the properties of a thin film of copper selenide and Cadmium/Telurium selenide to avoid photovoltaic modules heating in tropical regions. The optical properties of this filter were not adequate and although it reached the desired effect, there was no energy production gain with the filter application.

Many sol-gel coatings for ultraviolet radiation reflection and anti-glare for the near infrared radiation are intensively researched (Barrera et al., 2008; Prado et al., 2010; Amri et al., 2014).

In this context, there are no studies that calculate the near infrared or ultraviolet wavelength range that could be rejected, with efficiency gains, even promoting the photovoltaic effect.

1.2. Mathematical model of crystalline silicon solar cells

Radziemska (2003) and Radziemska and Klugmann (2002) modelled a crystalline silicon photovoltaic cell as a function of cell temperature to study the effect of temperature on its performance. In this study, the short circuit current, which the authors called photocurrent is calculated by Eq. (1).

$$I_{ph}(\lambda) = \eta(\lambda)\cdot e\cdot\frac{P(\lambda).\,\lambda}{h.\,c} \tag{1}$$

where

$I_{ph}(\lambda)$ is the photocurrent [A];
$\eta(\lambda)$ is the quantum efficiency of the cell;
e is the electron charge [1.6×10^{-19} C];
P(λ) is electromagnetic radiation [W/m^2];
λ is the wavelength [nm];
h is Planck's constant [6.63×10^{-34} m^2 kg/s]; and
c is the speed of light in vacuum [2.998×10^{8} m/s].

The dark current is set to 10^{-9} A for 0 °C and temperature coefficient of the dark current is 14.5%/K from Radziemska and Klugmann (2002).

$$I_{so} = (1+0.145\cdot(T-273))\cdot10^{-9} \tag{2}$$

The output current I_L is calculated by:

$$I_L = I_{ph}-I_{so}\cdot\left(exp\frac{e\cdot U}{m\cdot k\cdot T}-1\right) \tag{3}$$

where

I_L is the output current [A];
I_{ph} is the photocurrent [A];
I_{so} is the dark current [A];
e is the electron charge [1.6×10^{-19} C];
U is the output voltage [V];
T is the cell temperature [K];
K is the constant Boltzmann [1.38×10^{-23} J/K]; and
m is the ideality factor of the cell.

The open circuit voltage $U_{oc}(T_0)$ is calculated as:

$$U_{oc}(T_0) = \frac{m\cdot k\cdot T_0}{e}\cdot ln\left(\frac{I_{ph}}{I_{so}}+1\right) \tag{4}$$

For an E_{g0}, the semiconductor energy band gap is 1.12 eV for crystalline silicone at 300 K and the open circuit voltage corrected by the effect of the cell temperature T is calculated as (Radziemska, 2003):

$$U_{oc}(T) = U_{oc}(T_0)\left[\frac{E_{g0}}{e}-U_{oc}(T_0)\right]\cdot\left(\frac{T}{T_0}-1\right)-\frac{3\cdot k\cdot T}{e}\cdot ln\left(\frac{T}{T_0}\right) \tag{5}$$

where

$U_{oc}(T)$ is the open circuit voltage [V];
e is the electron charge [1.6×10^{-19} C];
T_0 is the reference temperature [300 K];
T is the cell temperature [K];
N_A is the acceptor concentration [10^{-22} m^{-3}];
N_D is the donor concentration [10^{-21} m^{-3}]; and
K is the constant Boltzmann [1.38×10^{-23} J/K].

Radziemska and Klugmann (2002) compute the derivative (5) and concluded that the voltage function of temperature variation is constant and equals −0.00245 V/K. Therefore, the open circuit voltage is calculated as:

$$U_{oc}(T) = U_{oc}(T_0)-0.00245\cdot(T-298) \tag{6}$$

In Benda (2012), the cell relative resistance to the intensity of radiation is evident. This is because the resistance is a function of temperature.

Bunea et al. (2006) studied the crystalline silicon cell performance at low radiation and assigned the shunt resistance to severe loss of efficiency at low radiation intensities. The voltage is calculated according to the short circuit current; it is not necessary to add correction. The correction commonly used for the shunt resistance is:

$$I_L = I_{ph}-I_{so}\cdot\left(exp\frac{e\cdot U}{m\cdot k\cdot T}-1\right)-\frac{U}{Rsh} \tag{7}$$

where

I_L is the output current [A];
I_{ph} is the photocurrent [A];
I_{so} is the dark current [A];
e is the electron charge [1.6×10^{-19} C];
U is the output voltage [V];
T is the cell temperature [K];
R_{sh} is the shunt resistance (Ω);
K is the constant Boltzmann [1.38×10^{-23} J/K]; and
m is the ideality factor of the cell.

In their study, Hirst and Ekins-Daukes (2011), modelled the cell efficiency depending on the temperature of the cell, the spectrum temperature and the solid angle of emission, since the solid angle of absorption is a parameter of the cell in question. This simplification uses the solid angle of emission, and is based on Markvart (2008). This variable is directly proportional to current and voltage. Thus, the intensity of radiation is demonstrated not to be affected the Boltzmann loss because this loss is a function only of the solid angle of emission of the source. The use of optical filters does not change the solid angle of emission.

2. Optical filters design methodology applied to photovoltaic cells

An optical filter is defined by the amount of electromagnetic radiation it reflects, absorbs or transmits in each wavelength. The optical filter can avoid the cell heating up unnecessarily if it reflects waves below a certain initial wavelength (WL_i) and reflects wave above a given wavelength (WL_f). Waves between WL_i and WL_f shall be transmitted as much as possible, forming a window of incident radiation absorption by the PV cell. Therefore, these two variables are decision variables to design the optical filter. The goal is to maximize the energy generated by the module (E_g) at a given time horizon under certain environmental conditions. The energy generated is calculated by: