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Effect of different operating conditions on the conversion efficiency of triple-junction solar cell

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Abstract

In this work, a theoretical study based on the detailed balance limit has been carried out for the performance evaluation of series-connected triple-junction solar cell. The effect of different operating conditions on the conversion efficiency of the solar cell is evaluated by numerical modeling using MATLAB. The performance has been measured for three standard spectra (AM0, AM1.5D and AM1.5 G) and over a range of temperatures (273 K–523 K) under varying solar concentration. It has been observed that changes in operating conditions have a significant impact on conversion efficiency. The conversion efficiency is found to be highly sensitive to spectrum distribution. By selecting the appropriate bandgap combination as per the incident spectrum, conversion efficiency is improved significantly. The effect of temperature on the conversion efficiency is mitigated by increasing the ratio of solar concentration. The finding of the present study indicates that appropriate combination of bandgap and solar concentration can be an effective tool to improve the conversion efficiency. This study can further be extended for higher generation solar cells to evaluate their performance.

1. Introduction

Solar cell is a semi-conductor device that directly converts light into electrical energy. To explore the new designs of solar cells, limiting efficiency is often used. In 1961 W. Schlocky and H.J. Queisser introduced detailed balance limit theory to calculate the upper conversion efficiency of P-N junction solar cell [1]. In the proposed methodology the solar spectrum is approximated as a black-body spectrum with surface temperature of 6000 K. Radiative recombination is only responsible for the losses inside the solar cell. Other losses such as resistive, optical and thermal are not considered in this methodology. In the detailed balance limit model, the conversion efficiency of the solar cell is independent of material property and the device design [2]. It only depends upon the bandgap of the material, which limits the absorption of the solar spectrum [3]. In this calculation method, it was assumed that a photon having energy (hν) greater than semiconductor bandgap energy (Eg) generates an electron-hole pair with 100% quantum efficiency. The maximum calculated efficiency for single-junction solar cells employing the detailed balance limit is reported to be 30% close to the bandgap of 1 eV [1]. In the recent calculations, the solar spectrum at the earth’s surface is defined by the American Society for Testing Materials (ASTM) [4]. At present, maximum conversion efficiency for single junction solar cell is reported to be 33.7% at band gap of 1.34 eV using the AM1.5D spectrum [5]. Over the years, several studies have been carried out for the estimation of maximum conversion efficiency of solar cells employing detailed balance limit with different assumptions. The detailed balance limit methodology has also been applied for different types of solar cells such as nanostructured solar cells, multiband solar cells and multi-junction solar cells [6–11]. Among them, Multi-junction solar cell appears to be one of the most promising designs to surpass the limiting efficiency of single-junction solar cells [12]. In multi-junction solar cells (MJSC), different semiconductor materials having different bandgaps are stacked monolithically in order to absorb a wide range of solar spectrum leading to high conversion efficiency [8]. The concept of multi-junction solar cell having double and triple junctions has been pursued extensively as reported in literature [13]. Based on the detailed balance limit, maximum theoretical
conversion efficiency for dual and triple junction solar cell is estimated to be around 45% and 51% respectively [9]. Triple-junction solar cells are based on III-V semiconductors which have shown high efficiency among the photovoltaic technology. Currently it is being used in commercial production. At high solar concentration, triple junction solar cells are the typical choice for terrestrial and space application [14, 15]. In addition, their operations at high solar concentration make it cost-effective due to its high conversion efficiency. Irrespective of these advantages, triple-junction solar cells are still facing critical challenges such as lattice matched bandgap combination and reduced efficiency at real-time operating condition, which requires in-depth study.

Most solar cells are rated and designed as per the standard reference spectrum, such as the black-body spectrum at 6000 K or AM1.5D spectrum with the operating temperature of 298 K. However, the conversion efficiency of solar cells is highly dependent upon the operating conditions such as spectrum distribution, cell temperature and solar concentration. Furthermore, the sensitivity to operating conditions is critical for solar cell design, especially for current constrained multi-junction solar cells [16]. In real time operating condition multi-junction solar cell is exposed to much higher solar concentration, along with different spectrum distribution and elevated temperature. To the best of our knowledge no study has been performed systematically considering the effect of varying solar concentration with spectrum distribution and operating temperature.

In this paper, a theoretical investigation has been carried out for the performance evaluation of the triple-junction solar cell under different operating conditions. Using numerical modeling with MATLAB, under varying solar concentration, effect of different solar spectra along with range of cell operating temperature on the conversion efficiency has been studied. At the same time, the effect of bandgap optimization at different operating conditions is also discussed. The findings of this study could be used for selecting the design parameter of solar cells for improving conversion efficiency under real-time conditions. This study can also be extended for other generation solar cells for their performance evaluation at different operating conditions.

2. Methodology

2.1. Modeling and calculation

In the proposed model, a classical single diode model is used to describe the current-voltage characteristics of the PN junction solar cell. In this model output current of the solar cell under illumination can be described as [17]

\[ J = J_o \left[ e^{\frac{qV}{kT}} - 1 \right] - J_{ph} \]  

where \( J \) corresponds to output current density, \( J_{ph} \) is light generated current, \( J_o \) belongs to recombination current, \( q \) denotes the charge of an electron, \( V \) is the terminal voltage, \( kT \) represents thermal energy and \( T \) is the operating temperature. In equation (1), series resistance \( R_s \) is taken as zero, shunt resistance \( R_sh \) is assumed to be infinite and diode ideality factor \( n \) is considered to be unity. Usually \( J \) is calculated assuming zero reflection. The photo-generated current \( J_{ph} \) can be calculated using the solar spectrum [5]. It is expressed as

\[ J_{ph} = \int_{E_g}^{E_{max}} \phi_{ph}(E) \, dE \]  

where \( \phi_{ph}(E) \) represents the photon flux of reference solar spectrum (AM 1.5D). Here \( E_g \) is band gap energy of the semiconductor material and \( E_{max} \) is the band gap energy 4.43 eV (\( \lambda = 280 \text{ nm} \)) taken from ASTM G173-03 data [4]. Photon flux \( \phi_{ph}(E) \) can be expressed as

\[ \varphi_{ph} = \left( \frac{q \lambda}{hc} \right) \text{AM1.5D} \]  

where \( \lambda \) corresponds to wavelength, \( h \) represents the Planck’s constant and \( c \) is the speed of light. For the calculation of saturation current, only radiative recombination is considered in detailed balance limit. Using Planks radiative law, the saturation current \( J_o \) could be expressed as [9]:

\[ J_o = q \int_{E_g}^{\infty} \frac{2\pi E^2}{h^2 c^2} \frac{1}{e^{E/kT} - 1} \, dE \]  

Where \( E \) is the photon energy, \( V \) represents the applied voltage, Boltzmann’s constant is \( K_B \) and \( T_c \) is the cell temperature. The voltage across the output terminal \( V \) can be calculated by using equation (1) and assuming series resistance \( R_s = 0 \) and \( J_{ph} \approx J_{sc} \). It is expressed as:

\[ V = \frac{nK_T}{q} \ln \left( \frac{J_o + J_{ph} + f}{J_o} \right) \]  

The expression for open-circuit voltage \( V_{OC} \) can be obtained by setting \( J = 0 \) in equation (3). It can be expressed as:
\[ V_{OC} = \frac{nKT}{q} \ln \left( \frac{J_{sc}}{J_0} + 1 \right) \]  

(6)

\[ V_{oc} \text{ in terms of solar concentration } C \text{ can be further expressed as} [18]: \]

\[ V_{OC} = \frac{nKT}{q} \ln \left( \frac{J_{sc} \cdot C}{J_0} \right) \]  

(7)

Where \( J_{sc} \) is the short-circuit current at one sun concentration and \( C \) is the solar concentration ratio.

The generated power in terms of voltage and current density can be expressed as using equations (1) and (5):

\[ P = J_{out} V_{out} = J_{out} \left[ \frac{nKT}{q} \ln \left( \frac{J_{sc} + I_{c} + J}{J_0} \right) \right] \]  

(8)

The fill factor (FF) of the solar cell is the ratio of maximum power from cell to the product of \( V_{oc} \) and \( J_{sc} \) which can be expressed as:

\[ FF = \frac{V_{mpp} J_{mpp}}{V_{oc} J_{sc}} \]  

(9)

The output efficiency of solar cell is calculated from the product of current and voltage at maximum power point divided by the power of incident light. It can be computed using the equation (9) it is expressed as:

\[ \eta = \frac{V_{mpp} J_{mpp}}{P_{in}} = \frac{V_{oc} J_{sc} FF}{P_{in}} \]  

(10)

Here, \( P_{in} \) is the incident power density and \( P_{max} (V_{mpp} \cdot J_{mpp}) \) is the maximum power of the solar cell. For Multi-junction solar cell, the current-voltage data of each sub-cell are combined to generate the resultant current-voltage curve. In the case of the series-connected multi-junction solar cell, output voltage is the sum of individual voltage. Output current would be equal to the minimum current produced by any one of the sub-cell due to current constraint. The conversion efficiency is then calculated using the product of voltage and current divided by incident power, as expressed in equation (10).

### 2.2. Optimization of bandgap for maximum efficiency

Conversion of the solar energy of multi-junction cell is highly dependable upon the bandgap combination of the sub-cells. The search of optimum bandgap is performed over the 3D space for triple-junction solar cell by sweeping the bandgap in all possible combination. The best combination is expected to reach at one particular combinations of bandgap. In the developed algorithm objective function efficiency (\( \eta \)) is to be maximized for a set of unique bandgap combinations. The bandgap optimization is performed for a given set of cell temperature, concentration and spectrum distribution which corresponds to maximum power generated by cell. To extract the optimum bandgap combination iteration is performed for each bandgap combination for given set of operating condition. Maximum power in each iteration is calculated by output current-voltage curve of the solar cell. The sweeping interval between two consecutive bandgaps is taken as 0.01 eV in the developed algorithm. From the recorded data set maximum conversion efficiency and corresponding bandgap combination is extracted using the MATLAB function. The initial guess for bandgaps is based upon the physical acceptable range.

### 3. Results

Impact of the operating condition on the multi-junction solar cell is investigated using numerical modelling based on mathematical equations as described in the previous section. In this study, a series-connected triple-junction solar cell is used. As described earlier, maximum conversion efficiency is calculated for different bandgap combinations in the 3D space. Figure 1 shows the efficiency curve of triple-junction solar cell for different bandgap combinations at 298 K under one solar concentration and AM1.5D solar spectrum. Due to atmospheric absorption, different peaks appear in the efficiency curve. The maximum conversion efficiency is found to be 51.2% for the bandgap combination of 1.75/1.18/0.70 eV. Similar results have been reported in the literature for the triple-junction solar cells [19]. The calculated maximum conversion efficiency differs slightly from the reported results due to the use of different integration methods.

Similar approach has been applied to calculate the conversion efficiency and optimum bandgap combination at different operating conditions such as distinct solar spectrum and different temperature under varying solar concentration.

The impact of distinct solar spectrum and different temperature under varying solar concentration are discussed below.
3.1. Effect of solar spectrum distribution

As described earlier, solar cells are usually rated and designed for a standard reference spectrum AM1.5D or blackbody radiation at temperature 6000 K with cell temperature of 298 K. Under real-time operating conditions, solar cells are exposed to the different solar spectrum, which strongly affects the performance of solar cells [20, 21]. When exposed to different solar spectrum, series-connected multi-junction solar cell shows significant degradation to conversion efficiency due to current constraints. Optimizing the bandgap combination according to the incident spectrum could significantly improve the degradation in the conversion efficiency. Three standard solar spectra AM0, AM1.5D and AM1.5 G are considered in this study, which are plotted in figure 2. To assess the effect of spectral distribution on solar cell, an optimized triple junction (1.75/1.18/0.70) for AM1.5D spectrum is taken. This triple-junction solar cell is tested for three standard solar spectra under varying solar concentration.

Conversion efficiency for different solar spectrum under varying solar concentration is depicted in figure 3. It has been observed that when optimized solar cell for AM1.5D spectrum is exposed to AM1.5 G and AM0 spectrum; there is a significant drop in the conversion efficiency. As expected, with the rise in solar concentration, the conversion efficiency data changes logarithmically as depicted in figure 3.

At the same time, no correlation is observed between solar spectrum distribution and solar concentration on the conversion efficiency. When bandgap combination is optimized as per the incident solar spectrum and
keeping the solar concentration ratio equal to 1, significant improvement is observed in the conversion efficiency. The conversion efficiency for optimized solar cell as per incident spectrum is depicted in figure 4.

The optimum bandgap combination for different spectrum and corresponding conversion efficiency is summarized in table 1. The calculated efficiency is also compared with previous reported data [22].

The optimization is also performed at higher solar concentration ratio. However, it produces almost no change in the conversion efficiency. The combination of bandgap also remains unchanged. Similar results are also reported in the literature [22] for the concentration ratio 100 and 1000 with maximum deviation less than 2% from our calculated conversion efficiency for AM1.5D spectrum.

The above result reveals that the incident solar spectrum has a strong impact on the conversion efficiency of triple-junction solar cell. Conversion efficiency can be improved significantly by the bandgap optimization as per the incident spectrum [23]. At the same it is observed that optimization as per the solar concentration doesn’t bring any significant change in the conversion efficiency. The impact of temperature on conversion efficiency under varying concentration is discussed in the next section.

Table 1. Maximum conversion efficiency and optimum band gap combination for triple junction solar cell at 1-sun concentration for different solar spectrum.

| Spectrum | Optimum Band gap combination | Efficiency Calculated | Efficiency Ref[22] |
|----------|------------------------------|-----------------------|--------------------|
| AM0      | (1.84/1.21/0.77)             | 48.7                  | 47.77              |
| AM1.5D   | (1.75/1.18/0.70)             | 51.2                  | 49.97              |
| AM1.5 G  | (1.90/1.36/0.93)             | 51.6                  | 50.74              |

Figure 3. Conversion efficiency of AM1.5D spectrum optimized triple junction solar cell for different spectrum under varying concentration.

Figure 4. Conversion efficiency for triple junction solar cell optimized as per the incident spectrum and concentration.
3.2. Effect of temperature

The design parameters of solar cells are based upon the operating temperature of 298 K. The operating temperature of solar cell depends upon different operating conditions such as solar concentration, ambient temperature etc. Thus, the dependence of conversion efficiency on temperature is essential to predict its performance for photovoltaic system [24]. Different studies have been performed to study the effect of temperature and concentration on the performance of the solar cell operation [25]. When cell temperature rises it gives rise to intrinsic concentration. At the same time bandgap of the semiconductor material also shrinks [26]. Due to these phenomena solar cell shows lower conversion efficiency at higher temperature. To demonstrate the effect of temperature on triple junction solar cell, conversion efficiency is calculated over a range of temperatures under varying concentration. An optimized solar cell for AM1.5D spectrum (1.75/1.18/0.70) is used for the performance evaluation. The conversion efficiency for different temperature as a function of concentration is depicted in figure 5.

As expected, it has been found that conversion efficiency drops with the rise in temperature. The same study has also been performed at higher solar concentration. It is observed that dependence of conversion efficiency on temperature reduces at higher concentration as depicted in figure 5. The relative dip in the conversion efficiency due to cell temperature is reduced at higher sun concentration. Solar cell optimized for 298 K shows a reduction in the conversion efficiency of 8% at 353 K operating temperature when exposed to one solar concentration. For the same relative temperature change keeping the 1000 solar concentration there is drop of 3.84% in conversion efficiency. Similar trend has been observed for different temperature operations as illustrated in figure 5. The reason behind this observation is that, change in the output parameters like voltage and current due to temperature rise is compensated by the effect of concentration on solar cell output parameters. To observe the effect of band gap optimization on conversion efficiency, same study is performed for different temperature under varying solar concentration. Conversion efficiency of optimized triple-junction solar cell is shown in figure 6. The band gaps of sub-cells are optimized as per the operating temperature under varying concentration.
As an example, when the bandgap optimization is performed at 523 K at one solar concentration there is a 3.4% improvement in conversion efficiency and the new bandgap combination is found to be 1.85/1.33/0.90 eV. At 10 solar concentrations, improvement in conversion efficiency is found to be 1.4% for the bandgap combination of 1.85/1.33/0.89 eV. At 1000 solar concentration optimum bandgap combination is found to be 1.75/1.18/0.70 eV which is same as 298 K optimized solar cell bandgap combination. In summary, at high concentration ratio, cell temperature does not affect the conversion efficiency significantly. Here it is to be noted that as solar concentration increases, band gap optimization does not bring any significant change in conversion efficiency.

4. Conclusion

A theoretical study has been performed to evaluate the effect of different operating condition on the conversion efficiency of the triple-junction solar cell. The conversion efficiency is found to be sensitive to operating conditions. By choosing the bandgap combination as per incident solar spectrum, it brings a significant change in conversion efficiency. The same study has been extended to assess the effect of temperature over different concentration ratio. Rise in operating temperature leads to reduced conversion efficiency. When the bandgap optimization is performed for the higher temperature no significant improvement is observed in conversion efficiency. The effect of the temperature on conversion efficiency could be nullified by operating the solar cell at high concentration. Overall, depending upon the operating conditions, by choosing the appropriate bandgap combination and concentration ratio, efficiency can be improved significantly. This study could be helpful in the design of solar cells at real-time operating conditions for improving the conversion efficiency.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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