Renewable Energy 74 (2015) 917–924

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Modeling of multi-junction photovoltaic cell using MATLAB/Simulink to improve the conversion efficiency

Narottam Das [a, b, *], Hendy Wongsodihardjo [a], Syed Islam [a]

[a] Department of Electrical and Computer Engineering, Curtin University, Perth, WA, Australia
[b] Department of Electrical and Computer Engineering, Curtin University, Miri, Sarawak, Malaysia

A R T I C L E I N F O

Article history:
Received 8 April 2014
Accepted 14 September 2014
Available online

Keywords:
MATLAB/Simulink
Multi-junction solar cell
MPPT
Photovoltaic cell
PV cell working temperature

A B S T R A C T

This paper focuses on modeling of multi-junction solar cell (MJSC) to improve the conversion efficiency using MATLAB/Simulink software. The multi-junction photovoltaic (PV) cell is investigated to obtain its maximum performance compare to the conventional silicon PV cell. MATLAB/Simulink modeled results show that tandem cell can provide almost 3-times maximum power compared to the conventional PV cells. Maximum power point tracker (MPPT) has also been performed to improve the conversion efficiency of the PV systems. The MPPT is able to assist the PV cells to attain more power efficiently and deliver electricity to the grid.

1. Introduction

World Bank statistics predicted the number of global population which reaches almost 7 billion human live by the end of 2011 [1]. This huge number of human race strongly influences energy consumption on daily basis. International Energy Agency (IEA) recorded consumer energy usage in 2010 as 535 EJ (1 eJ = 10^{18} J) and this number is increasing continuously over time [2]. However, more than 80% of that energy is still extracted from limited sources, such as coal, natural oil and natural gas. If this continues, extinction or even disappearance of some resources may be faced in such a short term. To avoid this critical situation, renewable energy sources need to be developed and people should utilize the availability of them.

Photovoltaic (PV) system is a device that can convert the sunlight as renewable energy into DC voltage. Then this PV system is connected into an inverter, so the generated DC electricity transformed into AC source and it is applicable for household usage. With the assistance of solar cell, there is a high possibility of decrement in demand on fossil fuels as energy sources.

Nevertheless, the performance of PV cells these days are still far from the satisfaction. Despite its high initial cost, electrical energy generation is highly depended on the surrounding circumstances. The most common condition is during the cloudy day, where the PV cell produces less power as compared to a sunny day when the sun is shining very bright. The installation dwelling of the PV module also becomes another important consideration as 4 seasons tends to have variation in the temperature which may decrease the performance of PV cell because it cannot reach to its MPPT and reduces the cell conversion efficiency.

Several problems also arise for the PV cell itself. Semiconductors are used as the main element of the solar cell that can be selected from different materials. Nowadays, silicon is one of the most popular semiconductors because of its wide availability in nature, makes it cheaper to construct and produce the device. However, the efficiency of silicon solar cell is considerably a bit low [3]. The assembly process of the module itself can affect the performance of the PV cells. Also, any manufacturer defect may create the losses through cells junction and dropped to the earth connection.

With the aid of computer, focus on optimizing the PV cell performance, MATLAB/Simulink software is used for the device modeling. The MATLAB/Simulink is high-level software which can simulate numerical model, generate algorithms and analyze the data. . This programming tool is specifically designed to model data flow using graphical design language and integrated effectively with the MATLAB system. Accommodating these editor tools and mathematical analysis of the PV cell, it is modeled using the block diagram and analyzed the results. The improvement focuses on the design of each cell, and devices which might help instruct better final results.

The improvisation techniques in this research were based on the most popular demand by simulations only. There were few

* Corresponding author. Department of Electrical and Computer Engineering, Curtin University, Miri, Sarawak, Malaysia. Tel.: +61 432187226.
E-mail addresses: narottam.das@curtin.edu.au, narottam@ieee.org, narottam@curtin.edu.my (N. Das).

http://dx.doi.org/10.1016/j.renene.2014.09.017
0960-1481/

introductions, how the generation efficiency could be improved. Note that all the models designed in this paper are based on the reference value as standard test condition (STC), 1000 W/m^2, 25 °C. Besides, all prototypes are presented in single cell or individual parts only. This is to ensure the simplicity of analysis and modeling even though the final results might be pretty small. Evermore, this action is maintained well throughout the task to keep the details stability. The combination of multiple devices is free to organize, depending on consumers demand.

This paper is organized as follows: Introduction is in Section 1, theory and modeling of multi-junction PV cell using MATLAB/Simulink is in Section 2, Installation of MPPT onto the PV cell is in Section 3. Finally, the conclusion is presented in Section 4.

2. Theory and modeling of multi-junction PV cell using MATLAB/Simulink

2.1. Historical background of MJSC

Concentrated PV (CPV) cell which is based on the multi-junction solar cell (MJSC) become a breakthrough for solar electricity production by the utility company.

The tandem solar cell was first introduced by the Research Triangle Institute and Varian Research Center in late 1970s to mid of 1980s. They presented dual-junction devices that formed by aluminum gallium arsenide (AlGaAs) junction, interconnected on top of a gallium arsenide (GaAs) junction by a semiconductor tunnel junction [4].

Amazed by the bright future of stacked concentrator solar cell, scientists continued their research for further improvement of the device performance. Later in 1990s, changes in the top cell thickness and addition of new layer led to a great conversion efficiency that had never been matched before. A tandem (3-junction) solar cell was demonstrated by the combination of gallium indium phosphide (GaInP) with GaAs both on the top of active germanium (Ge) substrate [5].

In 2012, Sharp Corporation's product was claimed by Fraunhofer Institute for Solar Energy (Germany based organization) that they had break the record of most effective concentrator solar cell in the world via technology development that reached ~43.5% efficiency from a triple junction compound solar cell [6]. However, this record did not perform well long enough. In September 2013, Fraunhofer again announced a new world record of concentrated PV cell with ~44.7% efficiency which was completed with the collaboration of Soitec, CEA-Leti and the Helmholtz Center in Berlin [7]. They presented that four-junction solar cell is improved in terms of material composition, optimization of the structure and introduction to a new procedure called wafer bonding. This latest connector method has ability to connect 2 semiconductor crystals with very high quality level [8,9].

Due to concerns about the changing environment and prompted controversy of fossil fuel depletion, the *MJSC* bears very high expectation to be the best device for converting the renewable (solar) energy into the electricity. Meanwhile, within these 40~50 years from the beginning it was introduced but not been much improved. There were many issues while proposing this design for the improvement.

2.2. Basic criterion for modeling MJSC

The MJSC is constructed by stacking of two or more p–n junction semiconductors with different characteristics. The good candidates to construct the stacks of semiconductors are by gathering the alloys from group III–V of the periodic table. Despite on its high expectation, the MJSC has a few limitations with the aim of choosing materials to generate the high efficiency PV system. To get the layer of semiconductors to be combined, there are some essential requirements to follow. These are as follows:

2.2.1. Lattice matching

The first consideration is the material selections which are extremely important to be lattice-matched. Lattice constant is used to check whether each material is matched to each other or not. This constant value measures the spacing of atom on the crystal structure.

Mismatch on the lattice constant will create dislocations in the lattice, which results loss of photo-generated minority carriers. Many researches put this factor as a secondary concern, but the US National Renewable Energy Laboratory (NREL) researchers already mentioned that even ±0.01% mismatch on the lattice matching causing a significant degradation of the PV quality or conversion efficiency [10,11].

2.2.2. Bandgap energy matching

Another important matter on the stacking each junction is diversity of the bandgap level on each sub-cell [12]. Basically, the sun rays consist of different spectrum while each of the semiconductor material can absorb only certain wavelengths depending on its substance or materials. Therefore, having a wide range of bandgap, the possibility for highest amount of spectrum level, the absorption also increases.

The first layer absorbs the highest photon energy from the sun. Furthermore, the sub-bandgap light is transmitted to the lower sub-cell and processed further until the last or bottom layer of the cell. This is the basic understanding of MJSC's working principles that depends on the bandgap energies. However, if the bandgap range is too far, the amount of unabsorbed light forms into heat and exceed to the air, cause losses through the crystal junction. In order to reduce the losses, the bandgap of the closest junctions need to be as tight as possible for high conversion efficiency of the cell.

2.2.3. Current matching

Each sub-cell is connected in series, which means it requires same or at least a minimum difference on current characteristics [13]. While this condition does not fulfill, the total current read may be decreased by the nature of the series circuit connections. The current generation is limited to the lowest current produced by an individual layer.

Basically, the current of each junction depends on the number of photons that passes through the material's absorption capacity [14]. When the absorption coefficient is very high, the photon can easily pass through and the material thickness can be decreased. On the other hand, the layer with low absorption capacity is better to be thickening in order to provide some space for the photon passes through during the sunlight captivation.

2.3. Various combination of MJSC

As mentioned earlier, the process of developing the *MJSC* is grounded on limitations of how each layer must produce a similar amount of current. The thickness justification of each material is important to ensure that all of them are matched to produce an optimum current [15].

Fig. 1 shows an equivalent circuit model of a *MJSC*, which is a series connection between one type of cell and the other materials. They are connectable in any desired number of cells. This model is used to simulate the *MJSC* characteristics using MATLAB/Simulink.

In this analysis, various types of tandem cell are observed, each of them are grouped into dual and triple-junction model.

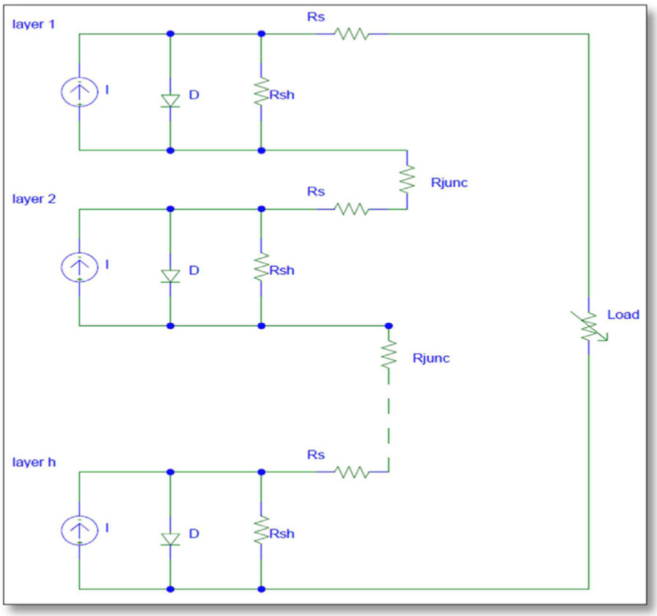


Fig. 1. A simple equivalent circuit diagram of a tandem solar cell.

2.3.1. Double-junction solar cell

The most common dual junction tandem cell is the combination of InGaP (Indium Gallium Phosphide) and GaAs (Gallium Arsenide) cells in which both of them are from III–V group alloy. Their bandgap energy coefficient does not vary significantly but it is wide enough to receive more energy sources, which are shown in Table 1. The InGaP is closely lattice matched with the GaAs, which makes them first option to form the tandem cell [16,17]. Currently, both of them are frequently being used in space application either in tandem form or separately.

The practices on developing the stacked junctions do not always stick to the III–V group, but also merging different types of material whichever possible. For example, solar cell from thin film family can be utilized as they are able to generate high energy. In this case, Copper Indium Gallium Selenide (CIGS) is selected and it would be united with other cells. The CIGS formed by small crystallites material or else called polycrystalline material. There are numerous advantages on using this thin film. Its absorption coefficient is relatively high, so its thickness can be reduced. Besides that the current density of the CIGS solar cell is also useful for producing high amount of output current.

In second tandem cell observation, the CIGS is connected with GaAs. Despite using the crystalline cell, in this combination GaAs is compressed to form a thin film which is similar to the CIGS. This option is taken not a prioritizing in efficiency increment, but to create a harmonious combination with the CIGS, especially for junction connections [18]. From this approach, wider range yet thinner the *MJSC* is possible to make and can be used in large-area, such as automated production of PV power [19].

Furthermore, another option is also designed for lattice matched ZnSe (Zinc Selenide) and AlAs (Aluminum Arsenide) is anticipated. The ZnSe is a semiconductor material which rarely occurs in nature as its toxic contents might be dangerous. However, as the practice is performed by MATLAB/Simulink software, the simulation is obviously done without any risk. By itself, ZnSe has very high bandgap coefficient. So, connecting it with Aluminum Arsenide (AlAs) can create a wide range of absorption chance. This arrangement is done with the cross section of II–V material in which ZnSe is created by the combination of II–IV intrinsic semiconductor, while AlAs is almost identical with GaAs from II–V alloy in the periodic table.

2.3.2. Triple-junction solar cell

Experimental procedures face greater challenges when more materials to be added on the sandwich stack. Based on data of lattice constant for III–V semiconductor material, it has seen that AlAs, GaAs, and Ge are matched on its lattice constant. Because of that these materials are able to be grown with less strain. Their bandgap variation is also quite wide to perform a great absorption. Therefore, they can be used on the process of making the MJSC.

However, the researchers stated that the bandgap variation is not showing the satisfactory choice. An ideal triple junction can produce energy effectively with the combination of 1.89, 1.28 and 0.84 eV materials [10,20]. Therefore, AlAs is considered having too high bandgap energy and can be substituted by InGaP. Because of that a 3 junctions solar cell designed by stacking InGaP, GaAs, and Ge all together with statistic as shown in Table 2 [21,22]. This is simply similar with the first double cell experiment but with addition of germanium. Option on choosing the Ge as third layer is not just by it is lattice and bandgap matched with the other two, but its characteristic is similar with the silicon. Purified germanium can appear close to elemental silicon [23].

2.4. Experimental procedures of combined MJSC

The objective of this research is to find the behavior of *MJSC* and how to improve it. There are few steps to check the performance of each tandem cell.

2.4.1. Mathematical formulation of single cell

In order to create a basic model of the *MJSC* using MATLAB/Simulink, mathematical formulation of current and voltage relationship is necessary. Therefore, the generated voltage (V) for each cell can be represented as follows [36].

$$V = V_{sh} + IR_s \tag{1}$$

where,, V_{sh} is the voltage that dropped by the shunt resistance, I is the load current, and R_s is the series resistance.

Furthermore, the current flows to the grid can be represented by the following equation [24,25,36].

$$I = \left[I_{sc} + K_i\left(T_C - T_{ref}\right)\right]\frac{G}{G_{ref}} - I_S\left(e^{\frac{V_D}{NV_T}} - 1\right) - \frac{V_{sh}}{R_{sh}} \tag{2}$$

where, I_{SC} is the short circuit current at ambient temperature (T_{ref}) and reference irradiation (G_{ref}). Meanwhile, cell working temperature and irradiation is symbolized as T_c and G respectively. K_i is the

Table 1
Bandgap energy of each dual-junction solar cell.

Combination	[1] Top layer	[2] Bottom layer
InGaP/GaAs	1.86 eV	1.42 eV
CIGS/GaAs	1.70 eV	1.39 eV
ZnSe/AlAs	2.7 eV	2.12 eV

Table 2
Bandgap energy of each triple-junction solar cell.

Combination	[1] Top layer	[2] Middle layer	[3] Bottom layer
InGaP/GaAs/Ge	1.86 eV	1.42 eV	0.67 eV
AlAs/GaAs/Ge	2.12 eV	1.39 eV	0.67 eV

cell's short circuit current temperature coefficient, set at 0.065 ± 0.015%/°C.

Meanwhile, I_s is the diode saturation current, V_D and V_T representing voltage across diode and latter is the thermal voltage diode can held with factor of diode ideality (N) which set as 1. The diode current is formulated as follows [26,27],

$$I_S = I_{RS}\left(\frac{T_C}{T_{ref}}\right)^3 e^{\frac{E_g}{NV_T}\left(\frac{T_C}{T_{ref}}-1\right)} \tag{3}$$

I_{RS} characterizes diode reverse saturation current. Subsequently, semiconductor bandgap energy is shown as E_g. All of these formulas are derived for the single layer only. Therefore, the model can be adjusted easily depends on the desired number of combinations.

2.4.2. Modeling in MATLAB/Simulink

Based on those theories and equations, the model of a *MJSC* is created by MATLAB/Simulink. Fig. 2 shows the sub-layer of a tandem cell which can join with other sub-cells.

2.4.3. Extraction result from MATLAB/Simulink

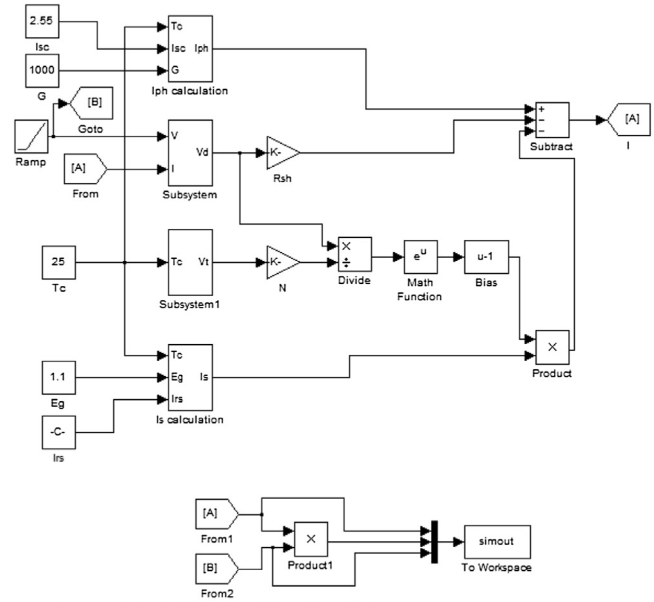
Based on the Simulink models, tandem cell performance can be plotted in terms of generated power and voltage. In order to create a better comparison method, several results/plotted graphs are compared. As result, the MJSC is able to generate more power or energy than the conventional single cell. The following simulated (analyzed) results show how each stacked cell can perform for PV energy generation. Note that sampling curves were created at 1-sun (i.e., 1000 W/m^2) radiation and fixed ambient temperature same as reference (i.e., 25 °C).

2.5. Analyzed results of MJSC

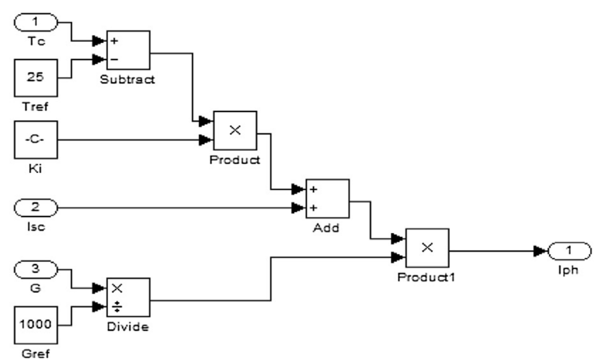
For the construction of *MJSC*, wafer type semiconductor combinations are adapted [28]. For comparison, 2 single junction cells performances are considered. They are single Si and single GaAs type of cell, which is used broadly for PV manufacturing. Based on the modeled results, Si produced a lower amount of power than GaAs, which able to deliver 40 mW from a single cell, but in reality, the GaAs is pretty expensive compare to Si. Because of that, the latter type is mainly used on solar space in which need great energy and also supported by high capital investment. The GaAs cell has recorded ~20% more effectiveness than the Si cells.

Furthermore, the comparison for 3 different types of double junction cells performance is shown in Fig. 3. As mentioned earlier that InGaP and GaAs has similar lattice and matched well to be paired, this is really effective as they can generate more power for the user's satisfaction. On the other hand, a better result is provided by the new design of thin film couple cells, in which it is formed by GaAs and CIGS, they are able to increase the maximum power ~36%. The main reason for this benefit is, because they have wide enough thick to absorb more energy without increasing their thickness. Another factor is that the GaAs is a thin film and had better performance than other materials with the possibility to deliver 0.1 W of power to the grid.

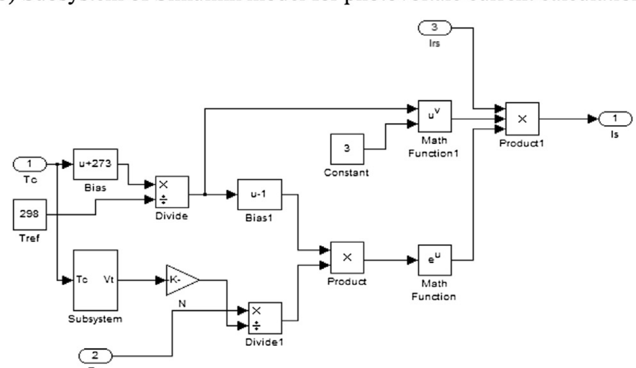
However, the combination from II–IV and III–V class has not delivered significant performance. Even though ZnSe and AlAs have pretty high bandgap, it is not useful to create a better hybrid structure. They are a bit behind in term of conversion efficiency. They are not functioning well because their bandgap level is widening too far and resulting not absorbing enough energy but releasing more energy into heat. Besides that, it is difficult to match their current as they come from different material classifications.



a) Basic model of single cell in Simulink.



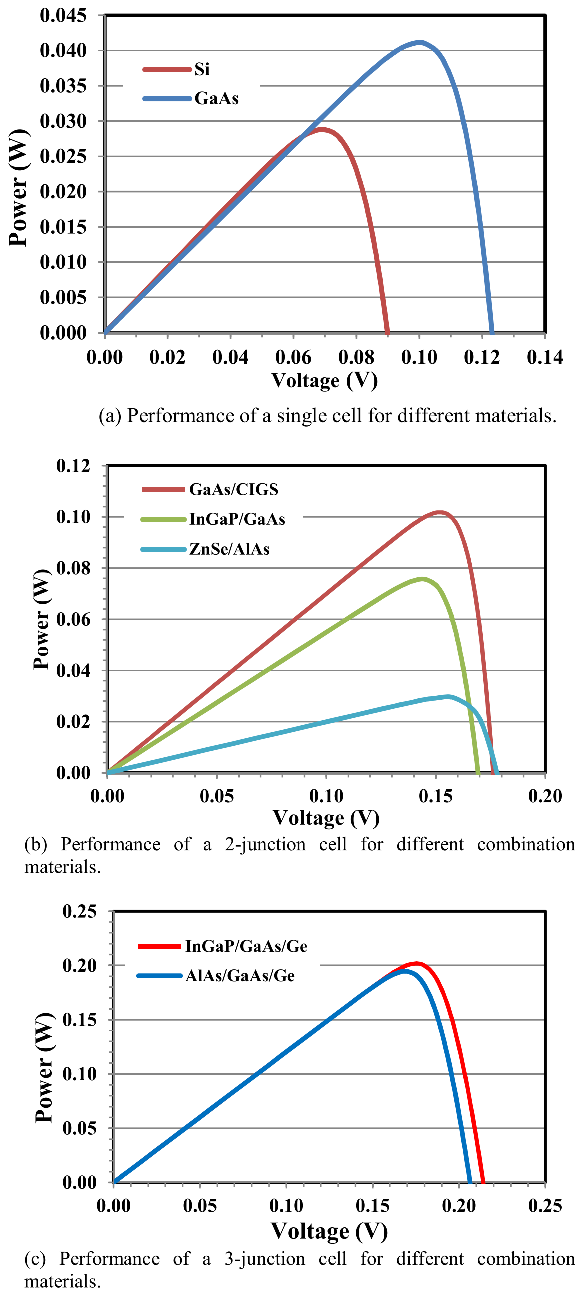
b) Subsystem of Simulink model for photovoltaic current calculation.



c) Subsystem of Simulink model for diode saturation current calculation.

Fig. 2. MATLAB/Simulink model of a sub-cell for *MJSC* with the (a) full basic model, (b) I_{ph} calculation, (c) I_s calculation.

For a triple junction combination, the simulated results are able to provide double the maximum power as previously noted, which is 0.2 W for a single cell. The first design of AlAs, GaAs, and Ge provided a satisfactory result. However, when AlAs is changed with InGaP, the whole statistic is increased even though not significantly. This means that the difference from first design has a wider range but not closer to each other, which cause more losses and form



(a) Performance of a single cell for different materials.

(b) Performance of a 2-junction cell for different combination materials.

(c) Performance of a 3-junction cell for different combination materials.

Fig. 3. Comparison of PV characteristics with different junctions and materials. (a) Single junction, (b) Double junction, and (c) Triple junction cells.

heat. Even though there were not much changing, their final results are satisfactory to provide a better improvement in the future.

2.6. Future improvement of MJSC production

According to the investigated results, thin film CIGS is considered to hold a better prospect for solar or renewable energy production. It copes well with GaAs which is the best option for solar cell manufacturing. Triple junction solar cell also required to put it into most consideration despite the hardship of combining different junctions.

However, the manufacturing of tandem cell needs to put further attention on the lattice constant of each material as the dislocation of matching may create a chain reaction in the decrement of the open circuit voltage (V_{OC}), short circuit current density (J_{SC}), maximum power delivered (MPP), and the fill factor (*FF*). The awareness also comes from the connection method, where the defected layer or poor construction may increase the resistance between the layers or junctions. Therefore, with the intention of decreasing the junction losses, manufacturers are required to check their product properly. These losses also affect the generated current in which create an unmatched current flow between the cells and finally reducing the cell conversion efficiency.

3. Installation of MPPT onto the PV cell

For improving the PV cell design and its material other electronic devices are available to get the maximum stable power or energy generation. The MPPT is one of the important factor for many devices formed to accomplish this deficiency and improve the conversion efficiency of PV systems.

The MPPT plays an important role in PV system as it can optimize the power output of electricity generator for a given set of surrounding weather. Thus, number of arrays connected in the module can be decreased which results in price reduction or optimizing the existing module to produce more electricity.

Numerous MPPT techniques had been proposed in many research papers, literature and conference presentations. Basically, the methods can be classified either into (i) *look up* method, (ii) *perturb and observe* method or *increase conduction* method [29,30,32]. Each of these algorithms has its own relative merits, which allow them to be utilized in variety of applications. For special condition, some techniques can work together to initiate the maximum energy. However, among all of them, perturb and observe technique is the most popular due to the high tracking accuracy at steady state condition. MATLAB/Simulink simulation results will be compared each of the class's performance and also specified the way to improve the PV system.

3.1. MPPT algorithm

Each of the method is compared and discussed about their strengths and weaknesses. The observed techniques are for electronic tracker system to vary the operating point of modules, not mechanical system which can shift the PV modules to obtain the maximum sun intensely. These algorithms help for pushing the generator to stay at steady condition during its full capability for a longer period.

3.1.1. Fractional open circuit voltage

The basic of this method is about observing the percentage of MPP voltage (V_{MPP}) as an open circuit voltage (V_{OC}) of the I–V curve; this V_{MPP} ratio is known as K_1, which is expressed by the following equation.

$$V_{MPP} = K_1 V_{oc} \tag{4}$$

where, V_{OC} is extracted open circuit voltage when the PV array is isolated from the MPPT; then based on that V_{OC} voltage, V_{MPP} is calculated in accordance with a constant value K_1. However, there still a problem in deciding what is the real value of K_1. Approximately, the value of K_1 varies from 73%~80% [30]. After setting the K_1 value, the MPPT can adjust the operating voltage of the PV array until the maximum voltage is reached. This cycle is repeated for a period of time in order to acquire the maximum power delivered.

Working criteria of this procedure is very simple, so it is more advantageous for manufacturer to create this algorithm-based device. However, there are also some disadvantages, such as during the measurement of V_{OC}, the PV power is interrupted due to the discontinuity of the supply from the PV array to the MPPT point. Besides, exact maximum value of K_1 still undecided, it needs more adjustment when the variation happens in irradiance and/or temperature of that specific day or time. Therefore, to improve the PV system performance, this method requires dynamical adjustments while the maximum efficiency is desired. However, with the automatic adjustment, it will be similar with the Perturb and Observe technique.

3.1.2. Fractional short circuit current

Based on the behavior of PV cell, there is a fact that the current at MPP (I_{MPP}) is approximately linear to the short circuit current (I_{SC}). Therefore, it is possible for the PV cell to maintain its performance by producing an operating current near the I_{SC}. With the similar operation, to find the V_{MPP}, an absolute constant is required, which is represented by the factor K_2. The following equation (5) is the simple relation between the I_{MPP} and I_{SC}.

$$I_{MPP} = K_2 I_{sc} \tag{5}$$

The value of K_2 for the current ratio is also undecided. An approximate value stated that the I_{MPP} works somewhere between 78%~92% of I_{SC} [30]. In order to find the I_{SC} value, the PV modules are shorted and recorded, so the output power is reduced and interrupted. Moreover, the MPP value may or may not be perfectly matched with the optimum performance characteristics. For this reason, the best circumstance is to apply this practice, when an external situation is changing, such as when it starts cloudy or raining.

3.1.3. Perturb and observe (P&O)

The working system of a P&O is by "*hill climbing method*". It works by checking the basic behavior of the PV cell's curve by making small increment in the operating voltage [31]. When the power delivered to the load seems to rise, it will make further perturbation in voltage until the power reaches to its maximum capacity and start to fall below the *MPP*. In this step, the adjustments are not continued but it will be reversed to move back toward the *MPP*. In summary, (i) if the change in power is positive, the perturbation is kept at the same direction. (ii) Inversely, if the power difference is negative, it means the *MPP* is in different direction and next perturbation will be at the opposite direction.

This method is widely used in the MPPT console because of its simplicity and ease implementation. The method of finding the global maxima of curve will continue throughout the PV operation, so power generated will not stay on the *MPP* but will oscillate around it. There is also some observation time, which causing the disturbance in the output power. Moreover, it is difficult to discriminate the location of the *MPP*, when the sun radiation is low, as the *I*–*V* curve will be flattening out. One way to reduce the oscillation at *MPP* is by decreasing the perturbation size, but it will make the MPPT working time become slower.

3.2. MPPT MATLAB/Simulink model for P&O method

To simulate the MPPT performance, basic PV cell system shown in Section 2 is combined with the MPPT technique to generate the voltage for its maximum performance. Several methods are being used for this simulation.

The P&O method is widely used among other techniques and is designed by using the Simulink as shown in Fig. 4. It shows the combination of a PV cell system and the MPPT technique using the P&O method. The power delivered by a PV cell becomes an input for the algorithm. Then, this is perturbed with a step of 0.005. These steps are adjustable and can be set into a desired value. Afterward, the data is stored in memory then used in the next instruction [32,33].

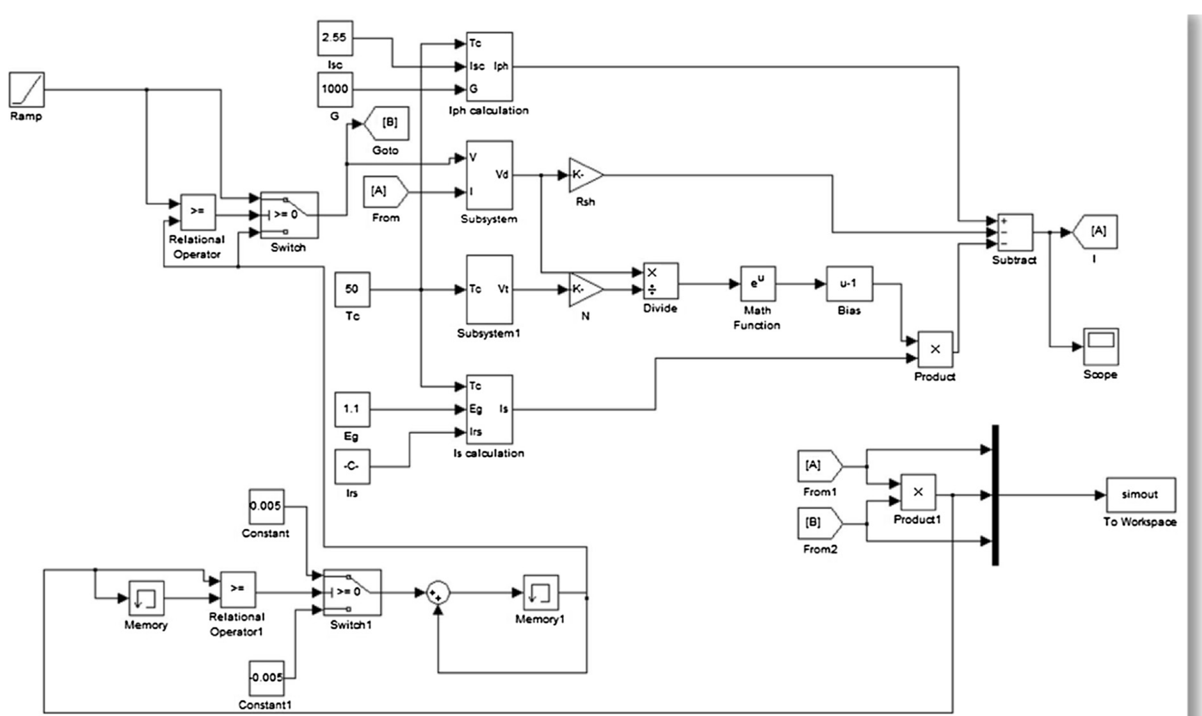
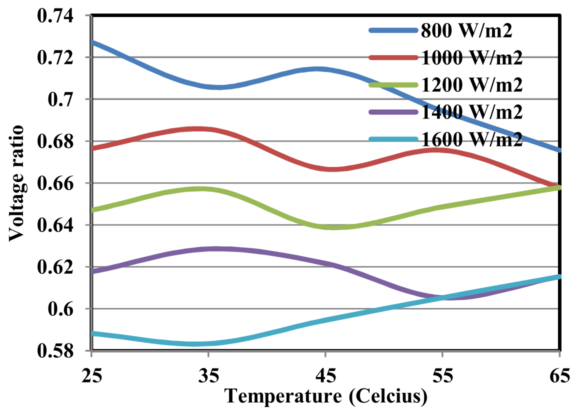
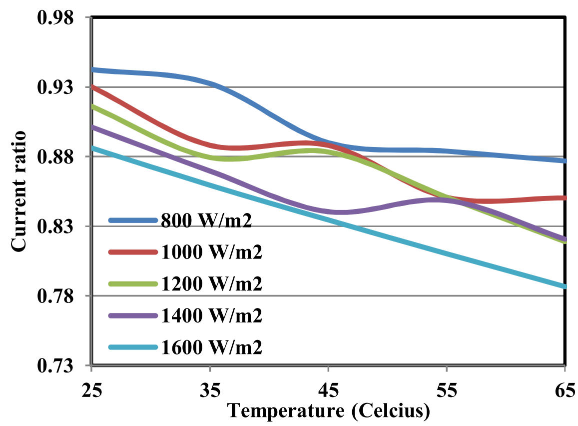


Fig. 4. The combination of a PV cell and the P&O algorithm.



(a) Voltage coefficient on fractional V_{oc} method.



(b) Current coefficient on fractional I_{sc} method.

Fig. 5. Fraction coefficient based on temperature for (a) V_{OC} method and (b) I_{SC} method.

3.3. Simulation results on fractional method

In order to analyze the performance of other 2 methods, which are fractional open circuit voltage and fractional short circuit current, each of the coefficient decision is compulsory.

Basically, fractional method is based on the constant that used to multiply either V_{OC} or I_{SC}. However, the real MPP is not at those two points. Provided in Fig. 5 are comparison from coefficient of V_{MPP} over V_{OC} and I_{MPP} over I_{SC} with the temperature variation.

They show that the specified points of open and short circuit does not really match with maximum power points. For the voltage and current comparison, higher irradiance even leads greater dissimilarity. However, with grater temperature, matching percentage of high irradiance is able to be increased. Differ with the current coefficient, the graphs trend to keep stepping down along with the temperature increment. These behaviors are not in linear motion, but keep fluctuating.

3.4. Performance comparison of the MPPT techniques

In this section, the results on MPPT techniques were plotted and compared. First 2 algorithms are using the fractional calculation method and plotted as shown earlier in Fig. 6. For this calculation, the value of K_1 and K_2 are chosen 0.75 and 0.85, respectively. Then, the results are compared with the maximum power of a conventional PV cell.

Different design of MPPT provides different characteristics from one technique to another. Constant voltage tracker or fractional process did an open circuit to find the V_{OC} or else shorting the load to find the I_{SC}. During this momentary time, some of the energy may be wasted which is not a good way to generate electricity. Constant values of the ratio also keep changing during the operation of PV cell, which makes them not functioning well. One benefit is its low cost and simplicity for the application. The results provided are not recommended to be referenced for manufacturer product. Because, the value of K used in both fractional voltage and current are not stable. Meanwhile, when the weather changes suddenly, it may cause the performance to drop. Otherwise, the weather is good for continuous operation. This technique cannot cope well to set its constant ratios for long duration.

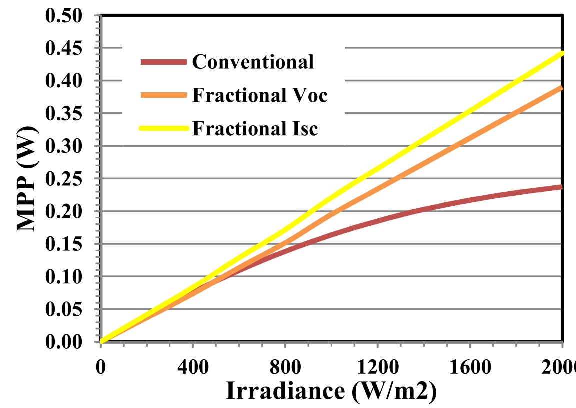


Fig. 6. Comparison among conventional, fractional constant V_{OC} and I_{SC} of the MPP performance based on irradiance.

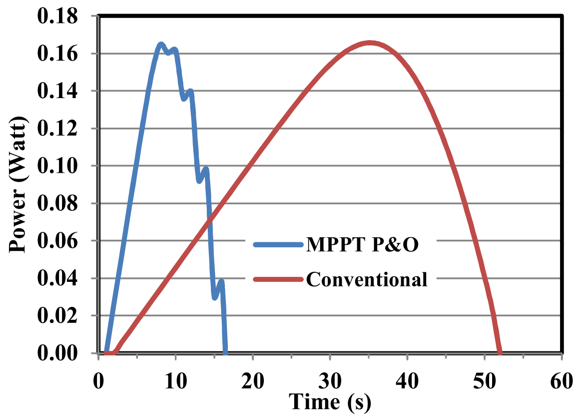
Fig. 7 shows the power generated using the P&O technique with different time steps, such as (a) 0.01 steps and (b) 0.005 steps. The P&O method will increase the step of power to find the operating condition of the module. However, this will lead to some oscillations around the MPP, because it keeps perturbing every specified period, even during the steady state condition.

The results plotted for the P&O design show how the oscillation dominating the power generation. Even when the perturb step is increased to 0.01, the power will suddenly drop because of the higher oscillation. The value of the perturbation step is too high as compared to the voltage value of the cell, which cause the defection during the first simulation. However, when the steps were reduced, the MPP can easily be reached and kept to be working on around that point. The disadvantage for this smaller step is the time consumption. It consumes more time to find the optimum power availability comparing with the larger steps, which has better dynamic performance and operates faster.

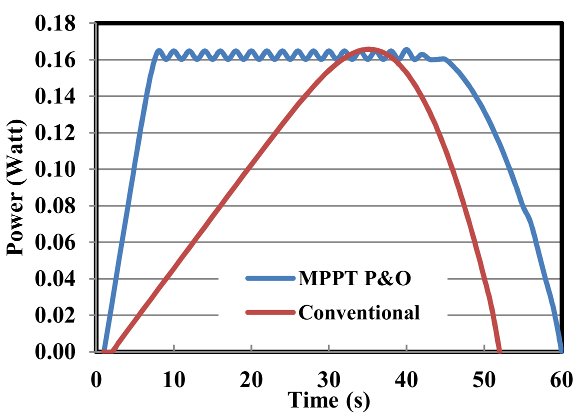
In comparison, how good these techniques are, they still need further improvements. The recommendation comes to try a *variable* method. The constant K is set to be as a variable which can cope with the ambient temperature. The relationship will depend on manufacturer's product. This *variable* method can also be applied to the P&O algorithm to find a better perturbation. During the tracking period, steps are set to be higher compare to the time when the maximum power was found. When the dark time coming, then the perturbation steps are set to be higher than normal values.

4. Conclusion

In summary, based on the simulation results, the single multi-junction solar cell can generate about 0.2 W, which is more than two-times of power compared to the conventional silicon PV cells. The combination InGaP/GaAs/Ge offered the best performance in tandem cell performance. The P&O tracking method is also studied and shown ability to locate the maximum power in one-third



(a) Comparison of MPPT with 0.01 steps.



(b) Comparison of MPPT with 0.005 steps.

Fig. 7. Performance comparison of stand-alone PV system with P&O MPPT of (a) 0.01 steps and (b) 0.005 steps.

shorter period. However, this technique is highly dependent on its perturbation value. When the value is too high then the PV cell have a good dynamic performance, but the static performance was not so significant [34]. In the future, this tracking performance can be improved, by adding such as a feedback system to the Programmable Logic Controller [35]. Finally, it is confirmed from the simulation results that the MJSC can generate more than two-times of power compared to the conventional Si PV cell and improve the conversion efficiency of the PV systems.

Acknowledgment

This research is supported by the Centre for Smart Grid and Sustainable Power Systems, the Faculty of Science and Engineering, Curtin University, Perth, Australia.

References

[1] Bank W. World development indicators and global development finance. 31 October 2012 [Online]. Available from: http://www.google.com.au/publicdata/ [accessed 09.11.13].
[2] World energy outlook 2010. Paris, France: International Energy Agency; 2010.
[3] González-Longatt FM. Model of photovoltaic module in Matlab™. In: 2do Congreso Iberoamericano De Estudiantes De Ingeniería Eléctrica, Electrónica Y, Venezuela; 2005.
[4] Virshup GF, Chung B-C, Werthen JG. 23.9% monolithic multijunction solar cell. In: Proc. of the 20th IEEE Photovoltaic Specialists Conference, Las Vegas, NV; 1988. p. 441–5.
[5] Yamaguchi M, Takamoto T, Araki K, Ekinsdaukes N. Multi-junction III–V solar cells: current status and future potential. Sol Energy 2005;79(1):78.
[6] Shahan Z. Sharp hits concentrator solar cell efficiency record, 43.5%. Clean Technica 2012 [Online]. Available from: http://cleantechnica.com/2012/05/31/sharp-hits-concentrator-solar-cell-efficiency-record-43-5/.
[7] Fraunhofer Institute for Solar Energy Systems. World record solar cell with 44.7% efficiency. ScienceDaily. [Online] from http://www.sciencedaily.com/releases, [accessed 23.09.12].
[8] Mohr PJ, Taylor BN, Newell DB. The 2010 CODATA recommended values of the fundamental physical constants. 2011.
[9] Cotal H, Fetzer C, Boisvert J, Kinsey G, King R, Hebert P, et al. III-V multijunction solar cells for concentrating photovoltaics. Energy & Environ Sci 2008:174–92.
[10] Tobias I, Luque A. Ideal efficiency of monolithic, series-connected multijunction solar cells. Prog Photovolt 2002;10:323–9.
[11] Landis GA, Belgiovane DJ, Scheiman DA. Temperature coefficient of multijunction space solar cells as a function of concentration. In: Proc. of the 37th IEEE Photovoltaic Specialists Conference (PVSC); June 20–24, 2011. p. 1583–8. Seattle, WA, USA.
[12] Takamoto T. Status of multijunction solar cells and future development. In: CS MANTECH Conference; May 18–21, 2009. Tampa, Florida, USA.
[13] Bertness KA, Friedman DJ, Olson JM. Tunnel junction interconnects in GaAs-based multijunction solar cells. In: proc. of the 1994 IEEE First World Conference on, vol. 2; 1994. Waikoloa, HI.
[14] Yastrebova NV. High-efficiency multi-junction solar cells: current status and future potential. University of Ottawa; 2007.
[15] Azab M. Improved circuit model of photovoltaic array. Int J Electr Power Energy Syst Eng 2009;2(3).
[16] Or AB, Appelbaum J. Estimation of multi-junction solar cell parameters. Prog Photovolt Res Appl June 2013;21(4):713–23.
[17] Bhattacharya Indranil, Foo Simon Y. Effects of gallium-phosphide and indium-gallium-antimonide semiconductor materials on photon absorption of multijunction solar cells. In: proc. of the IEEE SoutheastCon 2010 (SoutheastCon), Concord, NC; 2010.
[18] Green MA, Emery K, Hishikawa Y, Warta W. Solar cell efficiency tables. Prog Photovolt Res Appl 2009:85–94.
[19] CIGS technology. Solarex. Inc.; 2007 [Online].
[20] King RR, Law DC, Edmondson KM, Fetzer CM, Kinsey GS, Yoon H, et al. 40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells. Appl Phys Lett 2007:90.
[21] Spectrolab. California US Patent 6,380,601. 2008.
[22] Emily C, Leite MS, Atwater HA. Photovoltaic efficiencies in lattice-matched III-V multijunction solar cells with unconventional lattice parameters. In: Proc. of the 37th IEEE Photovoltaic Specialists Conference (PVSC); June 20–24, 2011. p. 570–4. Seattle, USA.
[23] Aiken DJ. InGaP/GaAs/Ge multi-junction solar cell efficiency improvements using epitaxial Germanium. In: Proc. of the 28th IEEE Photovoltaic Specialists Conference (PVSC); Sept. 15–22, 2000. p. 994–7. Anchorage, AK, USA.
[24] Hernanz R, Martin C, Belver Z, Lesaka L, Guerrero Z, Perez P. Modelling of photovoltaic module. In: Proc. of the International Conference on Renewable Energies and Power Quality, Granada, Spain; Mar. 23–25, 2010.
[25] Chun WN, Yue WM, Sheng SG. Study on characteristics of photovoltaic cells based on MATLAB simulation. IEEE; 2011.
[26] Queisser WS, Hans J. Detailed balance limit of efficiency of p-n junction solar cells. J Appl Phys March 1961;32:510–9.
[27] Solarex. MSX-60 and MSX-64 Photovoltaic modules. USA Patent 6059-8. 1997.
[28] Keener DN, Marvin DC, Brinker DJ, Curtis HB, Price PM. Progress toward technology transition of $GaInP_2$/GaAs/Ge multijunction solar cells. In: Photovoltaic Specialists Conference, 1997, Conference Record of the Twenty-Sixth IEEE, Anaheim, CA; 1997.
[29] Qin LJ, Lu X. Matlab/Simulink-based research on maximum power point tracking of photovoltaic generation. In: International Conference on Applied Physics and Industrial Engineering. Physics Procedia, vol. 24; 2012. p. 10–8.
[30] Hohm DP, Ropp ME. Comparative study of maximum power point tracking algorithms. Prog Photovolt Res Appl 2003;11(1):47–62.
[31] Das B, Jamatia A, Chakraborti A, Kasari PR, Bhowmik M. New perturb and observe MPPT algorithm and its validation using data from PV module. Int J Adv Eng Technol July 2012;4(1):579–91.
[32] Revankar PS, Gandhare WZ, Thosar AG. Maximum power point tracking for PV systems using MATLAB/SIMULINK. In: Second International Conference on Machine Learning and Computing; Feb. 9–11, 2010. p. 8–11. Bangalore, India.
[33] Walker G. Evaluating MPPT converter topologies using a Matlab PV model. J Electr Electron Eng Aust 2011;21(1):49–55.
[34] Florea ML, Baltatnu A. Modeling photovoltaic arrays with MPPT Perturb & Observe algorithm. In: Proc. of the 8th International Symposium on Advanced Topics in Electrical Engineering (ATEE); May 23–25, 2013. Bucharest, Russia.
[35] Utaikaifa K. Reduction of power ripple in P&O MPPT system using output feedback. In: Proc. of the Fourth International Conference on Power Engineering, Energy and Electrical Drives (POWERENG); May 13–17, 2013. p. 427–32. Istanbul, Turkey.
[36] Babar M, Al-ammar EA, Malik NH. Numerical simulation model of multi-junction solar cell. J Energy Technol Policy 2012;2(7).