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Maximum Power Point Tracker Optimization for Photovoltaic Systems based on III-V Elements.

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Abstract. A photovoltaic system consists of several components that are interconnected into a grid network or standalone system. The overall efficiency of a photovoltaic system is the result of component selection, accurate implementation, and stable operation. Therefore, if these factors are not in harmony during the design and execution of the system, optimal efficiency will not be achieved. This paper summarizes the technological trend of photovoltaic cells which lead to the development of multijunction photovoltaic cells based on III-V elements. Additionally, the challenges within the implementation of multijunction cells based on III-V elements into terrestrial applications will also be discussed, followed by a potential solution to counter the efficiency loss of these cells caused by the atmospheric gases filtering the solar irradiance across the optical band length of absorption. The implementation of Adaptive-Perturbation-Frequency (APF) in a Perturb and Observe (P&O) algorithm, instead of a linear step size variation, combined with several hardware optimizations on the Maximum Power Point Tracker (MPPT), maybe an ideal approach to reduce the impacts of having a multijunction photovoltaic cell based on elements III-V operating at terrestrial conditions.

Keywords. MPPT; Renewables; Photovoltaic.

1. Introduction

Harvesting electricity from solar irradiance by using photovoltaic systems has become common practice over the last decades. The continuous development of new materials and manufacturing techniques has ignited the advancements of silicon based photovoltaic modules to generate electricity.

In recent years, photovoltaic systems have become one of the cheapest energy systems. With the combination of low energy production costs and rising global awareness around the negative impacts of carbon dioxide emissions into the atmosphere, it is projected that photovoltaic systems are evolving towards being one of the largest platforms for energy production in the world.

Global agreements have enforced deadlines for considerable reductions in carbon emissions within various nations. Consequently, governments have established incentives for their citizens within taxation rules and lower rates for investment in, and using, carbon-free systems.

As the financial benefits combined with the relatively low cost of investment increase the viability of photovoltaic systems, a foreseeable limiting factor within this market becomes the displacement area required for photovoltaic installations. This results in a continuous motion for efficiency enhancement of these systems, therefore, reducing the displacement area required.

Regardless of economic incentives related to renewable energy systems, a continuous optimization trend has been established within these systems creating a performance criterion, and accelerating the divestment of fossil fuel systems [22].

There are multiple ways to optimize a photovoltaic system allowing its maximum rated performance and various techniques to increase the overall efficiency of the system.

The objective of this paper is to address one of the largest issues within the implementation of multijunction photovoltaic cells based on III-V elements when implemented in terrestrial installations.

As the solar irradiance spectrum is filtered by the gases in the atmosphere, the majority of the nominal efficiency of multijunctional cells based on III-V materials is lost. The efficiency loss becomes greater when the hardware utilized for the rest of the photovoltaic system does not match the electrical characteristics of the cell. the solar irradiance on the photovoltaic cells. To address the hardware losses, a possible solution based on the optimization of the Maximum Power Point hardware to adjust the optimal power point as quickly as possible will be explored. A proposal of several algorithms will be included to ensure that any change on the power point is as accurate as possible, ultimately maximizing the power output of the system.

2. Photovoltaic cell

Photovoltaic modules are defined as a series or parallel connections of cells. These cells consist of semiconductive material doped in a single junction, like a diode. Different materials can be used and combined to achieve a similar channel, with distinct properties such as III and V materials [7, 17].

Elements such as Cu, Zn, Cd, Al, Ga, In, Si, Ge, P, As, Sb, S, Se and Te are considered semiconductor materials, therefore a P or N junction can be generated when combining these elements in a substrate base. Currently, for photovoltaic systems, the usage of Si, which is an IV element, is the most common approach for cell manufacturing. Over the past few decades, however, the doping process has evolved drastically, allowing the combination of elements from columns III and V, creating an III-V junction [4].

There are several classifications for photovoltaic cells with a silicon base, such as monocrystalline, polycrystalline, thin film and half cut. These classifications are typically related to the manufacturing process and homogeneity of the silicon layer within the cell arrangement [12, 17, 27].

Each type of solar panel sharing the same base material has a similar I/V curve and frequency response. Consequently, its efficiency becomes the main diverging factor [26].

Based on recent studies, the highest theoretical efficiency rating achievable by photovoltaic modules with silicon base material is 26.1% [27]. Understandably, engineers are trying to increase the efficiency of these modules without modifying their base material [12].

As the maximum theoretical efficiency for silicon cells is defined, researchers and manufacturers are currently working to reduce the thermal variation impact on the cells by increasing the heat transfer of the module [12] and developing new structures for silicon modules with the implementation of Passivated Emitter and Rear Cell (PERC) [6, 13, 18, 25].

Monofacial PERC has a silicon base, however, it has back-surface passivation, allowing the reflected solar irradiance to also be harvested by the module. This manufacturing technique provides an increase in efficiency of 5% over a non-PERC cell [1].

After several years, PERC cells are replaced with Passivated Emitter and Rear Cell Enhanced (PERC+) cells. PERC+ cells use a fragmented aluminum panel, instead of a solid rear panel. The implementation of a fragmented rear panel allows the development of Bifacial modules.

Bifacial PERC+ modules have a similar concept as mono facial PERC+ cells, but instead of having their core construction on the top layer of the photovoltaic module, it replicates their construction to the bottom of the module. Typically, the bottom face of the module is exposed to a maximum of 70% of the solar irradiance to which the top is exposed. It can increase the overall efficiency of the module by 22.3% depending on the albedo characteristics [19, 20].

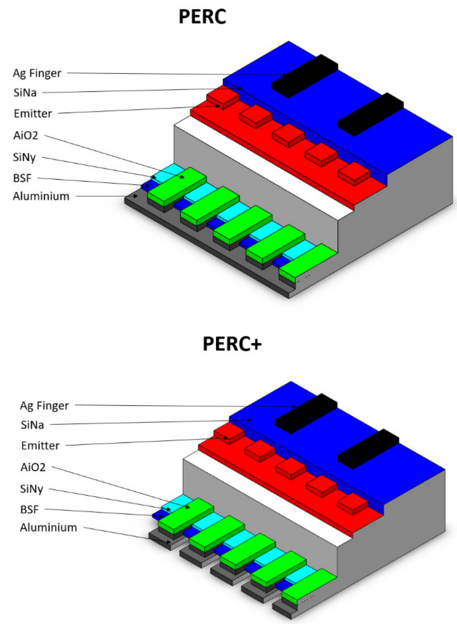

Fig. 1. PERC and PERC+ cell structure [6]

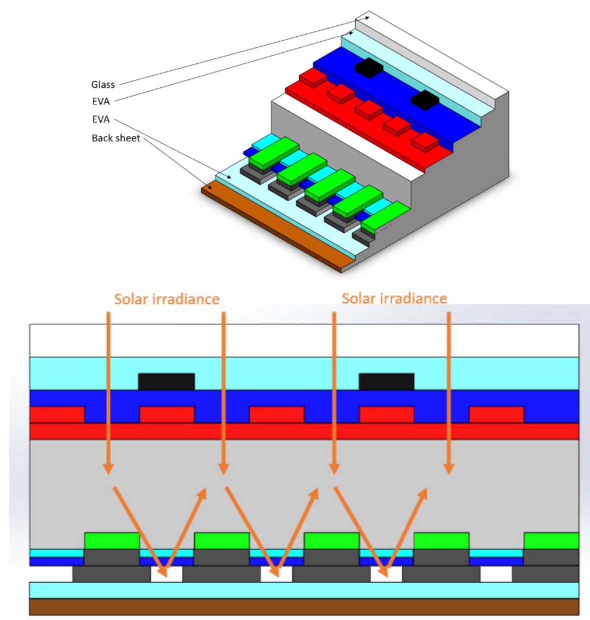

Fig. 2. Monofacial PERC+ cell structure [6]

Albedo is a constant based on the reflection characteristics of the material at the ground surface. It directly impacts the performance of bifacial panels as its performance is proportional to the solar irradiance exposure reflected at the ground The combination of III-V materials to achieve high efficiency in photovoltaic cells has been a common approach for non-terrestrial applications. Its wide spectrum band allows the absorption of solar irradiance across multiple lengths. Consequently, its theoretical efficiency can reach over 47.1% in controlled environments [8, 17].

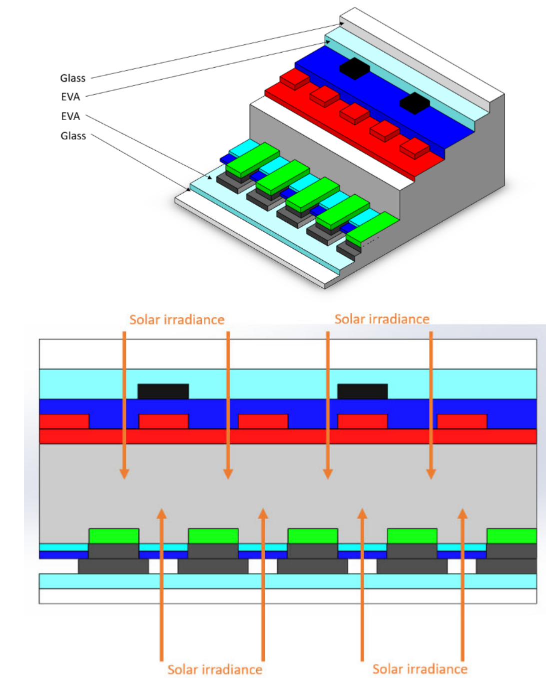

Fig. 2. Bifacial PERC+ cell structure [6]

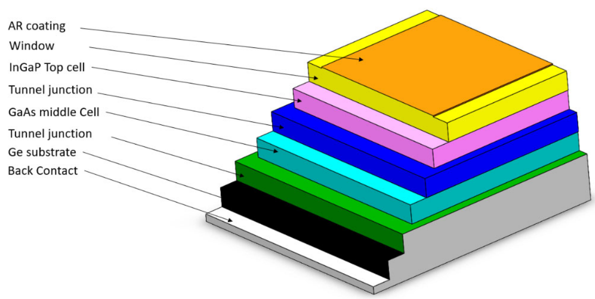

Fig. 3. InGaP/GaAs/Ge triple junction solar cell structure [10]

When implemented in terrestrial applications, the theoretical efficiency of III-V materials will rarely be achieved as its construction interconnects all the different materials in various junctions. Typically, a III-V cell can vary from 2 to 6 junctions interconnected in series. Each junction absorbs an irradiance band, which determines the conductivity of the junction [21].

As all the junctions in a III-V cell are connected in series, once one of the junctions has its solar irradiation absorbed by atmospheric gases, it may interrupt the current flow within the circuit as a result of the non-biased semiconductive material. As such, even with all the other internal junctions saturated, the module will be in open circuit condition [21].

This effect also happens in silicon base cells. As silicon base cells are typically single junctions, their performance is commonly affected by direct shading [17].

To avoid the loss of efficiency in a module caused by various cells in open circuit conditions, bypass diodes are placed in parallel with the cell or in some cases with the module.

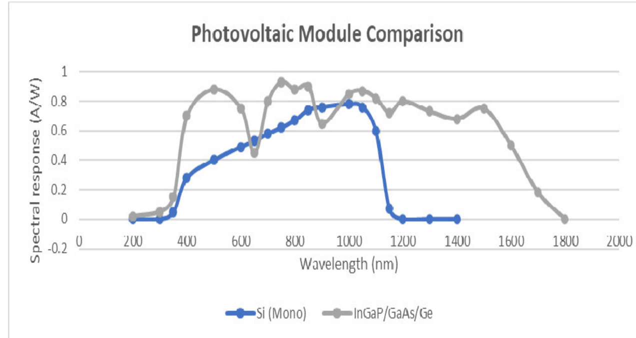

Fig. 4. Si Monocrystalline cell and InGaP/GaAs/Ge spectral response [23]

The figure below illustrates the equivalent circuit of a multijunction III-V cell, consisting of three junctions: a top junction of InGaP, a medium junction of GaAs, and a bottom junction consisting of Ge. As mentioned previously, each junction acts like a diode that is saturated by the solar irradiance operating at a certain band, or non-biased, blocking the current flow in the circuit.

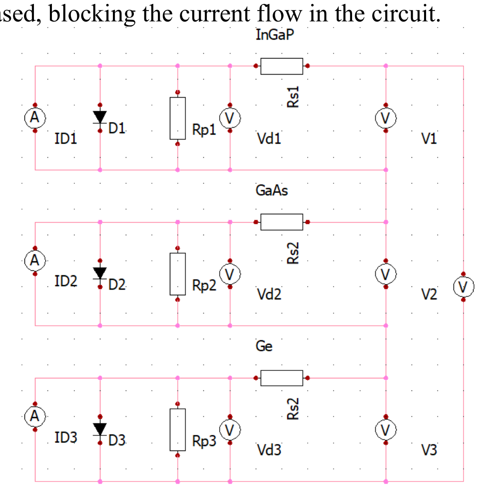

Fig. 5. InGap / InGaAs / Ge equivalent circuit [9]

A bypass diode becomes saturated when the forward-biased voltage is achieved while the cell or module connected in parallel is not producing electricity.

Bypass diodes can be extremely costly. Typically, silicon base cells are placed across the entire module as an external device or built inside the module encapsulation. When installed in silicon modules, these diodes are doped within a silicon film, creating a P-N junction. This of which is not efficient due to its elevated voltage drop, nor is it effective given its slow frequency response.

In multijunction panels, bypass diodes are often built inside the cells, substituting one of the junctions. It commonly shares the same base material as the rest of the cell. Germanium is one of the most common base materials for III-V cells. Therefore the P-N junction is just as efficient and responsive as the rest of the cell [7]. The figure below illustrates the equivalent circuit of an III-V cell with an inbuilt bypass diode.

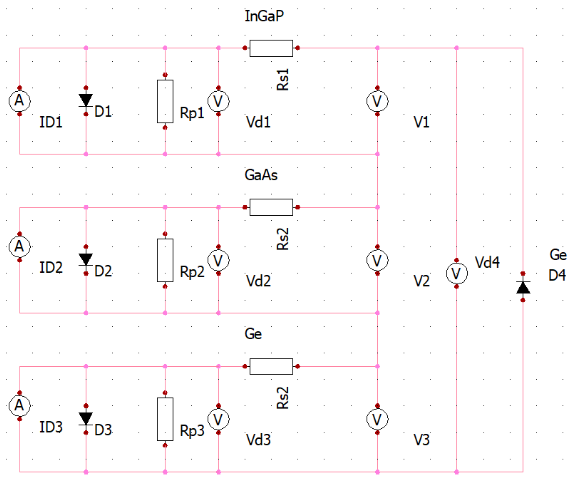

Fig. 6. InGaP / InGaAs / Ge + Ge bypass equivalent circuit

It is possible that the next generation of silicon-based cells will have a hybrid structure mixing III-V elements with silicon. Therefore, creating a hybrid subtracts results in the bounding of Si and Ge [26]. This approach would combine the wide solar irradiation absorption of III-V elements with the optimal irradiation absorption of terrestrial applications as a consequence of Si cells. The III-V junctions would have to be interconnected in series and the Si junction would have to be connected in parallel to the III-V junction. Consequently, if one band of the III-V junction is not biased, due to partial shadowing of the irradiance band required, it will not affect the Si junction which will be operating in a distinct spectrum [7, 26, 28].

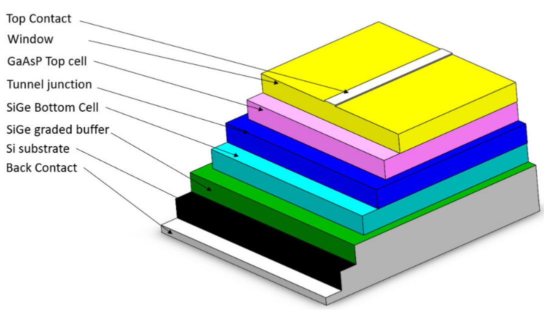

Fig. 7. Cross-sectional graph of GaAsP on SiGe/Si fabricated 3-T [26]

3. Maximum Power Point Tracker

Maximum Power Point Trackers (MPPT) are fundamentally a voltage and current regulators, adjusting the input power to its optimal point and delivering it to the inverter, which converts the direct current (DC) to alternating current (AC).

Fig. 9. Typical Power Flow connection in a grid connected photovoltaic system

Photovoltaic systems do not have a linear power curve. To achieve an optimal power, MPPTs have an internal algorithm capable of predicting the optimal power point and adjusting its internal hardware to match the required power delivery.

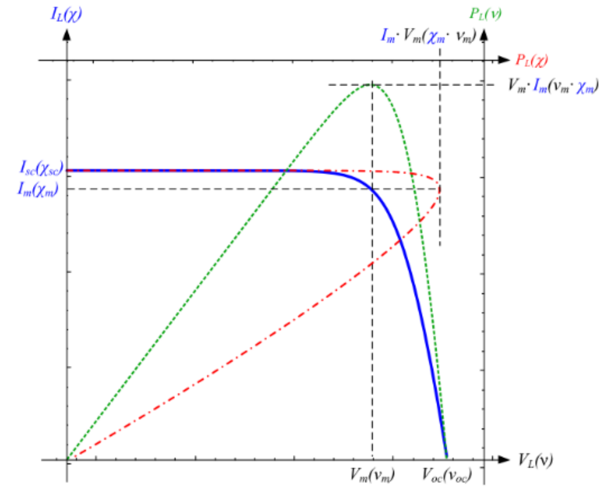

Fig. 10. Typical IxV curve of Si base photovoltaic panels [2]

Fundamentally the hardware topology required in an MPPT is defined by data acquisition, data process, and system response. Despite hardware variations due to components selection, algorithm selection is the most important design factor during the development of an MPPT. Currently, there are multiple algorithms and techniques available to adjust the MPPT circuit to the optimal power curve of a solar panel.

There are logical approaches using constant parameters such as constant voltage, open circuit voltage, and short circuit voltage. Furthermore, algorithms using trial and error such as Perturb and Observe (P&O), and DC-Link capacitor Drop. Some algorithms use mathematical calculations such as curve fitting, differentiation method, and incremental conductance. and algorithms with intelligent prediction, such as Fuzzy logic control and Artificial Neural Network (ANN) [3, 5, 17, 24].

Each algorithm has its own characteristics. P&O for example can perform better than ANN in stable and predictable weather conditions. On the other hand, utilizing ANN might improve the performance of a system commissioned in a volatile environment with unpredictable weather [5]. These differences are related to the overall efficiency of the controller, as ANN is a proactive approach, forcing the control circuit to operate constantly while P&O only reacts when there is a response or a variation in the system.

Defining the ideal algorithm for each photovoltaic system can potentially increase the overall efficiency of the system by 4%, without impacting the investment required during the development and implementation of the system [14, 24].

It is difficult to define the best algorithm for an MPPT as basic variables including the rate of meteorological variations, or intensity of the solar irradiance will drastically impact the performance of these devices.

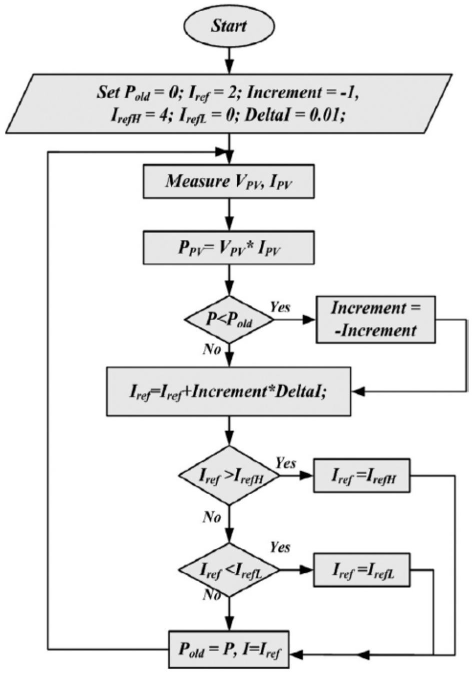

Fig. 11. Flowchart of P&O Algorithm [16]

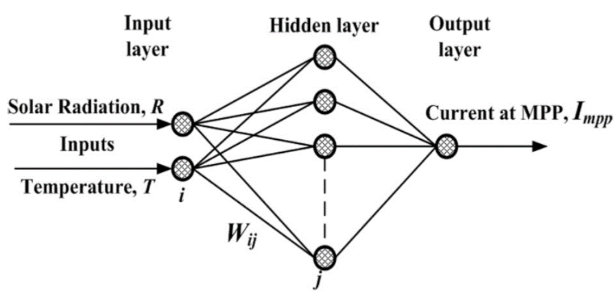

Fig. 12. Construction of ANN algorithm [16]

4. MPPT optimization for multijunction photovoltaic cells based on III-V elements

With photovoltaic cells based on III-V elements, algorithms need to be responsive and match the response time of the junctions within the cells.

Fundamentally, multijunction cells might achieve a frequency response of 180kHz [15], at this frequency, the switching performance of the MOSFETs from the switching circuit inside the MPPT might be impacted as a result of paradisiac capacitance. Given this, the usage of MOSFETs based on SiC and GaS might be an ideal approach.

In addition to the hardware, the MPPT algorithm might require optimization. For instance, the implementation of P&O algorithm with fixed step size, as shown in figure 11, will not be able to achieve the frequency variation required, due to the small step increment or decrement. Alternatively, the utilization of ANN would stress the microcontroller. Therefore, resulting in potential delays in the response due to the wide data process which refers to the circuit status with a predetermined set of parameters, based on a database.

The combination of an adaptive-perturbation-frequency in a P&O algorithm to constantly match the frequency variation of the photovoltaic cell with the maximum power point [11] might be the optimal solution for multijunction photovoltaic cells based on III-V materials. When implemented in terrestrial applications, however, it will require matching hardware to achieve an exact operating frequency.

The P&O algorithm, with an adaptive-perturbation frequency, would also have a variable step size. The step would be proportional to the variation between the Instantaneous Power Measurement and the Power at Maximum Power Point (MPP). This approach would also minimize the frequency response required on the MPPT circuit, therefore reducing power losses caused by the system during calibration.

5. Conclusion

It is certain that photovoltaic systems will be one of the main energy sources for the next decades. Si based cells are almost reaching peak efficiency, however, a transition towards photovoltaic cells based on III-V elements is inevitable.

This research explains the differences between photovoltaic cells based on Si and based on III-V elements and discusses potential issues with the implementation of III-V cells in terrestrial applications. A brief discussion comparing ANN and P&O was also conducted, followed by a possible solution for the efficiency loss in cells based on III-V elements.

The usage of Maximum Power Point Trackers with a variable step-size algorithm, combined with adaptive-perturbation-frequency in a P&O algorithm and implemented with matching hardware with the power modulation circuit semi-conductors also being based on III-V elements, may be the optimal solution for terrestrial systems using photovoltaic systems based on III-V elements.

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