LIMITS OF THE SINGLE DIODE MODEL IN VIEW OF ITS APPLICATION TO THE LATEST PV CELL TECHNOLOGIES

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ABSTRACT: The single diode model is a fundamental element in photovoltaic (PV) performance simulation tools, playing a pivotal role in characterizing PV module behavior as a function of irradiance and temperature.

This study is underscored by advancements in PV cell technology. Recent developments have yielded cells with exceptionally high fill factor, particularly prominent in TOPCon and Heterojunction cells. This brings the methods that are currently used to derive the single diode model parameters to their limit and can lead to situations where in order to describe accurately the MPP behavior, the precision for describing the open circuit voltage V_{oc} is compromised.

The primary objective of this study is to explore the boundaries of the single diode model as a means to describe the I-V characteristics of PV cells. The focus lies in investigating the implications of these high fill factors that inherently result in an elevated $\frac{V_{MPP}}{V_{OC}}$ ratio and how the single diode model can effectively encapsulate such behavior. By addressing this challenge, we aim to advance our understanding of the model's limits and its potential adaptations to accommodate the evolving landscape of PV cell technologies.
Keywords: Single diode model, Advanced PV cell technology, Modelling, Simulation, Limits of parameters

1 SINGLE DIODE MODEL

The single diode model [1] is an equivalent circuit that can be used for an individual PV cell, a module consisting of several cells or an array consisting of several modules. The concept of the single diode model finds its root in the history of solar cell research with foundational work dating back to several decades.

1.1 Description of the single diode model

The equivalent circuit to describe a PV cell is illustrated Figure 1 and the expression describing the general single-diode model for a given set of references conditions (STC: $1000\ \mathrm{W/m^2}, 25°\mathrm{C}, \mathrm{AM} = 1.5$) reads,

$$I = I_{ph} - I_0\left(e^{\left(\frac{V+I\cdot R_s}{N_{cells}\cdot n\cdot V_{th}}\right)} - 1\right) - \frac{V + I\cdot R_s}{R_{sh}} \quad (1)$$

with, two unknowns,

- I: output current of the PV module [A],
- V: output voltage of the module [V],

five parameters to be determined,

- I_{ph}: photocurrent generated by the module[A],
- I_0: diode saturation current [A],
- R_s: series resistance [Ω],
- R_{sh}: shunt resistance [Ω],
- n: diode ideality factor,

and physical constants,

- V_{th}: thermal voltage (given by $\frac{kT}{q}$, where $k = 1.381 \times 10^{-23}$ J/K is Boltzmann's constant, T is the temperature in Kelvin, and $q = 1.302 \times 10^{-19}$ Coulomb is the electronic charge).

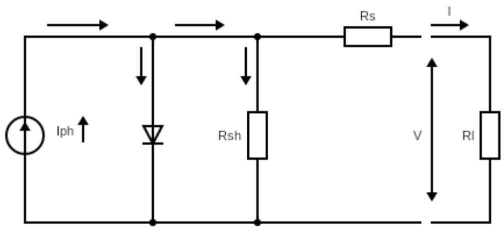

Figure 1: Diagram of the equivalent circuit to describe a PV cell.

The model parameters can depend on the irradiance and temperature. In the simplest approach, I_{ph} is proportional to the irradiance G, and I_0 is a function of the temperature, T.

The single diode model in PVsyst adds two small modifications to this basic description:

1. The shunt resistance, R_{sh} is assumed to increase exponentially with falling irradiance. This is described by two additional parameters. The value for R_{sh} at $G = 0$ and the exponential factor for the decrease.
2. A small temperature dependance of the ideality factor, n which allows to tune the MPP temperature coefficient at standard test conditions (STC) to a given measured value.

In this work, we restrict out considerations to the STC and to the behavior at $200\ \mathrm{W/m^2}$ and 25 °C. Therefore, the temperature dependences will have no impact on the discussion and the results.

To solve equation (1) , we will first have to determine the five parameters based on the STC data of the modules commonly provided by manufacturers. The details on the determination of these parameters are not explained [2] in this paper, and for the interested reader, please refer to [1] [2].

1.1 Output of the single diode model

After obtaining the five parameters, the single diode model can be solved either by using a successive approximation approach to predict the I-V characteristics of a PV cell, or by explicitly expressing I(V) with the help of the Lambert W function[2]. The typical I-V and P-V curves of solar cells are shown in Figure 2 along with its characteristic points, including the (i) short-circuit point $(I_{sc}, 0)$, (ii) open-circuit point $(0, V_{OC})$ and (iii) maximum power point (I_{MPP}, V_{MPP}). These characteristic points are normally known from the data sheet of the module.

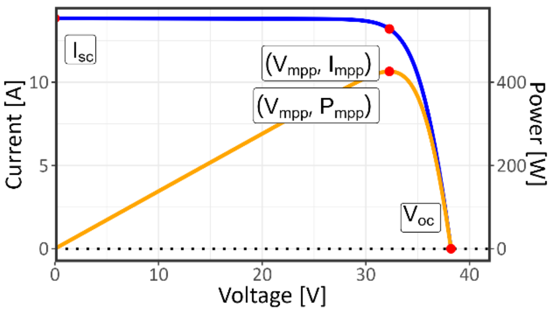

Figure 2: I-V and P-V curve a PV cell with its characteristic points $I_{sc}, V_{oc}, (V_{MPP}, I_{MPP})$ and (V_{MPP}, P_{MPP}).

The single diode model allows to describe the PV module behavior at all temperatures and irradiances as illustrated in Figure 3. These curves show the efficiency as function of irradiance for different temperatures. They exemplify the behavior of a typical state of the art monocrystalline PV module. The detailed parameters that were used for these curves are given in section 3.

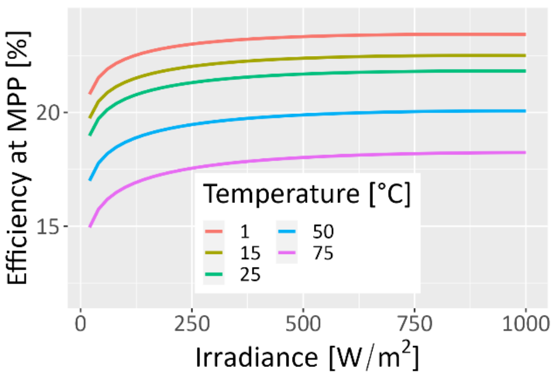

Figure 3: Behavior of a PV module at all temperatures as a function of irradiance.

2 HISTORICAL TRENDS OF: VMPP/NCELLS

Photovoltaic technology encompasses a range of technologies and materials. The preeminent technology is centered on silicon-based PV modules where silicon solar cells offer an optimal balance between cost-effectiveness and efficiency. However, driven by the quest for enhanced efficiency and improved performance, the technology of solar cells has been evolving. This evolution has a profound impact on the fill factor (FF). in the context of solar cells, FF represents a key parameter that characterizes the overall performance and efficiency of a PV module. This dimensionless quantity is represented as

$$FF = \frac{I_{MPP} \cdot V_{MPP}}{I_{SC} \cdot V_{OC}} \tag{2}$$

Technologies such as TOPCon and HIT are advanced silicon variants that serves at reducing recombination losses to enhance FF and efficiency. The trend to larger FF goes along with an increase of the cell voltage $\frac{V_{MPP}}{N_{cells}}$. The V_{oc} shows a less pronounced increase, leading to ever higher ratios of $\frac{V_{MPP}}{V_{OC}}$. Figure 4 illustrates the evolution of $\frac{V_{MPP}}{N_{cells}}$ for Si-mono, Si-poly and HIT PV modules in the PVsyst database and demonstrates an upward trend of the $\frac{V_{MPP}}{N_{cells}}$ between year 2000 and 2023.

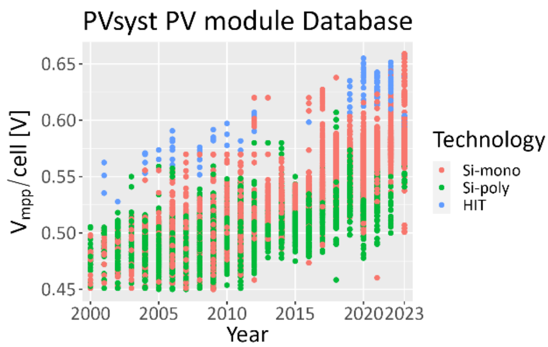

Figure 4: Trends of $\frac{V_{MPP}}{N_{cells}}$ of PV modules with different technologies, i.e., Si-mono, Si-poly and HIT, in the PVsyst database.

In the next section, we will study the interdependence of different outputs of the single diode model. We will look especially at the ratio $\frac{V_{MPP}}{V_{OC}}$, and how it is linked to the ratio $\frac{V_{MPP}}{N_{cells}}$ and the behavior of the model at low irradiance. This is motivated by the fact that the trend of increasing $\frac{V_{MPP}}{V_{OC}}$ is reaching a limit, where the single diode model cannot be mathematically established.

3 PARAMETER RANGES AND CONSTRAINTS

In order to analyze the behavior of the single diode model, we will start with a set of parameters that describes a typical monocrystalline 426 Wp module. The parameters for the single diode model for this PV module are presented in Table 1. The parameters I_{ph} and N_{cells} set the global power of the PV module and can be changed without changing the following discussion. The other parameters will have an impact on the detailed shape of the I-V and P-V curves which will change the values like $\frac{V_{MPP}}{V_{OC}}$ or $\frac{V_{MPP}}{N_{cells}}$.

Example PV module	
I_{ph} [A]	13.84
I_0 [pA]	15
N_{cells}	54
n	1
R_s[mΩ]	120
R_{sh}[Ω]	800

Table 1: Parameters of a monocrystalline 456 Wp PV module.

We first have a look at the parameter $\frac{V_{MPP}}{V_{OC}}$ and its dependence on R_s and I_0. The value of $\frac{V_{MPP}}{V_{OC}}$ increases as R_s and I_0 decreases. This behavior is illustrated in Figure 5 and Figure 6 where an almost linear dependency for R_s and a logarithmic dependency for I_0 is observed respectively. We can see that by changing these two parameters a large range of $\frac{V_{MPP}}{V_{OC}}$ ratios are covered, ranging from 0.80 to 0.88.

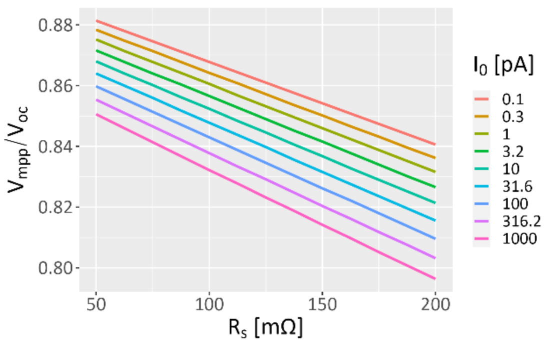

Figure 5: $\frac{V_{MPP}}{V_{OC}}$ in terms of R_s for different I_0.

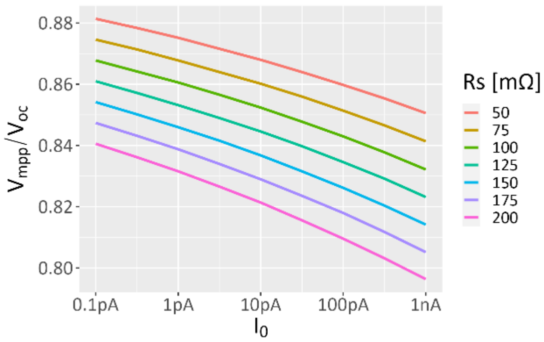

Figure 6: $\frac{V_{MPP}}{V_{OC}}$ in terms of I_0 for different R_s.

However, changing R_s and I_0 will have also an impact on other results of the single diode model, such as the $\frac{V_{MPP}}{N_{cells}}$ and the low light efficiency. A realistic modeling of a PV module will require that these quantities stay within certain limits, and as we will see, this will limit the $\frac{V_{MPP}}{V_{OC}}$ to a much smaller range.

Now, if we analyze the V_{MPP} of PV cells with different technology, it is observed that in general, the $\frac{V_{MPP}}{N_{cells}}$ does not change much. The histogram in Figure 7 shows this ratio for the PV modules that were introduced in the PVsyst database over the past five years. One can see that this value lies between 0.55V and 0.6V for Si-mono modules and between 0.60V and 0.65V for HIT modules. The medians for these distributions lie at 0.57V and 0.63V respectively. We will take the range from 0.55V to 0.65V as the range of realistic values for $\frac{V_{MPP}}{N_{cells}}$.

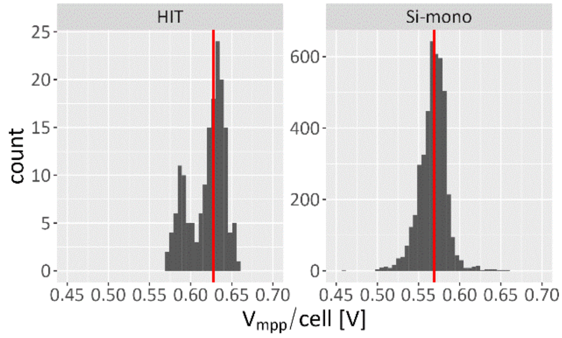

Figure 7: Histogram of $\frac{V_{MPP}}{N_{cells}}$ for HIT and Si-mono PV modules.

Another property of the single diode model that can be used as a criterion for a realistic description of crystalline Si PV modules is the low light behavior. As a measure for this behavior, we take the relative efficiency loss of the PV module at 200 W/m^2 and 25°C with respect to STC. Based on measurements for many silicon PV modules, we have observed that this relative drop in efficiency lies always very close to -3%. As shown in Figure 8, we can see that limiting the loss to values close to -3% puts a strong limit on the range of possible values for R_s. To calculate the relative efficiency loss in Figure 8, we assumed that R_{sh} at 200 W/m^2 is approximately 4 times the values of R_{sh} at STC. This assumption is based on the default values in Pvsyst for R_{sh} at G=0 and the exponential factor of 5.5.

In the following section, we will see how the restriction to these conditions, which we consider a realistic description of a crystalline Si module, will limit the possible ranges for $\frac{V_{MPP}}{V_{OC}}$ and $\frac{I_{MPP}}{I_{SC}}$, which together determine the Fill Factor of the PV module.

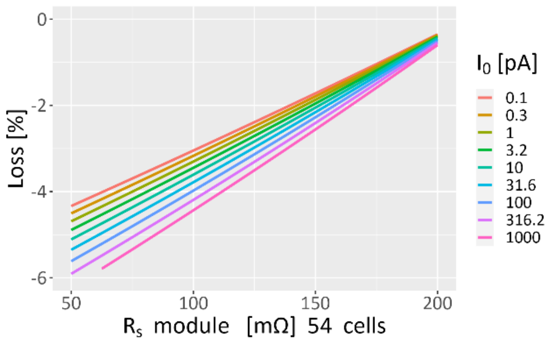

Figure 8: The low light efficiency in terms of R_s for different I_0.

4 LIMITS FOR THE RATIOS: V_{MPP}/V_{OC} AND I_{MPP}/I_{SC}

Now that we have seen the dependence of $\frac{V_{MPP}}{V_{OC}}$ on different parameters, we are in position to analyze the limits of ratios, specifically the $\frac{V_{MPP}}{V_{OC}}$ and $\frac{I_{MPP}}{I_{SC}}$.

The main findings show that limiting parameters $\frac{V_{MPP}}{N_{cells}}$ and low-light efficiency to typically observed values leads also to a limited range for $\frac{V_{MPP}}{V_{OC}}$ and $\frac{I_{MPP}}{I_{SC}}$. When the voltage at the maximum power point per cell, $\frac{V_{MPP}}{N_{cells}}$ is confined within the range of 0.55V to 0.65V and a relative efficiency loss of 3% is observed at an irradiance level of $200\ W/m^2$, an intriguing limitation emerges concerning the $\frac{V_{MPP}}{V_{OC}}$ ratio. This ratio is constrained to values encompassing the range of 83% to approximately 85%. The upper limit of 85% signifies the necessity for exceptionally diminutive saturation currents, I_0, that is typically on the order of a few pA at the standard temperature of 25°C. However, this constraint implied the emergence of even more minuscule saturation currents at lower temperatures, such as around -10°C, thereby emphasizing the profound sensitivity of diode behavior to temperature fluctuations within the PV system. Figure 9 shows the $\frac{V_{MPP}}{V_{OC}}$ ratio as a two-dimensional contour plot along with the ranges for $\frac{V_{MPP}}{N_{cells}}$ and the relative efficiency and the $\frac{V_{MPP}}{V_{OC}}$ for both Si-mono and HIT technology PV modules are included and represented with dotted lines.

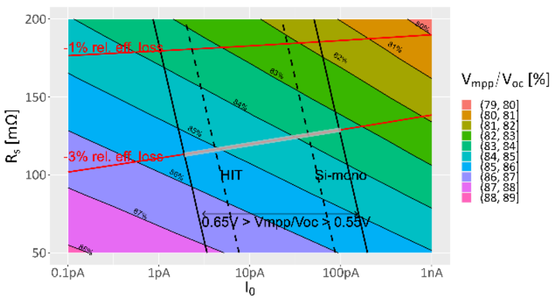

Figure 9: 2D contour plot of the $\frac{V_{MPP}}{V_{OC}}$ ratio - for $0.55V < \frac{V_{MPP}}{N_{cells}} < 0.65V$ and relative efficiency loss of 3% at G=$200\ W/m^2$, $\frac{V_{MPP}}{N_{cells}}$ is constrained between 83% to 85%.

As for the $\frac{I_{MPP}}{I_{SC}}$ ratio, the relationship between the short-circuit current I_{SC} and the current at the maximum power point I_{mpp} is primarily influenced by $\frac{V_{MPP}}{N_{cells}}$- In practical scenarios with typical values for $\frac{V_{MPP}}{N_{cells}}$, the ratio of $\frac{I_{MPP}}{I_{SC}}$ tends to remain within a relatively narrow range, generally between 95% to 96%. This observation implies that variations in I_{mpp} and I_{sc} have only a marginal impact on increasing the fill factor of the PV system. An illustration of the ranges of $\frac{I_{MPP}}{I_{SC}}$ along with the ranges for $\frac{V_{MPP}}{N_{cells}}$ and the relative efficiency for both Si-mono and HIT PV modules is presented in Figure 10.

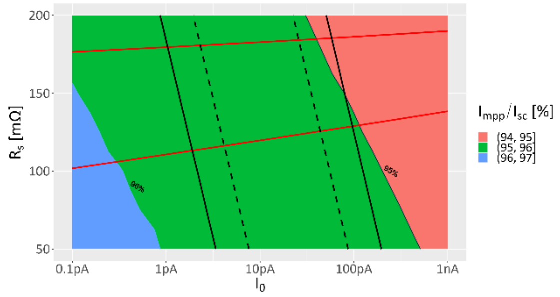

Figure 10: 2D contour plot of the $\frac{I_{MPP}}{I_{SC}}$. ratio - for $0.55V < \frac{V_{MPP}}{N_{cells}} < 0.65V$ and relative efficiency loss of 3% at G=$200\ W/m^2$, $\frac{V_{MPP}}{N_{cells}}$ is constrained between 83% to 85%.

5 DISCUSSION AND PERSPECTIVES

In the preceding section, we examined the intricated interplay of several parameters in PV modules and their influence on the $\frac{V_{MPP}}{V_{OC}}$ and $\frac{I_{MPP}}{I_{SC}}$ ratios. Several insights can be deduced from this analysis.

The key takeaway is that R_s should be meticulously determined to strike a balance between maximizing voltage ratios and minimizing efficiency losses. We observed that increasing R_{sh} marginally extends the range towards higher $\frac{V_{MPP}}{V_{OC}}$ and $\frac{I_{MPP}}{I_{SC}}$ ratios. However, it is crucial to note that a smaller R_s results in larger $\frac{V_{MPP}}{V_{OC}}$, yet this advantage comes at the cost of higher efficiency losses when the module operated under low irradiance conditions.

In PVsyst, the R_s is fixed by the required relative efficiency at $200\ W/m^2$. Furthermore, the ideality factor, n and reverse saturation current, I_0 play intricate roles in the behavior of the diode within PV modules. While it is understood that selecting values of $n < 1$ and reducing I_0 can widen the range of possible $\frac{V_{MPP}}{V_{OC}}$ ratios, a physical interpretation of these values remains elusive. A deeper understanding of semiconductor physics governing PV module operation is required in order to harness the benefits of adjusting n and I_0 for optimizing $\frac{V_{MPP}}{V_{OC}}$ ratios.

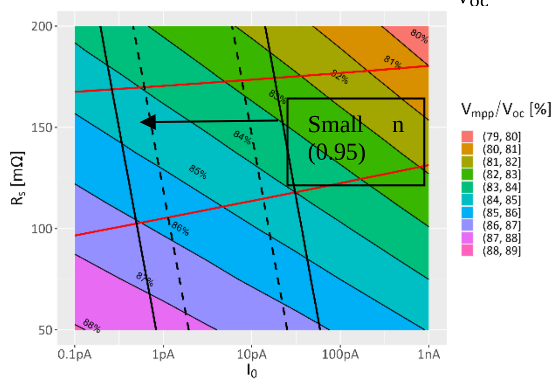

Figure 11: 2D contour plot of the $\frac{V_{MPP}}{V_{OC}}$ ratio with a smaller ideality factor n.

It occurs that in the PVsyst database, the $\frac{I_{MPP}}{I_{SC}}$ ratio has to be limited by increasing the values of V_{oc}. This ensures a description of the MPP that is consistent with the data sheets. [2]

6 CONCLUSION

The modules of new technologies (TOPCon, HJT) exhibit a very high Fill Factor. The main contribution to this increase is the $\frac{V_{MPP}}{V_{OC}}$ ratio; the $\frac{I_{MPP}}{I_{SC}}$ is rather stable and does not have a big importance in the Fill Factor.

The problem is that the one-diode model (especially the Shockley diode behaviour) is no longer applicable with such values. This study aims to identify the limits on the parameters, which mathematically allow to apply the one-diode model in satisfactory conditions, corresponding to the physical reality.

Some of these physical realities are derived from the PV modules characteristics, as present in the PVsyst database for recent modules (5 years). At STC, the voltage $\frac{V_{MPP}}{N_{cells}}$ is distributed between 0.55 and 0.65 V (0.63V average for HIT). And in most measurements that we have received from testing laboratories, the relative efficiency is close to -3% at $200\,W/m^2$. The diode saturation current should not become lower than some few pA at STC, as it has a huge decrease according to the lower temperatures.

Now the low-light efficiency is mainly related to the R_s value. Therefore, we have evaluated the $\frac{V_{MPP}}{V_{OC}}$ value, as a function of the R_s and the diode saturation current. We found that the low-light efficiency limit of 3% imposes a maximum $\frac{V_{MPP}}{V_{OC}}$ ratio of the order of 0.86, or more likely 0.84-0.85 for reasonable Io and $\frac{V_{MPP}}{N_{cells}}$ values. The R_{sh} value has a marginal effect on these limitations.

The main objective of the one-diode model is to evaluate the P_{mpp} value during the simulations, as a function of the irradiance and the temperature. The I-V curve is only used in special conditions, i.e., limitations of the inverter (overload) or electrical shadings calculations. In practice, we can "save" the one-diode model for modules of extreme fill factors, by artificially increasing the V value at STC (usually by some fractions of percent). This will not modify the P_{mpp} behaviour, and very slightly modify the I-V curve at low currents.

6 REFERENCES

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