CELL TO MODULE LOSSES OF AN MWT MODULE

L.H. Slooff, E.E. Bende, M.J. Jansen, L.A.G. Okel, F.J.K. Danzl, P. Manshanden,
ECN Solar Energy, P.O. Box 1, 1755 ZG Petten, The Netherlands
Phone: +31 88 515 4314, Fax: +31 88 515 8214, E-mail: slooff@ecn.nl

ABSTRACT: The efficiency of photovoltaic modules is for a large part determined by the solar cell efficiency, but the electrical losses from current transport between the cells and to the module contacts, and optical losses also play an important role. In order to investigate the losses in the module the Cell to Module (CtM) ratio is often used. It is determined by the ratio in performance between the module and the cell and gives an indication of the electrical and optical losses in the module. In principle this seems a straightforward approach. However, a good CtM measurement is not as trivial as it seems. Many factors play a role. Not only the way the measurement is done, but also which parameters are used for the cell in the comparison. After all, a module consists of many cells that are all slightly different. The various aspects in measurement and their influence on the CtM ratio will be discussed and suggestions for a correct measurement protocol to determine absolute CtM ratios will be given.
Keywords: Cell to module ratio, CtM ratio, PV module, MWT

1 INTRODUCTION

Research in the field of photovoltaic (PV) modules is always focused on increasing the efficiency and reducing the costs. The efficiency of a PV module is for a large part determined by the efficiency of the cell. But the final module efficiency is also determined by the losses that occur when the cells are put together in the module. To minimize these losses and to optimize the module efficiency it is important to know the cell to module loss, or CtM ratio. CtM losses are always expressed as the ratio between the module output and the cell output, where the output can be the power, short circuit current (Isc), fill factor (FF), open circuit voltage (Voc) or efficiency (η). This trivial definition is not as simple as it seems. The numbers for both the cell and module output are influenced by many factors in the measurements itself. As a result, the CtM ratio is related to the way the measurements were done and thus CtM ratios can only be compared if the measurements were done in a similar way. Besides that it is also affected by the cell parameter that is used for the comparison. As there are many cells in the module it is not straightforward which one should be used. In most of the publications on CtM these issues are not or only partly addressed[1,2,3,4] although there are a few exceptions.[5] This paper first addresses the importance of differentiation between an absolute and relative CtM ratio. Next the different factors that influence the measurements are discussed. Subsequently an example is given of relative CtM ratios that are based on three different approaches for the input of the cell parameters. Finally a measurement and calculation procedure is proposed that enables the comparison of CtM ratios between different institutes/companies.

2 RELATIVE AND ABSOLUTE RATIOS

The uncertainty in the measured current of a cell or module is determined by many factors. It depends for example on the reference cell that is used, the reproducibility in adjusting the irradiation of the solar simulator and the spectral mismatch between the spectrum of the solar simulator and the AM 1.5 spectrum. But it also depends on the uncertainty in the electrical measurements. However, the effects on the current are expected to be much smaller than the effect of the spectral mismatch. For this reason we will focus here on the effects resulting from the spectral mismatch. If a cell is measured on two different solar simulators, the measured currents will be different as the lamp spectra will be different. To obtain similar currents, the current needs to be corrected for the differences in the lamp spectra. This is done by measuring the spectral response (SR) of the cell and the lamp spectrum. I-V measurements of PV cells are often performed on a different setup than the module measurements and thus the currents cannot be directly compared. If the currents are not corrected for the spectral mismatch, only a relative comparison can be done. For an absolute comparison, the mismatch (MM) between the cell and module measurement needs to be determined. For this, the SR of both the cell and the module must be measured as well as the lamp spectra of both sun simulators. Then the MM factor can be derived using the following formula:

$$MM = \frac{I_{ref,AM1.5} * I_{test,lamp}}{I_{test,AM1.5} * I_{ref,lamp}}$$

Where $I_{ref,Am1.5}$ is the current from the calibrated reference cell/module for AM1.5 spectral conditions, is the current of the test cell for AM1.5 spectral conditions, $I_{ref,lamp}$ is the current of the reference cell as measured in the solar simulator and $I_{test,lamp}$ is the current of the test cell as measured in the solar simulator. $I_{ref,Am1.5}$ and $I_{test,Am1.5}$ are derived from the known AM1.5 spectrum and the measured spectral response.
The MM is determined with respect to the AM1.5 spectrum. This means that the current of both the cell and the module must be corrected before they can be compared. The correct current $I_{test,cor}$ can now be estimated from the measured current $I_{test,meas}$ and the mismatch factor as follows:

$$I_{test,cor} = \frac{I_{test,meas}}{MM}$$

From the above it is clear that when comparing CtM ratios between institutes or companies an absolute CtM must be used. Even within an institute absolute CtM is needed when different cell technologies are used, as again the SR will be different for the different cell technologies.
A relative CtM can be used only in the following situations:

- To check if a module line is performing according to specs. A CtM is determined for the specific module and trends in CtM can be followed.

- To study cell processing or module fabrication improvements that do not affect the SR of the module. For example metallization or tabbing, different and minor changes in cell processing.

3 MEASUREMENT FACTORS

The basics in performing measurements for determining the CtM ratio is that the cell measurement must be as similar to the module situation as possible. This means that the following points should be considered for each cell type and situation.

- Cell contacting,
- Chuck reflections,
- Reference cell,
- Reference module,
- Bi-facial cells.

Cell contacting

If an H-pattern cell is used, the number of contact pins on the cell can have an influence on the FF of the cell measurement. If in the module the tabs are soldered at more points than there are measurement probes in the cell measurement, a relatively higher FF will be measured. In that case a CtM gain in FF can be obtained whereas in reality the CtM will be lower or can even be a loss. Or the other way round. Especially if lower conducting or floating busbars are used this could have a large impact. Back contacted cells like IBC and MWT have fixed contact points, so for these cell types fill factor changes due to different contact points should not occur.

Chuck reflections

The measurement chuck on which the cell is positioned will reflect light that can eventually reach the solar cell and contribute to the current of the cell. For mono-facial cells this concerns mainly light that hits the chuck outside the cell, but for bi-facial cells this also holds for light that is not absorbed by the cell and is reflected from the chuck back to the cell. Therefore, the area outside the cell should be covered with non-reflecting material and for bi-facial cells between the chuck and the cell as well.

Reference cell

For accurate cell measurements a calibrated reference is used and the measured cell data are corrected for spectral mismatch. This means that the spectral response (SR) of the reference cell and test cell must be known as well as the spectrum of the lamp of the solar simulator. Preferably, the reference cell should be of the same type and size as the test cell. The size will be of influence if the irradiance is not homogeneous over the area.

Reference module

Module measurements also use a reference module. Like with the cells, the SR of both the reference and test module and the spectrum of the lamp of the flash tester must be known for spectral mismatch correction. Here also the type and size of the module are preferably similar to the test module.

Bi-facial cells

Besides the chuck reflection there are several other aspects that need to be considered when measuring bi-facial cells. A committee is working on a standardized norm for the measurements of bi-facial cells or modules[6], but at the moment there is no norm available. However it is suggested to measure a bi-facial cell [7] under front and rear side illumination and determine the bi-faciality ratio: bi-faciality=$I_{sc,rear}/I_{sc,front}$

Then the compensated current density can be derived:

$$I_{sc,com} = (1 + 0.2 * bifaciality) * I_{sc,front}$$

4 APPROACH

I-V measurements were performed on a series of 60 MWT cells that were processed at ECN. For each cell the I-V curve was subjected to a 2-diode model fit.[8,9] These fit parameters were put into a model that calculates the I-V characteristics of a series connection of cells. The module contained 3 individual strings as in a typical MWT module. For each string the series connection was calculated, as well as the series connection for the complete module.[10] This apprach will be called String to Module (StM). The measured currents were not corrected for MM so the results show only relative StM and CtM ratios. The I-V curve summing result was compared to more commonly used approaches for determining the CtM ratio:

1. The minimum Isc of the cells, the sum of the Voc's and an average FF: this allows for determining a CtM ratio for current, Voc, FF and Pmp
2. The average Isc of the cells, the sum of the Voc's and an average FF: this allows for determining a ratio for CtM current, Voc, FF and Pmp
3. Summing the powers from the measured individual cells: allows for determining a CtM ratio for Pmp only.

5 RESULTS

In Table I the calculated cell parameters for each string and the calculated parameters for the module are given. The table does not show CtM or StM ratios. It shows the string or module parameters that can be used as input for the CtM or StM ratio. For a CtM or StM ratio, also the module should be measured, which was not done yet. The overall difference in power between the different approaches can be more than 1%. It is clear that a CtM ratio can only be compared if it is based on the same approach for the cell or string input. The difference is mainly due to a difference in Isc. Often the minimum current of the cells in a string is used to obtain a CtM ratio for the current, as the cell with the lowest current determines the current in a series connected string. However, in reality this is not true as it also depends on the FF of the cells. In the examples below it is shown that the average current of the cells gives a much closer match to the current of the strings and the module. The sum of the Vocs and the average FF also are a good approach to determine CtM ratios.

Table I: Cell, string and module parameters for the various approaches. Percentage are relative to the sum of the I-V curves of the cells in the string.

string 1	**Pmp[W]**	**Isc[A]**	**Voc[V]**	**FF[%]**
∑ I-V of cells StM	100.24	9.188	14.00	77.96
min I_{sc}, ∑ V_{oc}, av FF	99.64	9.137	13.98	77.98
Δ wrt ∑ I-V	-0.60%	-0.56%	-0.08%	0.03%
av I_{sc}, ∑ V_{oc}, av FF	100.21	9.190	13.98	77.98
Δ wrt ∑ I-V	-0.03%	0.01%	-0.08%	0.03%
∑cell powers	100.36			
Δ wrt ∑ I-V	0.11%			
string 2	**Pmp[W]**	**Isc[A]**	**Voc[V]**	**FF[%]**
∑ I-V of cells StM	95.56	9.191	13.36	77.81
min I_{sc}, ∑ V_{oc}, av FF	94.85	9.122	13.35	77.86
Δ wrt ∑ I-V	-0.76%	-0.75%	-0.06%	0.06%
av I_{sc}, ∑ V_{oc}, av FF	95.59	9.194	13.35	77.86
Δ wrt ∑ I-V	0.03%	0.03%	-0.06%	0.06%
∑cell powers	95.70			
Δ wrt ∑ I-V	0.14%			
string 3	**Pmp[W]**	**Isc[A]**	**Voc[V]**	**FF[%]**
∑ I-V of cells StM	78.18	9.256	10.83	78.02
min I_{sc}, ∑ V_{oc}, av FF	77.40	9.169	10.82	77.99
Δ wrt ∑ I-V	-1.02%	-0.95%	-0.04%	-0.03%
av I_{sc}, ∑ V_{oc}, av FF	78.20	9.265	10.82	77.99
Δ wrt ∑ I-V	0.02%	0.09%	-0.04%	-0.03%
∑cell powers	78.27			
Δ wrt ∑ I-V	0.11%			
Module	**Pmp[W]**	**Isc[A]**	**Voc[V]**	**FF[%]**
∑ I-V of cells StM	273.95	9.205	38.18	77.94
min I_{sc}, ∑ V_{oc}, av FF	271.34	9.122	38.16	77.94
Δ wrt ∑ I-V	-0.96%	-0.90%	-0.06%	0.00%
av I_{sc}, ∑ V_{oc}, av FF	274.12	9.216	38.16	77.94
Δ wrt ∑ I-V	0.06%	0.12%	-0.06%	0.00%
∑cell powers	274.33			
Δ wrt ∑ I-V	0.14%			

6 CtM PROTOCOL

The paragraphs above show that both the measurements procedure as well as the calculation procedure influence the resulting CtM ratios. For this reason it is important that similar procedures are used when comparing data between institutes or companies. We propose the following protocols:

Measurement protocol.

- Measure all cells in the solar simulator: area outside the cell should be masked to avoid chuck reflections.
- Measure the SR of at least 3 typical cells.
- Calculate the MM factor for the cells using the average SR, the solar simulator lamp spectrum, the SR of the reference cell and the AM1.5 spectrum.
- Correct cell power and current with the MM factor.
- Measure the module in the flash tester: unmasked.
- Measure the SR of the module.
- Determine the MM factor using the SR of the module, the lamp spectrum of the flash tester, the SR of the reference module and the AM1.5 spectrum.
- Correct the module power and current with the MM factor.

For bi-facial cells and modules the protocols are rather similar, but now the cell should be measured on a black background to avoid chuck reflection from underneath the cell and the module should be measured under front and rear side illumination. Furthermore the proposed measurement standard for bifacial power measurement, as described above should be followed.

Calculation protocol

CtM ratio of the power:

- Take the average MM corrected Isc of the individual cells, the sum of the Voc's of the cells and the average FF of the cells.
- Calculate the expected module power from these numbers.
- Take the ratio of the measured MM corrected module power over the expected module power.
- For a CtM ratio for the efficiency, also the cell and module area become important. Here total cell area and total module area, including frame, should be used.

7 CONCLUSIONS

Various aspects in PV cell and module measurement and their influence on the CtM ratio have been discussed and suggestions for a correct measurement protocol to determine absolute CtM ratios will be given. The importance of absolute CtM ratios for comparisons between companies and institutes is explained and the influence of the cell parameters are shown. For determining CtM ratios the average Isc, sum of Voc and average FF give a good approximation with respect to the summing of the individual IV curves. For that approximation the difference is well below 0.1% whereas summing of the power of the individual cells gives an error of 0.1% to 0.15%. It is therefore recommended to either sum the individual IV curves or to take the average Isc, sum of Voc and average FF as cell parameter input in CtM ratios.

8 ACKNOWLEDGMENTS

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9 REFERENCES

[1] I. Haedrich, M. Wiese, B. Thaidigsman, D. Eberlein, F. Clement, U. Eitner, R. Preu, H. Wirth, Energy Procedia 38 (2013) 355.
[2] I. Haedrich, U. Eitner, M. Wiese, H. Wirth, Sol. En. Mat & Sol. Cells 131 (2014) 14.
[3] S.M. Dasari, P. Srivastav, R. Shaw, S. Saravanan, P. Suratkar, Renew. Energy 50 (2013) 82.
[4] T-H. Jung, H-E. Song, H-K. Ahn, G-H. Kang, Solar Energy 103(2014) 253.
[5] J.P. Singh, Y. S. Khoo, J. Chai, Z. Liu, Y. Wang, Photovoltaic International 31 (2016) 90.
[6] IEC/TS 60904-1-2 Ed. 1.0 Photovoltaic devices - Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices.
[7] https://pvpmc.sandia.gov/pv-research/bifacial-pv-project/bifacial-pv-characterization-and-rating-standards/.
[8] A.R. Burgers, J.A. Eikelboom, A. Schönecker, and W.C., Sinke. Improved treatment of the strongly varying slope in fitting solar cell I-V curves. In Proceedings 25th IEEE PVSC Conferenc (1996) 569.
[9] In-house built model ivfit. Commercial available via **pvwebtools@ecn.nl**.
[10] G. Friesen, S. Dittmann, S. Williams, R. Gottschalg, H.G.Beyer, A. Guerin de Montgareuil, N.J.C.M. van der Borg, A.R. Burgers, R. Kenny, T. Huld, B. Müller, C. Reise, J. Kurnik, M. Topic. 24th European Photovoltaic Solar Energy Conference (2009) 3189.