Why are acceptance angle of P_m and I_{sc} different in spite of uniform illumination onto concentrator solar cells?

K. Araki , R. Herrero , I. Antón , G. Sala , H. Nagai , K-H. Lee , and M. Yamaguchi

***Abstract* — The acceptance angle of concentrator modules measured by short circuit current *Isc* is always larger than that by maximum power *Pm* even by use of advanced concentrator optics that keep uniform illumination onto the concentrator cells. The purpose of this study is to investigate the cause of that myth. An expanded Monte Carlo method that calculates acceptance angle of CPV modules was developed with considering 2-dimensional misalignment error vector. It was shown that the gap from *Pm*-based acceptance angle from that of *Isc*-based was a function of deviation of assembles misalignment in the module. The rough rule for acceptable assembles misalignment is that the standard deviation of assemble misalignment level will be less than 10 % of acceptance angle of the optics.**

***Index Terms* — CPV, tracking, concentrator optics, acceptance angle.**

I. Introduction

HCPV (High Concentrator Photovoltaic) system uses optics that concentrates the sun light onto small solar cells. It is known as one of the highest-efficiency photovoltaic systems. However, it has inherent technological difficulties stemmed from optical alignment. Actually, it is relatively easy to achieve high efficiency by combination of a single lens/cell pair, but it is difficult to obtain high performance from system consist of array of modules.

The typical approach that relaxes tolerance is to expand acceptance angle of the modules. However, this "acceptance angle of the module" is confusing by double definitions, difficulty in control in module production, and difficulty in product testing (module). Taking example of measurement, it was historically done by walk-in method, so that the *Isc* of the module is monitored while tracker stays in the same position [1]. However, it has been recognized that the acceptance angle measured by this walk-in method is too optimistic. Alternatively, *Pm* or DC power input of the power conditioner has been proposed as the monitoring parameter. However, the value from *Pm* or DC power output is always significantly smaller than that of classical method using *Isc* as the monitoring source.

One of the possible reasons is that non-uniform illumination onto the cell result from off-axis concentration [2-3]. Since fill factor FF depends on uniformity of illumination and *Pm* is also affected of FF, the drop of FF by misalignment further reduces *Pm*. However, it was shown that it is not an only cause of the deterioration of acceptance angle in *Pm*. The experiment was done by modules with DFK optics [4-5]. DFK optics is excellent optics of 1,000 X concentration (lens to cell ratio with assemble margin) and 1,234 X concentration (lens to cell ratio of designed aperture area) with keeping uniformity under plus or minus 1 degree of acceptance angle range [4-5]. In spite of its uniformity in illumination onto solar cells, the module acceptance angle by *Pm* is smaller than that of *Isc* [6]. Precise measurement of optics (individual unit) was done in UPM and it was shown that it was valid that the illumination was uniform in spite of large acceptance angle range [7]. It was also shown that the acceptance angle of the single optics/cell pair did not differ from between *Isc* and *Pm* [7].

A hint was found in the analysis by MOA (Module Optical Analyzer) [8]. It looked like that the deterioration of module acceptance angle came from the difference of the positions of centroid *(i.e.,* pointing vectors) among optics/cell pairs in the module [9]. It was also shown that the deterioration of module acceptance angle also came from difference level of assemble control [10-11]. These two facts implied that the variation of misalignment levels of optics/cell pairs affects behavior of module to off-tracking and it was thought possible to treat by Monte Carlo simulation in general way.

II. APPROACH

Many CPV modules and concentrator optics tried to improve system performance by relaxing misalignment tolerance [12-14]. Although they were successful in specific product designs, systematic solution, especially in keeping or expanding acceptance angle of modules have not been done in the past. Our approach is to modify the Monte Carlo simulation that was originally developed for analysis of module performance deterioration by assembles error [10-11]. Although it was originally developed to anticipate module performance with given level of production control, it can be used for analysis of acceptance angle of the module with slight modification. The original Monte Carlo simulation used a 1-dimensional vector of a random number for representing lens/cell misalignment magnitude [10-11]. For analysis of acceptance angle, it was also necessary to consider direction of lens/cell misalignment and a group of misalignment error vector was expressed as a 2-dimensional matrix. This extension was necessary because the error of the cell/lens misalignment was not always in the same direction of the tracking error.

Its flow chart of the new Monte Carlo simulation is shown in Fig. 1.

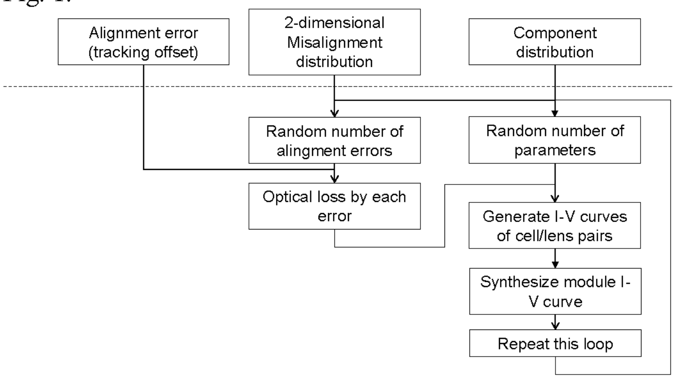

Fig. 1. Flow chart of the calculation of acceptance angle of the module by the Monte Carlo method for analysis of acceptance angle of CPV modules.

The error in the 2-dimensional misalignment distribution is mainly described as the standard deviation σ. It was calculated by the measurement of MOA by equation (1).

$$\sigma^2 = \sigma_x{}^2 + \sigma_y{}^2 \qquad (1)$$

where,

σ Standard deviation of misalignment error in the module.
σ_x Measured standard deviation along X-axis.
σ_y Measured standard deviation along Y-axis.

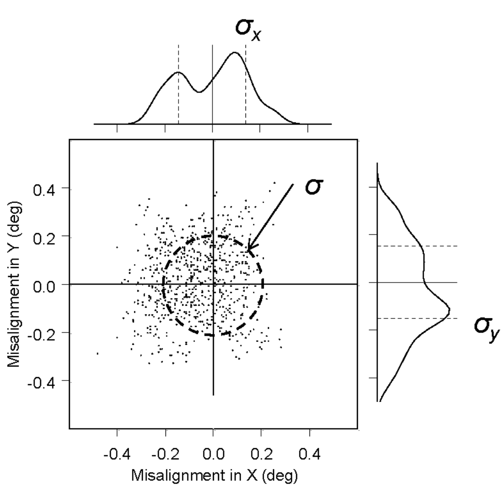

Fig. 2. Definition of the standard deviation in the 2-dimensinal alignment error distribution and the measured distribution in modules.

The measured distribution of the misalignment inside the real modules along both X-axis and Y-axis is plotted in Fig. 2.

One of the most important factors in this analysis was the characterization function of how optics behaves under off-axis conditions (*i.e.,* the angular transmittance). Some optics may have large acceptance angle but its optical efficiency sharply drops if tracking error exceeds some certain limit. Other optics may have low acceptance tolerance but its output is still high even with bigger incident angle than the acceptance angle value. In order to express typical response of misaligned concentrator optics, we used a power function as equation (2).

$$g(\delta) = \left(1 - 0.1\left(\frac{|\delta|}{\Delta}\right)^m\right)\left(0.1\left(\frac{|\delta|}{\Delta}\right)^m < 1\right) \qquad (2)$$

where,

$g(\delta)$ Function of relative output of the optics with given δ.
δ Incident angle to optics.
Δ Acceptance half angle of the optics (90 % output).
m Characterization parameter of optics.

Note that incident angle of the optics δ is normalized by acceptance half angle of the optics Δ.

The influence of non-uniform illumination onto concentrator cells can be included or exclude in equation (1). In this work, $g(\delta)$ was just fit to the trend of flux intensity. This means it was assumed that the concentration is uniform onto the cell and there will not be any additional deterioration performance by nonuniform illumination.

The parameter m was newly introduced in this study. This is a kind of shape factor of the angular transmittance of concentrator optics and becomes large when the optics becomes sophisticated.

It was decided by the data-fitting technique from response measurement or Ray-tracing calculation. The model equation is equation (3), and Δ and m were numerically calculated so that the sum of square of error vector ε will be minimized.

$$T_i = \left(1 - 0.1\left(\frac{|\delta_i|}{\Delta}\right)^m\right)\left(0.1\left(\frac{|\delta_i|}{\Delta}\right)^m < 1\right) + \varepsilon_i$$
$$\begin{pmatrix} m \\ \Delta \end{pmatrix} = Minimize\left(\sum_i \varepsilon_i{}^2\right) \qquad (3)$$

where,

δ_i Data vector of incident angle to optics.
T_i Data vector of relative output.
ε_i Error vector distributed by the normal distribution.

For a simple off-focused imaging lens, m =1. For DFK optics, it was calculated as m=3.445, Δ=1 deg in the direction parallel to cell sides, and m=3.077, Δ=1.05 deg in the direction parallel to the diagonal of the cell. Note that both off-axis magnitude and directions should be necessary to considered for simulating influence of tracking error to the module performance.

It is necessary to consider the behavior of the bypass diode for *Isc* response related to the unit with optical errors [14]. In this paper, it was assumed that the bypass diode turns ON ideally when it was biased more than threshold voltage.

III. RESULTS

At first it is important to note that influence to acceptance angle of the module, namely δ/Δ after normalization of tracking error, and regardless it is on *Isc* or *Pm*, is a function of level of assemble error, number of cells that is connected in series in the module, and this characterization parameter m.

In this analysis, the level of assembly error was represented by normalized standard deviation of misalignment in optics/cell pair σ/Δ where σ is standard deviation of misalignment angle in the sample group consists of the same number of the cells that is connected in series in the module, and Δ is acceptance half angle of the optics (defined at 90 % output). In the previous study, it was shown that σ/Δ value had a strong correlation to the degradation of module performance by bad process control [10-11]. The characterization parameter of optics m ($m=3.445$, $\Delta=1$ *deg* in the direction parallel to cell sides, and $m=3.077$, $\Delta=1.05$ *deg* in the direction parallel to the diagonal of the cell) and number of cells in a single string (series connected) inside the module N (N = 36) were set to that of DFK module.

One of the calculated examples of synthesized centroid of CPV module is plotted in Fig. 3. Equation (3) was used for fitting m and Δ to Equation (2).

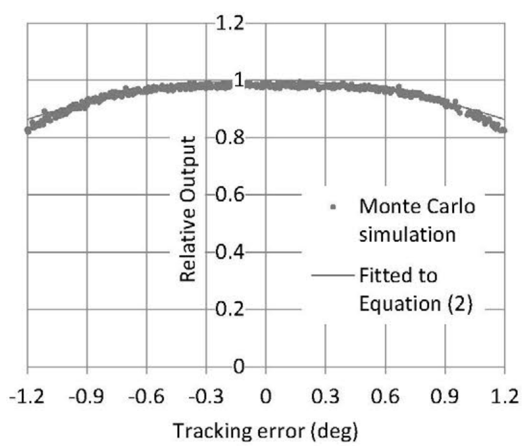

Fig. 3. Fitted result to the equation (2) from predicted output from the Monte Carlo simulation.

The calculated results of the synthesized angular transmittance of CPV module as a function of normalized misalignment σ/Δ is shown in Fig. 4.

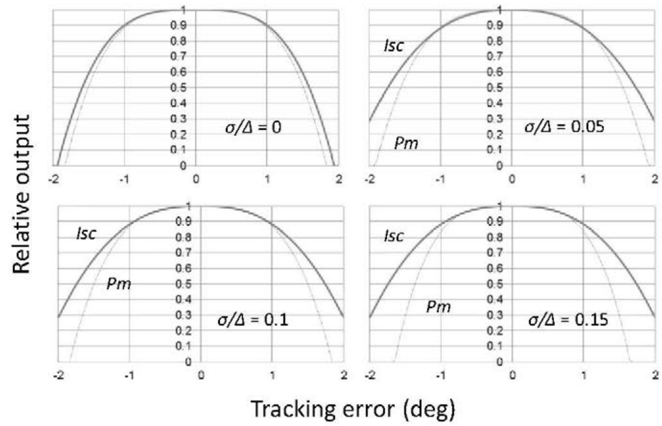

Fig. 4. Simulated result of the synthesized centroid by Pm and *Isc* with different levels of σ/Δ.

As it is shown in Fig. 4, when it was assumed assemble was done without any assemble errors, difference of module acceptance angle in between *Isc* and *Pm* was not significant, even with including component variance. However, with the increase of variance of assemble errors, acceptance angle of *Pm* gradually decreased while that of *Isc* increased. The increase of acceptance angle of *Isc* with the increase of misalignment errors was measured by other CPV system [14].

This trend is summarized in Fig. 5. This chart may be useful to anticipate the real acceptance angle of the module with given production control. After measurement of 20 modules, namely 1,440 measurements of misalignment of the lens/cell pair in both X and Y direction, and direct measurement of Δ of a single set of the optics and cell, the σ/Δ of the prototype line was measured to be as σ/Δ = 0.233 in arbitrary directions. The anticipated acceptance angle of the module by *Pm* was 0.76 degree, while the measured value was 0.77 degree.

The trend of *Isc* was also compared (Fig. 6). At the point of σ/Δ = 0.233, the anticipated angle of acceptance angle by *Isc* was 1.04 degree, while the measured one was 0.97 degree.

It can be said that the prediction by the new Monte Carlo simulation met the measured acceptance angle of the module in both *Isc* and *Pm*.

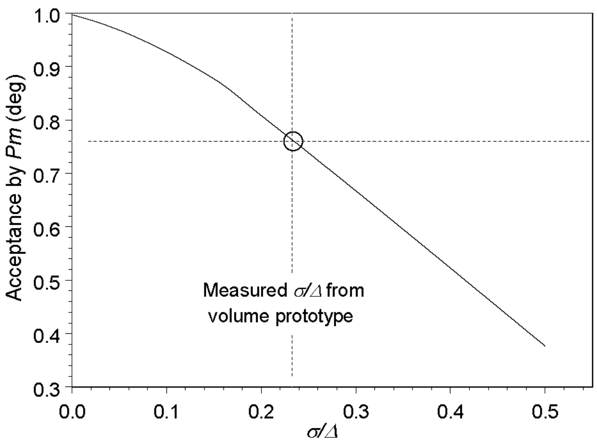

Fig. 5. Anticipation of deterioration of the module acceptance angle of *Pm* (defined at 90 % of the power point) at as a function of the level of the parameter assemble error σ/Δ.

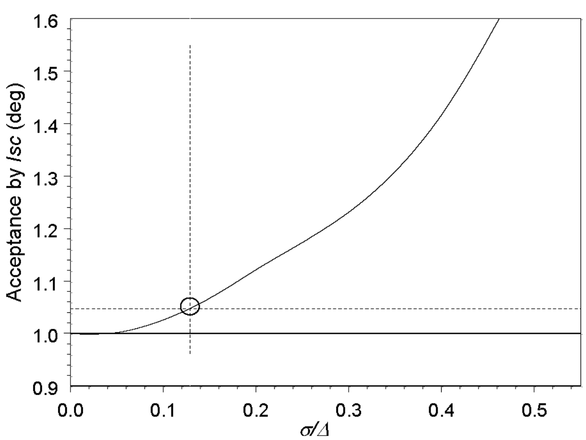

Fig. 6. Anticipation of deterioration of the module acceptance angle of *Isc* (defined at 90 % of the current) at as a function of the level of the parameter assemble error σ/Δ.

The trend of acceptance angle of the module by *Pm* (Fig. 3) varies by *m* and *N*, but the rough target of the production control that keeps good acceptance angle of the module close to the designed value may be 10 % of the standard deviation of assembles error to the designed acceptance angle of the lens/cell pair.

IV. Conclusion

Acceptance angle of the module measured by *Pm* is lower than that of *Isc*. This deterioration is responsible from variance of assemble error of the module. The deterioration of acceptance angle can be anticipated by a Monte Carlo simulation with considering 2-dimensional assemble error vector.

Acknowledgments.

This work has been partially supported by NEDO in Japan and by the European Commission through the funding of the project NGCPV EUROPE JAPAN PROJECT (EU Ref. No 283798).

References

[1] S. Surendran, "CPV Module Acceptance Angle Characterization", http://www1.eere.energy.gov/solar/pdfs/pvmrw2011_p13_cpv_surendran.pdf

[2] K. Nishioka et al., "Evaluation of InGaP/InGaAs/Ge Triple-Junction Solar Cell under Concentrated Light bySimulation Program with Integrated Circuit Emphasis". Jpn J Appl Phys. 43(3):882–9. (2004).

[3] C. Domínguez et al., "Probing the effects of non-uniform light beams and chromatic aberration on theperformance of concentrators using multijunction cells. 8th International Conference on Concentrating Photovoltaic Systems" (American Institute of Physics,2012).

[4] P. Zamora Herranz, P. Benitez Gimenez, Y. Li, J. C.Miñano Dominguez, J. Mendes Lopes, and K. Araki, "Dome-shaped Fresnel-Köhler: a novel high performance optical concentrator," in EU PVSEC Proceedings, Frankfurt, Alemania, 2012, pp. 253–256.

[5] Datas, A., "NGCPV: A new generation of concentrator photovoltaic cells, modules and systems," in 28th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC 2013. Proceedings. DVD-ROM, 2013, pp. 88–93..

[6] H. Nagai, K. Araki, K. Hobo, P. Zamora, P. Benitez, J.C. Miñano, K. Nishioka, Y. Ota, I. Luque-Heredia, J. Hashimoto, T. Ueda, Y. Hishikawa, R. Herrero, S. Askins, Ignacio Antón, R. Núñez, G. Sala, Marc Steiner, M. Niemeyer, G. Siefer, A.W.Bett, "Dvelopment of the New DFK CPV Module by NGCPV JAPAN-EU Collaboration", Technical Digest of 6th WCPEC, 2014.

[7] Research report to NEDO for NGCPV from Daido Steel, 2014, written in Japanese.

[8] R. Herrero, C. Domínguez, S. Askins, I. Antón, and G. Sala, "Luminescence inverse method For CPV optical characterization", Optics Express, Vol. 21, Issue S6, pp. A1028-A1034, 2013

[9] R. Herrero, C. Domínguez, S. Askins, I Antón, and G. Sala, "Two-dimensional angular transmission characterization of CPV modules", Optics Express, Vol. 18, Issue S4, pp. A499-A505, 2010..

[10] K. Araki, H. Nagai, R. Herrero, I. Antón and G. Sala," Off-axis Characteristics of CPV Modules Result from Lens-cell Misalignment – Measurement and Monte Carlo Simulation", IEEE J. Photovolt. submitted on Oct. 27, 2015.

[11] R. Herrero, A. Stephen, I.Antón, G. Sala, K. Araki, and H. Nagai, "Module optical analyzer: Identification of defects on the production line", AIP Conference Proceedings, 1616, 119-123 (2014),

[12] J. C. Hall, G. L. Martins, M. Cameron, and S. Marks. "Boeing high-efficiency low-cost concentrated photovoltaic technology." Proc. SPIE 8180, High and low concentrator systems for solar electric applications VI, volume 8108, pages 810802- 810802- 9, 2011.

[13] S. Askins, M. Victoria, R. Herrero, C. Domínguez, I. Antón, G. Sala, A. Coutinho, and J.C. Amador. "Optimization of tolerant optical systems for silicone on glass concentrators.", Proc. 8th

International Conference on Concentrator Photovoltaic Systems, 2012.
[14] V. Díaz, J.L. Alvarez, J. Alonso, A. Luque, and C. Mateos. "Towards a technology for mass production of very high concentration flat panels.", Proc. 19th European Photovoltaic Solar Energy Conference and Exhibition, pp 2086–2089, 2004.
[15] I. Antón, and G. Sala," Losses Caused by Dispersion of Optical Parameters and Misalignments in PV Concentrators", Prog. Photovolt: Res. Appl. 2004; 12:1–13.