Analysis Results of Maximum Power Point Mismatch on Grid-connected PV Systems

Yuzuru Ueda[1], Kosuke Kurokawa[1], Takamitsu Itou[2], Kiyoyuki Kitamura[2], Katsumi Akanuma[3], Masaharu Yokota[3] and Hiroyuki Sugihara[3]

[1]Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei, Tokyo, 184-8588, Japan
[2]MEIDENSHA CORPORATION, Riverside Building, 36-2 Nihonbashi Hakozakicho, Chuo-Ku, Tokyo, 103-8515, Japan
[3]Kandenko Co., Ltd., 4-8-33 Shibaura Minato-ku, Tokyo, 108-8533, Japan

This paper describes the method to estimate maximum power point of the PV systems under the measured irradiance and module temperature, reviews the error factors of the MPP estimation and summarizes the analysis results of the MPP mismatch analysis for grid-connected PV systems. Spectral mismatch is not always the loss factor but gain factor in cloudy condition. Regular loss including MPP tracking error is a major factor of MPP mismatch.

Keywords: PV systems, Maximum power point, loss, spectral mismatch

INTRODUCTION

Performance analysis of the PV systems normally uses irradiance data as an input energy and module temperature is used to estimate the ideal output energy and maximum power point (MPP) of the PV systems under the measured irradiance and module temperature. There are several factors which may affect the accuracy of the MPP estimation, some of them have non-linear characteristics for the irradiance and temperature. This research concentrates to analyze the loss of DC output energy using array output current and voltage. Simple MPP estimation methods are introduced and analysis results of MPP mismatch are summarized in this paper.

PV SYSTEMS AND MEASUREMENT

Data from “Demonstrative research on clustered PV systems” are used in this paper. “Demonstrative research on clustered PV systems” is a project of New Energy and Industrial Technology Development Organization and being conducted from December, 2002 to investigate about the potential issues of grid-connected PV systems.

One-minute averages of secondly measured data are used for the analysis. PV array’s output current and output voltage are measured at the input terminal of the power conditioning subsystems (PCS). Global irradiance and direct irradiance are measured at the meteorological stations. Incoming irradiation at the PV array’s plane is calculated using direct model for direct components, Perez model [1] for diffused components and uniform reflection model for reflected components. Module temperature is measured at the selected systems using thermocouple sensor.

More than 100 PV systems are initially evaluated and 80 PV systems which do not have shading loss are selected for this analysis. Orientations of the PV arrays are south, east or west. Some of the systems have single array but others have multiple arrays oriented different direction. Data from March 2005 to February 2006 are used in this study.

METHODS

Input data of the analysis are Irradiance [kW/m^2] on the PV array’s plane, PV module temperature [degrees Celsius], PV array’s output voltage [V] and output current [A]. Ratios of measured value to estimated MPP value for current, voltage and power are used for the MPP mismatch analysis.

Estimating maximum power points

Short circuit current (I_{SC}) and open circuit voltage (V_{OC}) under the measured irradiance at measured module temperature can be calculated using following equations.

$$I_{SC} = \frac{G}{G_0} I_{SC(0)} \left[1 + \alpha (T - T_0)\right] \quad (1)$$

$$V_{OC} = V_{OC(0)} \left[1 + \beta (T - T_0)\right] \quad (2)$$

Where
- G : Irradiance [kW/m^2]
- G_0 : Irradiance in STC (= 1[kW/m^2], AM 1.5G)
- $I_{SC(0)}$: Short circuit current in STC [A]
- α : Temperature coefficient of I_{SC} [degC^{-1}]
- T : Module temperature [degC]
- T_0 : Module temperature in STC (= 25[degC])
- $V_{OC(0)}$: Open circuit voltage in STC [V]
- β : Temperature coefficient of V_{OC} [degC^{-1}]

Ideal maximum power point current (I_{Pmax}) and maximum power point voltage (V_{Pmax}) are calculated from the following equations using the results of equations (1) and (2).

$$I_{P\max} = I_{SC} \frac{I_{P\max(0)}}{I_{SC(0)}} \quad (3)$$

$$V_{P\max} = V_{OC} \frac{V_{P\max(0)}}{V_{OC(0)}} \quad (4)$$

Where
$I_{Pmax(0)}$: Maximum power point current in STC [A]
$V_{Pmax(0)}$: Maximum power point voltage in STC [V]

Error factors

Spectral mismatch is one of the known error factor for the I_{SC} estimation. Equation (1) dose not have a term to correct spectral mismatch because spectral data are not available in the data set. Thus spectral mismatch between G_0 and G might be an error factor for the I_{SC} estimation.

V_{OC} estimation also has a known error factor. Actual V_{OC} will become lower along with the G decreasing compared with the estimated V_{OC} from equation (2). [2] However, this behavior is not considered in equation (2) due to the lack of the data of characteristics for installed PV modules.

Change of the fill factor (FF) [2] [3] is another error factor in equations (3) and (4).

Incident angle correction

Incoming irradiance is measured by pyranometer and incident angle dependence of the pyranometer is less than 3[%]. However, PV module's surface is normally flat so there will be reflection loss due to the large incident angle. Simplified calculation method [4] of reflection loss is used to correct this effect. Effective refractive index of 1.8 is used for the correction. Figure 1 shows relative transmittance of the PV module (τ_{PV}) as a function of incident angle. Assuming the reflection loss will reduce the input irradiance G, ratio of measured output current (I) to I_{Pmax} is calculated using equation (5).

Fig. 1. Relative transmittance of the PV module as a function of incident angle.

$$R_I = \frac{I}{I_{P\max} \cdot \tau_{PV}} \quad (5)$$

Where
R_I : Ratio of I to estimated I_{Pmax}

DC voltage correction

During the DC power transmission from the PV array to the measurement point at the PCS input terminal, voltage becomes lower due to the resistance of the cable and blocking diode. This voltage drop (Δ_V) is calculated using following equation.

$$\Delta_V = 0.6 + 0.2 \cdot I \quad (6)$$

0.6[V] represents the voltage drop at the blocking diode and 0.2[ohm] is the resistance of the cable that is calculated using 20[m] of CV cable (2[mm^2]), the most frequently used cable within the evaluated systems. Using the calculated Δ_V, ratio of measured output voltage (V) to V_{Pmax} is described as follow.

$$R_V = \frac{V}{V_{P\max} - \Delta_V} \quad (7)$$

Where
R_V : Ratio of V to estimated V_{Pmax}

Power calculation

The ratio of measured power (P) to estimated maximum power (P_{max}) is calculated using following equation.

$$R_P = \frac{I \cdot V}{(I_{P\max} \cdot \tau_{PV})(V_{P\max} - \Delta_V)} = R_I \cdot R_V \quad (8)$$

Where
R_P : Ratio of P to estimated P_{max}

Data filtering

To minimize the intentional MPP mismatch by PCS, data under the high grid voltage condition and PCS capacity shortage condition are excluded from the data set. The threshold voltage of high grid voltage is 107[V].

RESULTS AND DISCUSSIONS

Ratios of measured value to estimated MPP value for current, voltage and power are calculated for each one-minute data and its frequency are summarized for each irradiance level in an increment of 0.01[kW/m^2] . Results are shown in contour graphs of Figures 2, 3 and 4. Average ratios and standard deviations for each irradiance level are also shown in these figures.

As a result, both current and voltage showed lower R_I and R_V when the irradiance level is very low. Standard deviations at low irradiance level are larger in both current and voltage, one of the reasons is a small value of a denominator for the ratios calculation. R_I once have a peak around the irradiance level of 0.2 to 0.4 [kW/m^2]

then gradually go down but R_V have a peak at very high irradiance level. Higher voltage and lower current at the high irradiance level indicate that operation point is not on MPP but slightly shift toward V_{OC}.

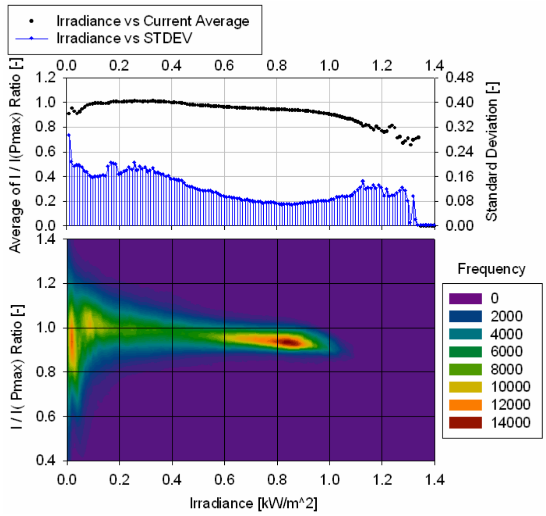

Fig. 2. R_I analysis results.

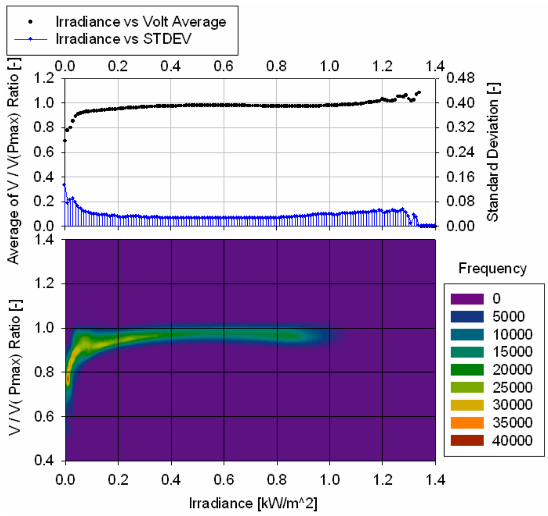

Fig. 3. R_V analysis results.

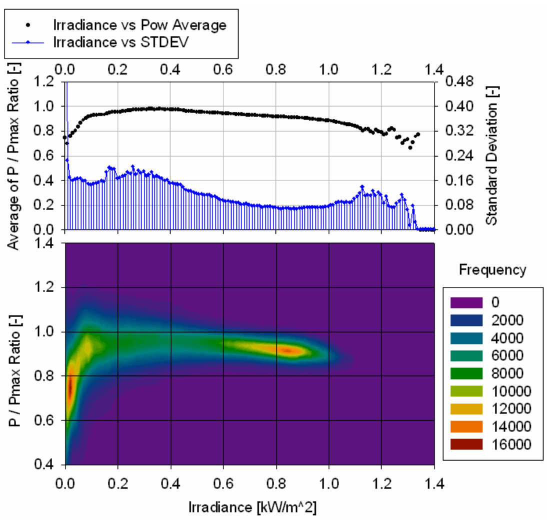

Fig. 4. R_P analysis results.

To analyze more detail about the results, all the data are classified into five conditions. The first condition is the irradiance level of less than 0.15[kW/m^2]. This category has lowest ratios and largest standard deviations. As it is mentioned before, voltage drop and change of FF are more severe in low irradiance level, thus this category can be assumed that estimated MPP values may have a lot of error. Generated power in this class is 6.2[%] of the total of generated power, loss in this class is 10[%] of the total loss. Generated energy and loss for each irradiance level and those cumulative percentages are summarized in figure 5.

The second condition is also the irradiance but more than 1.05[kW/m^2]. Data under this condition generate only 1[%] of the total so this category may have scatter. Loss in this class is 2.4[%] of the total loss.

After excluding these two conditions, rest of the data are classified to three weather conditions, i.e. clear, cloudy and other. The definition of the clear is the data which clearness index is more than 0.7, that of cloudy is the data which ratio of diffused light is more than 0.95. Classified results are summarized in table 1.

Table. 1. Analysis results for five conditions.

	Generated energy [kWh]	Loss [kWh]	Loss Ratio [%]	Average R_P	Standard deviation
≤0.15[kW/m^2]	19350.1	2365.1	0.70	0.802	0.280
≥1.05[kW/m^2]	3147.8	569.4	0.17	0.848	0.093
Irradiance: 0.15[kW/m^2] < G < 1.05[kW/m^2]					
Clear	111511.0	11034.8	3.27	0.912	0.063
Cloudy	29019.1	-46.8	-0.01	0.998	0.195
Other	151189.8	9722.0	2.88	0.941	0.123
All	314217.7	23644.5	7.00	0.905	0.179
Air Mass: 1.3-1.7, Irradiance: 0.15[kW/m^2] < G < 1.05[kW/m^2]					
Clear	22169.2	1929.9	0.57	0.922	0.034

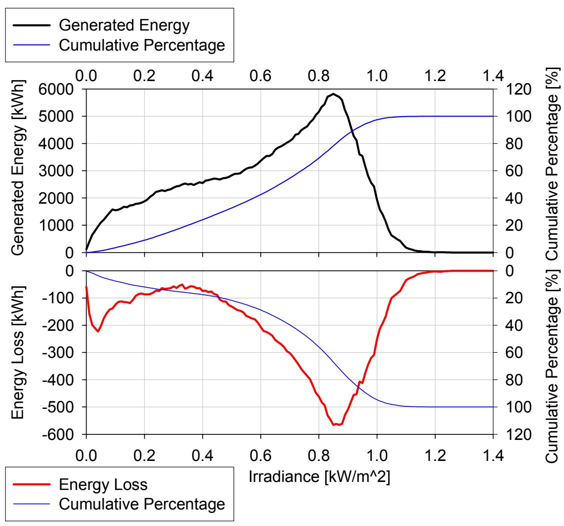

Fig. 5. Generated energy, loss and those cumulative percentages for each irradiance level.

As a result, clear and other condition have 46.7[%] and 41.1[%] of the total loss respectively but cloudy condition has 0.2[%] of gain. This gain can be explained as a spectral mismatch which is also mentioned before. Figures 6, 7 and 8 show the ratios R_I, R_V and R_P for each weather conditions. In addition to the above three weather conditions, air-mass of between 1.3 and 1.7 in clear condition are also plotted in these figures. As shown in figure 6 and 8, only the cloudy condition results more than 1 of R_I and R_P because of the "matching" of the spectrum. Figure 9 describes the examples of the relative spectral response of c-Si solar cell and normalized spectral irradiances of AM 1.5G, clear and cloudy conditions. Cloudy condition have relatively blue rich spectrum and this will match with the spectral response of c-Si PV modules. [5] Thus actual output current is larger than the estimated I_{Pmax} in cloudy condition. On the other hand, clear condition sometimes have red rich spectrum compared with the AM 1.5G spectrum and this will reduce the output current of the c-Si PV module. This spectral mismatch can be seen in figure 6. R_I of all clear condition are lower than the results of AM 1.3 to 1.7 condition specially at the higher irradiance level.

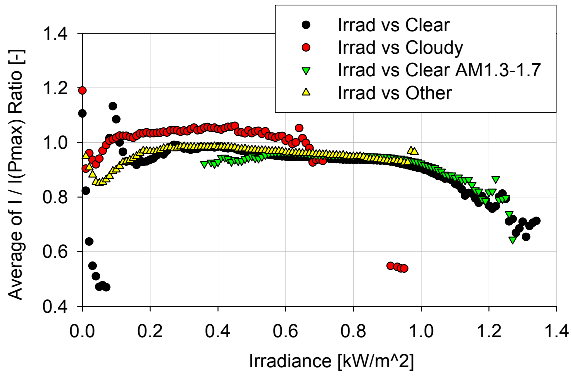

Fig. 6. Average R_I results for four weather conditions.

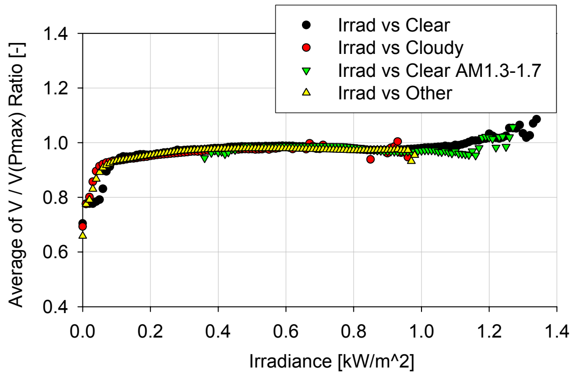

Fig. 7. Average R_V results for four weather conditions.

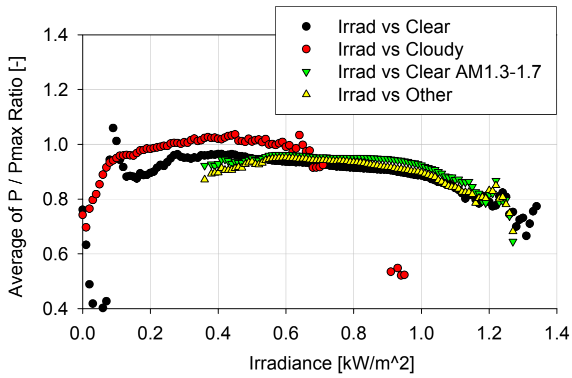

Fig. 8. Average R_P results for four weather conditions.

Another factor of MPP mismatch is the system configuration itself. Since these are not the results of PV modules but systems, array configurations and variations of the PV modules can cause mismatch of system peak power. Soiling and degradation are also the causes. To estimate this kind of regular loss, AM 1.3 to 1.7 clear condition is used because of its minimal standard deviation and better spectrum matching with the AM 1.5G. Considering the variation of the measurement error, average plus standard deviation is assumed as a regular loss. As a result, 62.9[%] of the loss are assumed as a regular loss including regular MPP tracking error, that is 4.4[%] of the expected energy out. Rest of them is assumed as spectral mismatch loss and gain, MPP tracking error and other non-identified loss factors, that is 1.7[%] of the expected energy out.

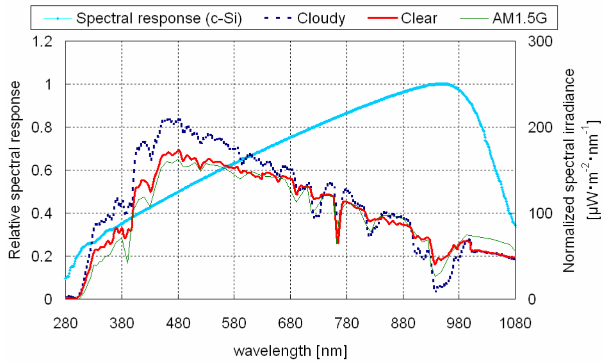

Fig. 9. Relative spectral response of c-Si and normalized spectral irradiance as a function of wavelength.

SUMMARY

Detailed analyses of MPP mismatch are performed in this paper. Results indicate the non-linearity of V_{Pmax} and FF are not the major error factor for MPP analysis because of the low irradiance level. Spectral mismatch is not always the loss factor but gain factor in cloudy condition. Regular loss including MPP tracking error was a major factor of MPP mismatch in this analysis.

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