PERFORMANCE RATIO AND YIELD ANALYSIS OF GRID CONNECTED CLUSTERED PV SYSTEMS IN JAPAN

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ABSTRACT

It is becoming more important to evaluate the installed PV system's performance and loss factors to enhance the system's efficiency and pull more electric power from the systems. This paper describes the evaluation method of PV systems and summarizes the results of annual performance and loss analysis. Grid voltage and snow coverage are two major serious loss factors for PV systems, optimized array configuration results more system yield on roof mounted residential PV systems.

INTRODUCTION

In the case that many of grid-connected residential photovoltaic (PV) systems are installed in the small area and connected to the same power distribution network, this situation called "Clustered", voltage raise of power distribution line due to the reverse power flow from the PV systems would be the problem. To prevent the overvoltage of the power distribution line, Japanese PV system's power conditioning subsystems (PCS) is monitoring its own output voltage, and if it is higher than the specification of the voltage, PCS will automatically reduce its output power. Because of this function, PV system's output will be restricted even though PV array is receiving enough solar irradiance if the grid voltage is too high [1] To investigate the issues which may happen in the clustered PV systems, "Demonstrative research on clustered PV systems" is being conducted from December, 2002 by NEDO. Approximately 550 PV systems will be installed on the roofs of houses and connected to the commercial power grid in the demonstrative research area in Oota, Japan. [2]

ANALYSIS METHOD

Loss factors

Input energy of PV systems is irradiation. Pyranometer is commonly used to measure the irradiation, however, pyranometer cannot cover the whole area of the PV array so shading on the PV array may occur in some systems. Incident angle dependence, spectral sensitivity and other characteristics of pyranometer are also different from the characteristics of PV modules. Because of these differences, there is a difference between the irradiation that measured by the pyranometer and the irradiation that PV array actually received. Dirt on the surface of the modules or degradation of EVA layer may reduce the input energy too. The following loss factors are considered as a factor to reduce the input energy in this method.

1. Shading
2. Regular loss (Dirt, Degradation)
3. Incident Angle / Reflection

The next step is photoelectric conversion. During the energy conversion, increasing of the modules temperature will lower the conversion efficiency especially in the c-Si based PV modules. Operation point on the I-V curve is also very important to pull the maximum power from the systems. The reasons of the maximum power point (MPP) mismatch have a lot of variations. PCS sometimes intentionally shifts the operation point from MPP to the bad operation point (normally towered the open circuit voltage (V_{OC}) so the voltage will be higher than the maximum power voltage (V_{Pmax})) to reduce its output current in order to prevent the over voltage of the power distribution line. PCS sometimes can not find the MPP due to the stepped I-V curve which is observed in the partially shaded PV array. In the case that the capacity of the PCS is smaller than that of the PV array's, output current will be restricted around the PCS's maximum output. PCS will not track the MPP and keeps constant voltage if the irradiance is very low. The following loss factors are considered as a factor to lower the conversion efficiency.

4. Module Temperature
5. Output restriction (over voltage)
6. PCS capacity shortage
7. MPP mismatch (high voltage side)

Among the MPP mismatch loss factors, MPP mismatch in higher voltage side are mainly considered in this analysis and lower voltage side are included in the miscellaneous loss because the amount of the loss are limited. There would be a regular conversion efficiency loss due to the mismatch of modules. The photocurrent of one string will be restricted by the worst module so the actual photocurrent will be lower than the value which is calculated by the input irradiance and module's rated output current. This loss is included in the regular loss.

In addition to these seven loss factors, the following loss factors are also considered in this method.

8. DC resistance
9. Inverter

10. PCS Off / PCS Standby
11. Fluctuation

During the DC power transmission from the PV array to the PCS, there will be some voltage drop and energy loss due to the resistance of the cable and voltage drop at the blocking diode. This loss is calculated using the formula of

$$l_A = \sum(0.6 \times DCI + 0.2 \times DCI^2) \qquad (1)$$

Where
l_A: Loss due to the DC circuit [Wh]
DCI: PV array output current [A].

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.

Inverter loss simply means the loss at the PCS. PCS off / standby means there is no output from the PCS even with the irradiation including the maintenance purpose.

Fluctuation means the loss during the fast fluctuation of irradiance. Since we are measuring irradiance at the metrological stations and there is some distance between the pyranometer and the PV array, ether pyranometer or PV array may shaded by clouds if the fluctuation of the irradiance is too fast. Fluctuation loss includes this kind of measurement error.

Shading analysis

The definition of "shading" in this paper is the situation that the pyranometer does not have any shading but PV array has. Only the static sunlight-blocking objects are considered, moving clouds or other accidental shadings are not included. The maximum shading losses are calculated for each solar height angle and solar azimuth in increments of 5 degree. [3]

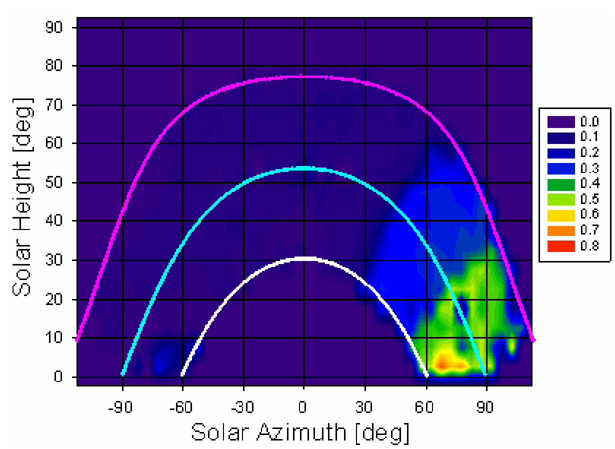

Figure 1: Example of shading analysis result

Example of the result is shown in Figure 1. Three arcs in this graph are the sun's path on the summer solstice, the equinox and the winter solstice from top to bottom respectively. Shading loss is observed when the sun is in west during evening time. This is because of the stepped roof as shown in Figure 2. Higher side of the roof is making the shadow on the lower side when the sun is in west.


Figure 2: Photo of analyzed PV system

Reflection loss calculation

Output energy loss due to the reflection of the incoming irradiance at the PV module's surface is calculated using geometrical optics theory. [4] Cover grass, EVA and anti reflective coating are assumed as a single layer and the effective refractive index n_E is used for the calculation.

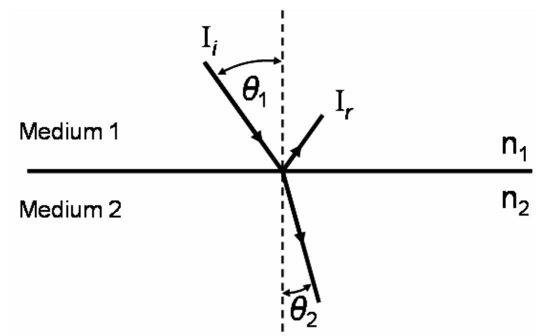

Figure 3: Schematic view of incident angle and refractive angle.

Figure 3 describes the schematic view of incident angle and refractive angle. The relationship of these two angles can be described using Snell's low;

$$n_1 \cdot \sin\theta_1 = n_2 \cdot \sin\theta_2 \qquad (2)$$

where
n_1: Refractive index of medium 1
n_2: Refractive index of medium 2.

Reflectance can be expressed using the equation of;

$$r = \frac{I_r}{I_i} = \frac{1}{2}(r_\perp + r_\parallel) \qquad (3)$$

where

$$r_\perp = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \qquad (4)$$

$$r_\parallel = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \qquad (5).$$

Assuming the incident angle = 0[deg] at the STC, reflection loss is calculated using the effective refractive index n_E of 1.8 which is obtained from a preliminary experiment.

RESULTS AND DISCUSSIONS

One-minute averages of secondly measured data are used for this analysis. Evaluation period is from Oct. 2004 to Sep. 2005. More than 300 PV systems were already installed in the demonstrative research area. Total capacity was nearly 1 [MW]. All the PV systems are connected to the same power distribution network. 104 systems out of more than 300 systems are used for the analysis due to the data availability. Performance and losses are quantified for every 30days because at least one sunny day is needed to quantify the shading loss and regular loss.

Annual performance and loss analysis

Annual performance analysis result is summarized in Figure 4. Average performance ratio was 79.3[%]. Even through these PV systems are clustered, loss due to the grid voltage was only 0.3[%] in average. However, this is demonstrative research and the grid condition is managed better than the conventional local power distribution networks, it could be worse in other cases.

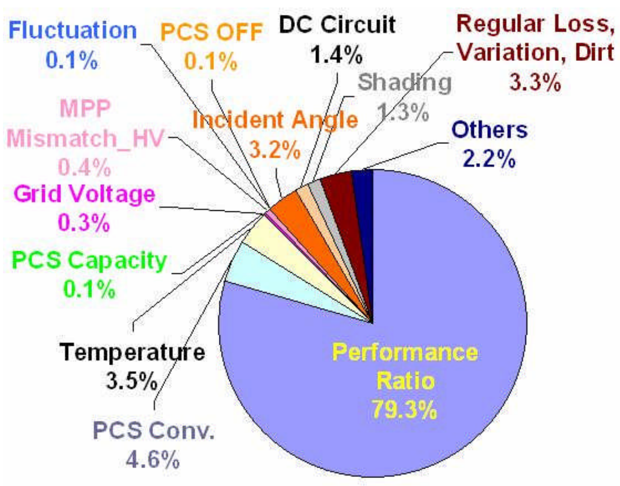

Figure 4: Annual performance analysis result of 104 PV systems.

Daily performance and loss analysis

Daily performance and loss analysis results are summarized in Figure 5,6,7,8. Each data point represents daily performance ratio of one system and 30days results are plotted in one box. The lower boundary of the box indicates the 25th percentile, a line within the box marks the median, dotted red line the average and the upper boundary of the box indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles respectively. Data with more than 5[%] daily losses due to the PCS off are excluded from these results.

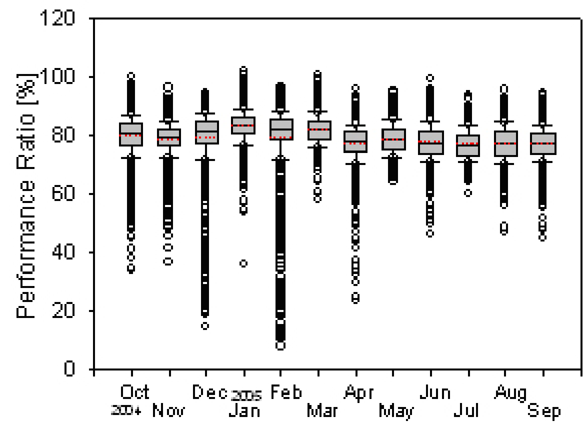

Figure 5: Distribution of daily performance ratio of 104 systems.

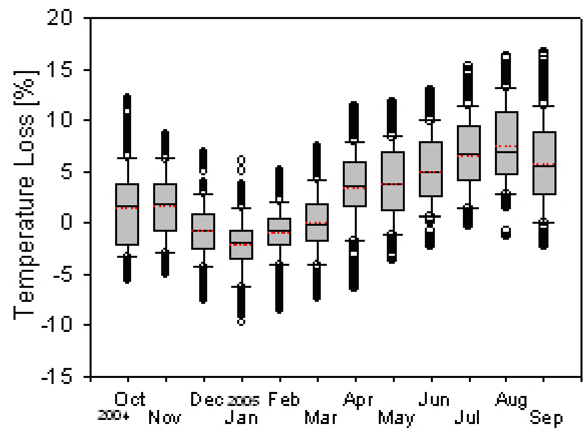

Figure 6: Distribution of daily output loss due to the module temperature.

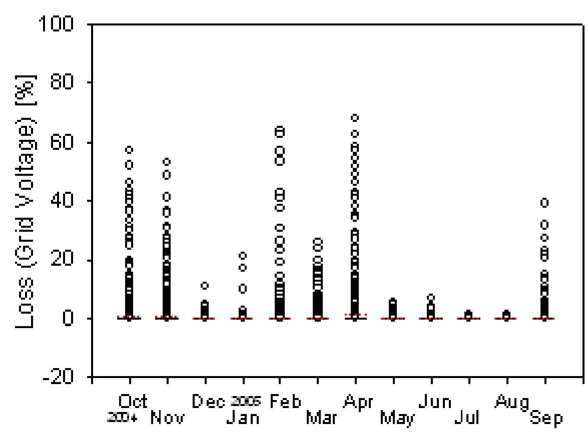

Figure 7: Distribution of daily output loss due to the grid voltage.

Averages of performance ratio are better in winter and lower in summer as shown in Figure 5. This is mainly because of the module temperature which loss is shown in Figure 6. Although the frequency is less than 10[%], less than 50[%] of performance ratio are observed through the year. The causes of these serious performance losses are grid voltage and snow coverage. Losses due to the grid voltage are shown in Figure 7, more than 50[%] of loss are resulted in Oct. and Nov. 2004, Feb. and Apr. 2005. Figure 8 shows the results of miscellaneous loss. More than 50[%] of loss are resulted in Dec. 2004 and Feb. 2005. The reason of these losses was snow coverage. Since we are measuring the irradiation by pyranometer, there was a situation that snow on the pyranometer melted but PV array still covered by snow. Except these two loss factors, other loss factors showed predictable range of loss through the year.

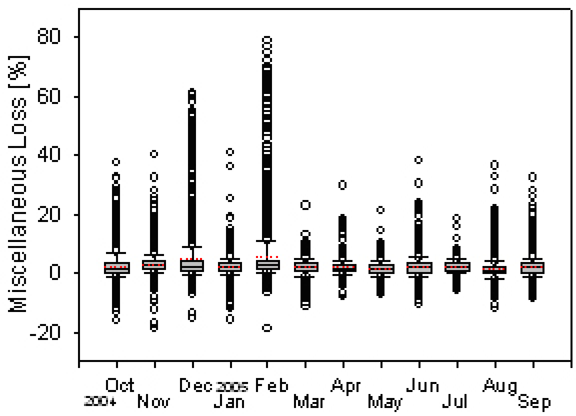

Figure 8: Distribution of daily miscellaneous output loss.

Comparison of array configuration

Since the design of the roof is not always optimized for PV system, some of the PV modules are installed on the roofs which have an orientation of east or west with non optimized tilt angles. To compare all the different configuration, all systems are classified according to the array configuration, i.e. single array oriented south as type1, multiple arrays oriented south and/or east and/or west as type2 and array(s) not oriented south as type3. Performance ratio and system yield are summarized in Figure 9.

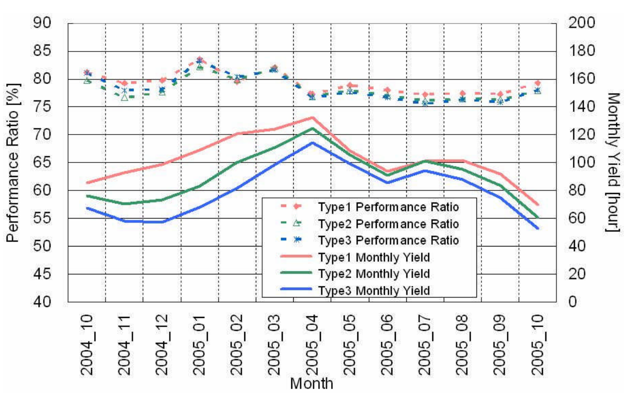

Figure 9: Annual performance ratio and system yield for three array configurations.

Performance ratio for all types are almost the same through the year but type1 has about 30[%] more system yield compare with type3. Type3 has more reflection loss especially in winter but less temperature increasing in winter compare with the type1. Detailed numbers are summarized in Table1.

Table 1: Analysis results of three array configurations.

	Type1	Type2	Type3
Annual system yield [h]	1330	1175	1039
Annual P.R. [%]	78.0	77.8	78.4
Loss (Temperature) [%]	2.8	2.5	1.8
Reflection loss [%]	3.3	4.5	4.9
Number of systems	74	17	5

CONCLUSIONS

Detailed performance analysis results of clustered PV systems are summarized in this paper. Characteristics of 12 loss factors including snow coverage are clarified. Results indicate that grid voltage and snow coverage caused serious performance loss in some cases. Different array configurations are also compared. Difference of the performance ratio between south oriented PV systems and others is only a few percent but approximately 30[%] of the system yield difference is observed.

ACKNOWLEDGEMENT

Demonstrative research on clustered PV systems is a project of New Energy and Industrial Technology Development Organization (NEDO). Authors would like to acknowledge the financial support of NEDO and cooperative discussions with project members.

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