DETAILED PERFORMANCE ANALYSES RESULTS OF GRID-CONNECTED CLUSTERED PV SYSTEMS IN JAPAN –FIRST 200 SYSTEMS RESULTS OF DEMONSTRATIVE RESEARCH ON CLUSTERED PV SYSTEMS

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ABSTRACT: Grid voltage is one of the loss factors for grid-connected photovoltaic (PV) systems. This paper describes results of performance and loss analysis for grid connected residential PV systems. Most of PV systems resulted more than 70% of performance ratio but some of them showed severe output yield reduction due to the over voltage of power distribution line. The voltage of power distribution line is raised by both PV systems output energy and reduced load which is mainly occurring during weekend. Over voltage of power distribution line induced output regulation of PV inverters. Results indicated that both PV systems and reduced load raised approximately 2V of distribution line's voltage and combination of two factors induced substantial output yield reduction for PV systems.
Keywords: Grid-Connected, PV System, Performance, Over voltage

1 INTRODUCTION

Voltage rising of power distribution line is one of the concerns for grid connected photovoltaic (PV) systems. Possibility of over voltage at the power grid is higher in the case of higher concentration of PV systems. "Demonstrative research on clustered PV systems" is being conducted by NEDO from December, 2002 in Gunma, Japan [1]. More than 200 residential PV systems are already installed on top of the roofs of houses and connected to the power grid in less than 1km^2 area. Detailed performance and loss analysis for these PV systems are performed to investigate a behavior of the grid connected PV systems.

2 OUTPUT REGULATION OF PV INVERTER

In the case that a large number of PV systems are connected to the same low voltage / medium voltage line, this situation called "Clustered", voltage rising due to the reverse power flow from each PV systems will occur as shown in Fig.1. To avoid the over voltage of the power distribution line, Japanese commercial PV system's power conditioning subsystems (PCS) is monitoring its own output terminal voltage. If the voltage exceeds the starting voltage of output regulation, PCS will automatically reduce its output power by reducing the output current to avoid over voltage of the power grid. Power factor (PF) control is also available in some PCS, however, the effect for over voltage protection is limited.

Examples of starting voltages and control speeds of the output regulation are shown in Table.1. A statutory control range of Japanese power system is 101 +- 6 [V] for 100V single phase line and 202 +- 20 [V] for 200V line. Since there will be some voltage drop from connecting point at distribution line to the PCS terminals due to the drop wire's resistance, a starting voltage is not necessary to be set for 107 [V] which is upper limit voltage of distribution line. However, these variations of starting voltage may cause uneven output energy loss between the PV systems.

During the output regulation, PV array's operation point on its I-V curve is restricted near the open circuit voltage (Voc), that means output voltage is higher than its maximum power point voltage (V_{Pmax}) and current is lower than the maximum power point current (I_{Pmax}). Thus restriction of output can be detected by these values and loss due to this regulation can be quantified [2].

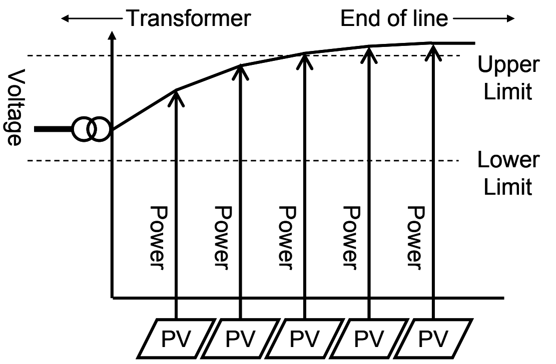

Figure 1: Image of voltage rising due to PV's power

Reactive power control		
Types	Starting Voltage	Speed
1	112V	PF=1 to 0.85 in 2.5sec
2	None	None
3	None	None
4	107V	PF=1 to 0.85 in 10sec
Active power control (Regulation)		
1	After PF reached 0.85	2A/sec, 100% to 0%=10sec
2	107V	43mA/4sec
3	109V	Immediately 0%
4	109V	100% to 0% in 4 to 10sec

Table 1: Examples of output regulation method

3 PERFORMANCE AND LOSS ANALYSIS RESULTS

Overall system performance is evaluated by performance ratio which is defined as a ratio of actual PV system output to expected rated system output during the evaluation period. 1 minute averages of the data recorded every second are used for this analysis. Total number of PV systems is about 200 and total capacity of PV systems is approximately 800kW (as of end of Y2004), all the systems are connected to the same medium voltage line trough the low voltage lines. Each low voltage lines have 5 to 15 PV systems under its transformer. 61 systems out of more than 200 systems are selected for performance analysis. All the selected modules and PCSs are produced by 3 different domestic makers. An average array capacity is 4.1 [kW], tilt angles are in between 20 to 45 [deg]. Orientations of 47 systems are south only, but the rest of 14 systems have more than 2 orientations like south and/or east and/or west which are connected in parallel to the PCS.

3.1 Performance ratio

Tow different seasons are selected for performance ratio analysis, which are from 8/10 to 9/12 (summer) and from 10/02 to 10/31 (autumn), 2004. Average performance ratios and loss ratios are shown in Fig.2 and 3. Because of lower ambient temperature and module temperature, performance ratio in autumn was slightly better than that of in summer. Other loss factors didn't change a lot from summer to autumn.

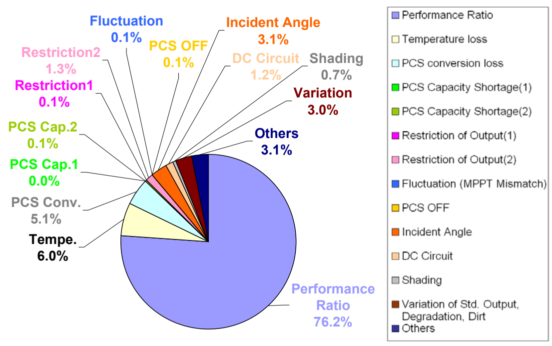

Figure 2: Average of 61 systems performance and loss analysis result, 2004/08/10 – 2004/09/12

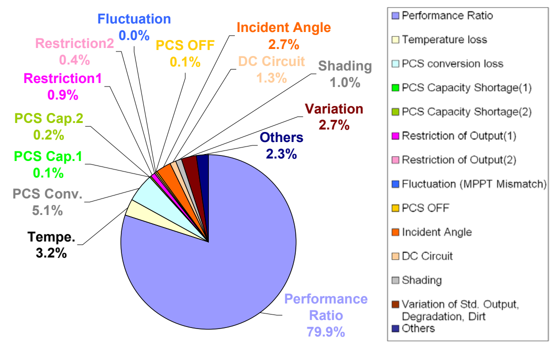

Figure 3: Average of 61 systems performance and loss analysis result, 2004/10/02 – 2004/10/31

3.2 PCS capacity shortage

A capacity of PCS is sometimes smaller than that of array's to reduce the initial cost of installation. An average PCS capacity for 61 systems is 3.8 [kW] so that is slightly smaller than that of the array's (4.1 [kW]). A loss due to the PCS capacity shortage is calculated based on the size of PCS. Loss type 1 is actual power loss and type 2 is simulated power loss under the standard test condition (STC), that means array output are temperature corrected for 25 [degC]. Both loss type 1 and 2 were less than 1 % so that the ratio of 3.8 to 4.1 is in acceptable range from system design point of view.

3.3 Incident angle

Incoming solar irradiance will be reflected by glass and EVA layer at the module surface. Effective reflective index of 1.526 is used for glass/EVA layer to simplify the reflection model. A loss due to the reflection is calculated using Snell's law. It can be assumed that incoming light is 100% direct component and its incident angle is 90 [deg] for module rating test under the STC, however, actual solar irradiance consists of direct, diffused and reflected component. To improve the accuracy of the model, actual incident angle is used for direct component and effective incident angle [3] which is approximately 60 [deg] is used for other two components.

As a result, 2.5 to 3.0 % of expected output was lost due to the reflection in south oriented PV arrays and 3.0 to 4.0 % was lost in multiple array orientation PV systems. The loss is slightly larger in summer and this can be explained by solar azimuth. Assuming the azimuth at south = 0deg, the sun will move to more than +- 90deg in summer that means incident angle is also larger than 90deg. In this situation all of the direct component of the solar irradiance will not reach to the PV array so the amount of power loss due to the incident angle will be larger in summer.

3.4 Restrictions

Even though the array is receiving enough sunlight to generate electricity, PCS sometimes have to regulate its output because of the restrictions. A grid voltage is mainly the reason of the restriction as mentioned in section 2. The output power loss due to the grid voltage is classified as Restriction1, this will be discussed in section 4. Another reason of restriction is temperature. PV system's PCS have an over temperature protection and if the temperature exceeds the limitation it will automatically shut off the power. Before shutting down the system, some of the PCS regulates its output current to prevent an over heating of the PCS. Restriction2 includes this kind of the output regulations.

The effect of both Restriction1 and 2 are not so severe on monthly average basis, but these have a very big variation for the system condition, weather condition and grid condition. Restriction2 has been often seen in the systems which have smaller PCS size compare with array capacity because the time to outputting its maximum output current is relatively longer during daytime in this case. Indoor types PCSs have larger loss because all of the PCSs are installed in the storage boxes without any air conditioning units.

4 LOSS DUE TO GRID VOLTAGE

4.1 Daily analysis results

Daily average of performance ratios, losses and PCS output terminal voltages were calculated for selected 61 systems to investigate more about the Restriction1. In addition to the previous two terms, spring (3/15 to 4/25) and winter (11/1 to 12/31) are also used for some data-available sites. Fig.4 shows the example of daily analysis result of one site. Different colors of bars represent performance ratio (as a positive number) and each loss factors (as a negative number). Line plot represents daily average of PCS output terminal voltage ($V_{D\text{-}PCS}$) during the sunlight available time.

From this figure, it is clear that the loss due to Restriction1 (grid voltage) was occurred only on 10/23 and maximum $V_{D\text{-}PCS}$ was also recorded in the same day. Thus daily average can be used to see the relationship between grid voltage and loss.

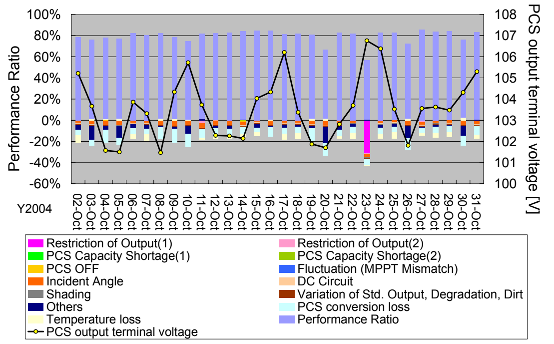

Figure 4: Example of daily performance and loss analysis result with daily average of PCS output terminal voltage, 2004/10/02 – 2004/10/31

4.2 Daily average of PCS output terminal voltage and output energy loss

Daily output energy loss due to the output regulation to avoid the over voltage (= Restriction1) is divided by daily expected possible output power, and results are plotted into scatter diagram with $V_{D\text{-}PCS}$. (Fig.5) Different mark represents different maker of PCS. Starting voltage of output regulation ($V_{th\text{-}Reg}$) is estimated by instantaneous data which are collected every second. $V_{th\text{-}Reg}$ for PCS-A is 109 [V] and 107.5 [V] for PCS-B. However, since output regulation did not happen to PCS-C, starting voltage for this PCS is unknown.

More than 7000 systems times days are plotted into this graph. As a result, loss ratios were exponentially increased if $V_{D\text{-}PCS}$ exceeds around the voltage of ($V_{th\text{-}Reg}$ -1) [V] that is around 108V for PCS-A and 106.5V for PCS-B. In the case that $V_{D\text{-}PCS}$ is higher than $V_{th\text{-}Reg}$ [V] more than 80% of expected possible output power was lost due to the output regulation. Since PCS-B has the lowest starting voltage for output regulation, most of the losses happened to this PCS. However a frequency of severe loss was not so high durig the evaluation time periods.

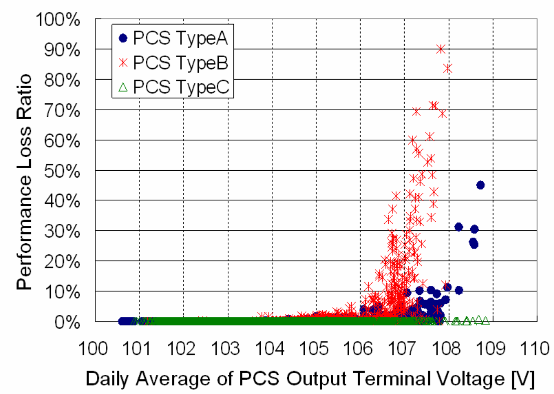

Figure 5: Scatter diagram of daily average PCS output terminal voltage and loss due to restriction1

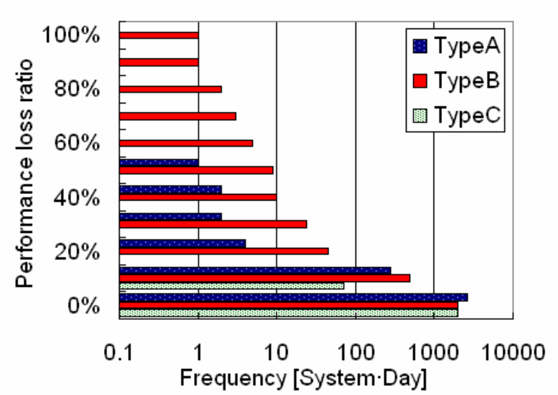

Figure 6: Numbers of systems times days for each loss ratio

Fig.6 describes numbers of systems times days for each loss ratio. Since x-axis is log scale, more than 90% of the systems times days resulted less than 20% of loss ratio.

4.3 PV output and grid voltage

Correlation between $V_{D\text{-}PCS}$ and output energy loss are shown in Fig.5, however the effect of PV output power for $V_{D\text{-}PCS}$ is still not clear because reverse power flow from the PV systems are not only the reason for grid voltage rising but the reduced loads also cause grid voltage rising at the connecting points of PV systems. [4]

Fig.7 shows correlation between daily global solar irradiation and $V_{D\text{-}PCS}$. $V_{D\text{-}PCS}$ gradually increased along with the daily global solar irradiation increasing. Irradiation of more than 5 [kWh/m^2] caused approximately 2 [V] of $V_{D\text{-}PCS}$ rising.

The loss ratios of energy output are also plotted as a function of daily global solar irradiations (Fig. 8). Loss ratios increased along with the irradiation increasing and it has a peak at 6 [kWh/m^2]. However, since frequency of over voltage is very low, it is still not clear if more irradiation causes more energy loss or 6 [kWh/m^2] is really the peak irradiation for output regulation. Longer term evaluation is needed to clarify this behavior.

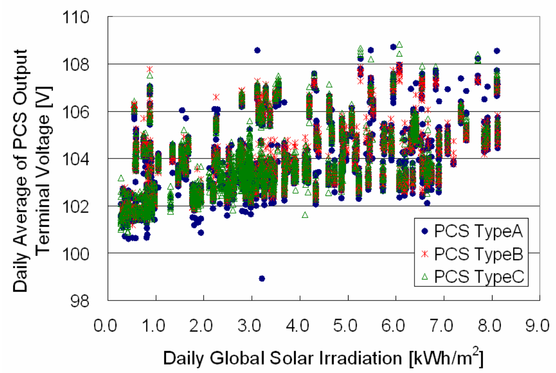

Figure 7: Correlation between daily global solar irradiation and daily average PCS output terminal voltage

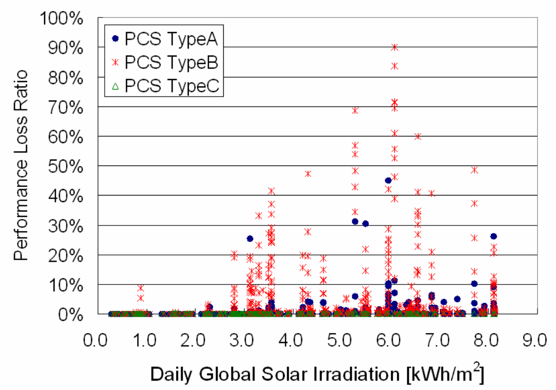

Figure 8: Loss ratio of energy as a function of daily global solar irradiation

4.4 Load and grid voltage

To investigate an empirical correlation between load and grid voltage, days of the week are one of the simple parameters. Fig. 9 shows average PCS output terminal voltage as white circles, and its distribution for each PCSs as colored marks. As shown in this figure, average voltages during weekends are 1.5 to 2.0 [V] higher than that of in weekdays. This can be explained by reduced industrial load during weekend because higher voltage was also recorded during national holydays.

Fig.10 shows output power loss for each day. It is clear that most of the output regulations (Restriction1) are occurring during weekends with reduced load.

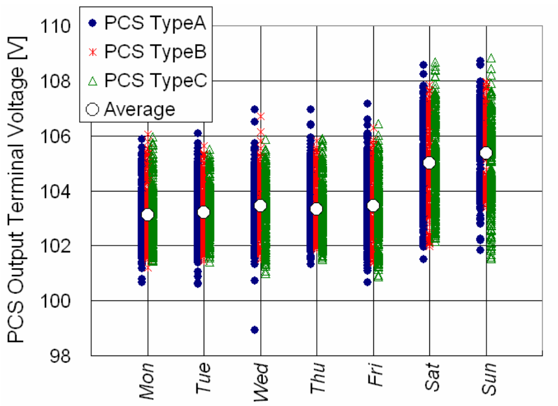

Figure 9: Daily average PCS output terminal voltage for each day of the week

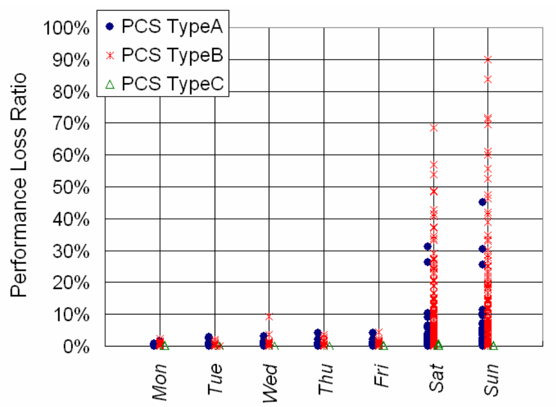

Figure 10: Output energy loss ratio for each day of the week

5 CONCLUSIONS

Detailed performance analyses for grid connected clustered PV systems are conducted in this paper. Output energy losses are calculated for 12 loss factors and the seasonal effects of temperature and incident angle are quantitatively analyzed. The frequency of output regulation was not so high but the energy loss was more than 50% in worst cases.

The influences of both PV systems and load for grid voltage rising are also evaluated in this paper. More than 5 [kWh/m^2] of daily global solar irradiation raised approximately 2 [V] of low voltage line's voltage when 200 PV systems (which is about 800 kW) are connected to the same medium voltage line through low voltage lines on daily average number basis. Reduced load during weekend also raised approximately 2 [V] of low voltage line's voltage. Combination of these two factors induced over voltage of the power distribution line and this over voltage induced substantial output yield reduction for PV systems in worst cases.

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