PERFORMANCE ANALYSES OF BATTERY INTEGRATED GRID-CONNECTED RESIDENTIAL PV SYSTEMS

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ABSTRACT: Grid connected PV systems will feed electric power to the power distribution network. Voltage at the connecting point to the grid will become higher along with the reverse power flow increasing. PCS output power is restricted by the grid voltage so the significant amount of the possible energy output will be lost if the grid voltage is too high. To avoid this output energy loss due to the high grid voltage, battery integrated PV systems are developed in the "Demonstrative research on clustered PV systems." More than 550 residential PV systems are installed in the demonstrative research area. Annual performance analysis results of commercial PV systems without battery and battery integrated systems are summarized in this paper. Variation of the output energy loss due to the grid voltage is observed in commercial PV systems due to the difference of the regulating method. Approximately 8% of additional performance loss is observed in battery integrated PV systems. Active power regulations due to the high grid voltage are successfully avoided in some cases.

Keywords: Grid-Connected, PV System, Performance

1 INTRODUCTION

Grid connected-residential photovoltaic (PV) systems such as roof mounted PV systems feed electric power to the power distribution line. Since radial power distribution system is designed for a power flow from the high voltage (HV) side to the low voltage (LV) side, reverse power flow from the end of LV side may cause voltage rise of LV line. [1](see Figure 1) To prevent the over voltage of the power distribution line, Japanese PV system's power conditioning subsystems (PCS) have a function to regulate output power when the voltage of the grid is too high. Because of this function, significant amount of electric power will be lost. [2]

"Demonstrative research on clustered PV systems" is being conducted from December, 2002 by NEDO to investigate about the voltage problem and other potential issues of grid-connected PV systems. Approximately 550 PV systems are installed on the roofs of houses and connected to the commercial power grid in the demonstrative research area in Oota, Japan. A total of nominal system power is more than 2[MW] and all the systems are connected to the same power distribution network. [3]

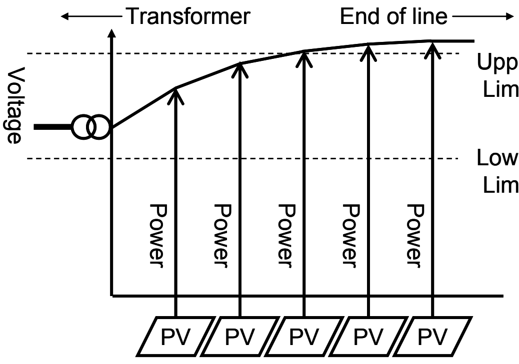

Figure 1: Voltage rising of power distribution line

2 BATTERY INTEGRATED PV SYSTEMS

2.1 Overview of battery integrated PV system

To minimize the output energy loss due to the high grid voltage and maintain the power quality of the grid, battery integrated PV systems are developed in the demonstrative research. Lead acid battery with a capacity of 49 [Ah] for single cell are used for the systems, 96 cells are series connected and installed in the outdoor storage box for each PV systems. Two types of charge controller are developed in the demonstrative research. One is the unified PCS for PV and battery and the other is the additional charge controller for commercial PV systems. Installation of the unified PCS is started from January, 2005. Additional charge controllers for the installed commercial PV systems are started in a year later.

2.2 Unified PCS for PV and battery

The unified PCS is composed of a DC/DC booster, DC/DC charge controller and DC/AC inverter. Figure 2 shows a schematic view of the battery integrated PV system with the unified PCS.

Only the power from the PV array will be charged to the battery, the charged power will be used in the in-house load. Unified PCS monitors a power flow at the connecting point, more than 150[W] of forward power flow are required for discharging in order to prevent the reverse power flow from the battery to the grid.

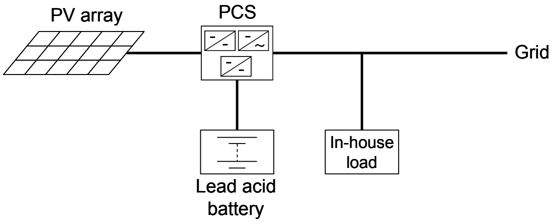

Figure 2: Schematic view of the battery integrated PV system with the unified PCS

3 ANALYSIS METHOD

One-minute averages of secondly measured data are used for the analysis. System yield [kWh/kW] and performance ratio are employed for the overall system performance analysis. In addition to these indexes, detailed loss analyses are performed to clarify the benefit of the battery integration.

Deployed PV systems performance is highly depending on the various loss factors, i.e. temperature, shading, array configuration, grid voltage and so on. Expected output power which would be generated in the normal grid voltage condition and lost energy under the high voltage condition need to be quantified in order to quantify the energy which is saved by the battery. Some of the losses occur exclusively but some of them occur simultaneously, the following loss factors are considered and separately quantified in this paper.

1. Shading
2. Regular loss (Soil, Degradation, Array config.)
3. Incident Angle / Reflection
4. Module Temperature
5. Output restriction (over voltage)
6. PCS capacity shortage
7. MPP mismatch (high voltage side)
8. DC resistance
9. Inverter
10. PCS Off / PCS Standby
11. Fluctuation

Input energy of the PV systems is irradiation. Irradiation is measured at the meteorological stations using pyranometer in this research. Shading, soil, degradation and incident angle are treated as factors to reduce the input irradiation of the PV array. Received irradiation will be used for the photovoltaic energy conversion. Module temperature, operation point on the I-V curve and array configuration are treated as factors to change the conversion efficiency of the PV array. Grid voltage, PCS capacity and MPP mismatch are considered as factors to determine the operation point on the I-V curve of the PV array.

Loss due to the incident angle and DC circuit resistance are calculated using theoretical model. [4][5] Loss due to the module temperature and inverter are directly calculated using measured module temperature, PV array's output power and inverter's output power. Other losses are quantified for each factor using empirical models. [5][6][7]

4 RESULTS AND DISCUSSIONS

4.1 System yield and performance ratio

Monthly averages of daily reference yield, daily system yield and daily fed power are summarized in Figure 3. Monthly performance ratios are also plotted in this figure as a right y-axis. In general, April has a longest reference yield but peak of the performance ratio is in winter. Performance ratio in summer is slightly lower because of the efficiency drop due to the module temperature increasing. PV systems with battery always result approximately 8% lower performance ratio due to the additional energy loss at the charge controller and battery. 30% of generated power is once charged in the battery for battery integrated systems. As a result, fed power is less than half of the non battery integrated systems.

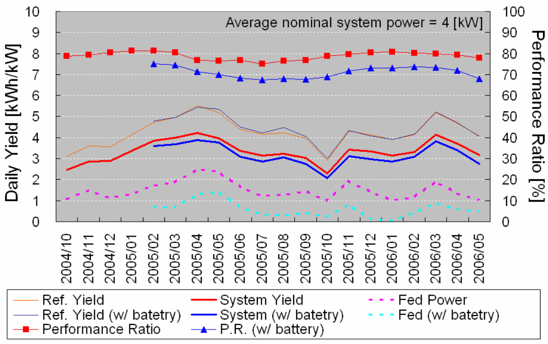

Figure 3: Reference yield, system yield, fed power and performance ratio for commercial and battery integrated PV systems

4.2 Annual system performance

Annual system performance and loss analysis results of commercial PV systems and those of battery integrated PV systems are shown in Figures 4 and 5 respectively. Data collected from March, 2005 to February, 2006 are used in these results. Numbers of PV systems used in these graphs are gradually increased during the evaluation period, numbers of commercial (non battery integrated) PV systems in March, 2005 are 134 and 140 in February, 2006. On the other hand, numbers of battery integrated PV systems are 19 in March and 197 in February. Both energy losses at the inverter and charge controller are included in a loss due to the unified PCS. Additional energy consumption of the measurement system and control system are also included.

Looking at the results, all the loss factors showed almost the same values and seasonal trend except the loss due to the battery and PCS. Since commercial PCS and unified PCS have almost the same DC/AC conversion efficiency, 4.7% of the expected energy can be assumed as a loss at the charge controller of unified PCS and other additional losses. 3.3% of the expected power is also lost in the battery itself so that the total performance ratio is around 8% lower in the battery integrated systems.

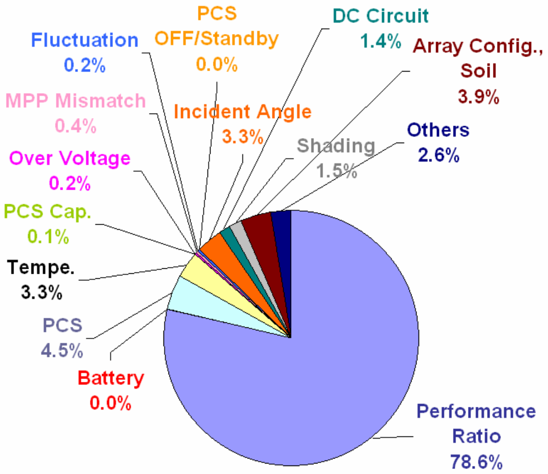

Figure 4: Annual performance and loss analysis result of commercial (non battery integrated) PV systems

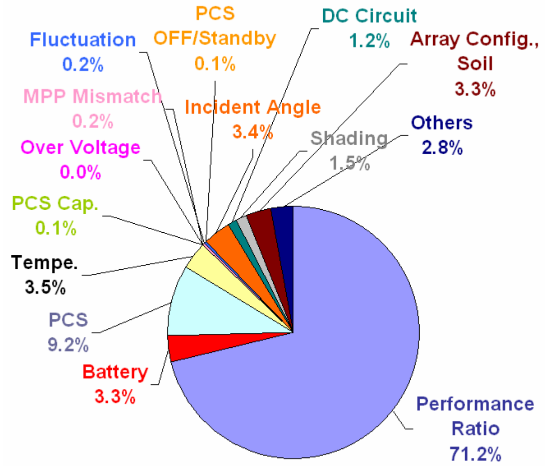

Figure 5: Annual performance and loss analysis result of battery integrated PV systems

It should be noted that charged energy have to go through the charge controller twice. When the generated electricity is being stored in the battery, current will go through DC/DC booster and DC/DC charge controller. During the discharging, current will go through DC/DC charge controller again and DC/AC inverter. Charging DC current are not the constant current but follow the PV array output, this is not the best way to charge the battery in terms of the efficiency stand point but necessary in the battery integrated PV systems.

4.3 Loss due to the grid voltage

The voltage at the power distribution line needs to be controlled within 101V +- 6V or 202V +- 20V in Japan. Flowing current and line impedance are two major factors to determine the voltage at the connecting point. If the sending voltage of the transformer substation and tap positions are the same but different current in the same line impedance, more current cause more voltage drop in forward power flow case but results voltage increasing in reverse power flow case at the end of LV line. Thus reducing the feeding power to the grid is necessary to avoid the over voltage for the distributed generator such as grid connected PV systems. Battery integration is one of the options for PV systems to minimize the risk of over voltage without sacrificing the output energy by mean of storing the electricity in the battery.

So far, energy loss due to the grid voltage is not so severe even in the non battery integrated PV systems. Percentage of the loss due to the grid voltage is less than 1% in annual average as shown in Figure 4. This is probably because of the good voltage control of the power grid. However, there are a few systems which tend to have more energy loss due to the grid voltage and amount of lost energy is sometimes more than 50% of the expected energy out. Figure 6 shows analysis result of the loss due to the grid voltage for commercial PV systems. Each data point represents the daily loss of one system and more than 3000 data are plotted in each month. Although most of the data are on the 0% line, some of the systems result significant energy loss on particular days. Most of these bad days are weekends and clear sunny days as shown in Figure 7. The results suggest that the reduced load (reducing forward current) in the power distribution network in weekends and more reverse power flow (increasing reverse current) in clear sunny days caused higher grid voltage.

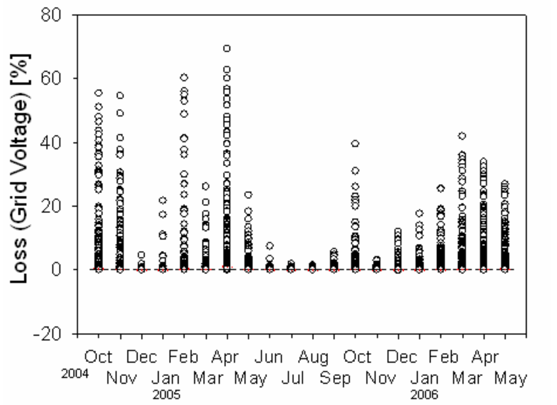

Figure 6: Daily loss ratio due to the high grid voltage for commercial (non battery integrated) PV systems

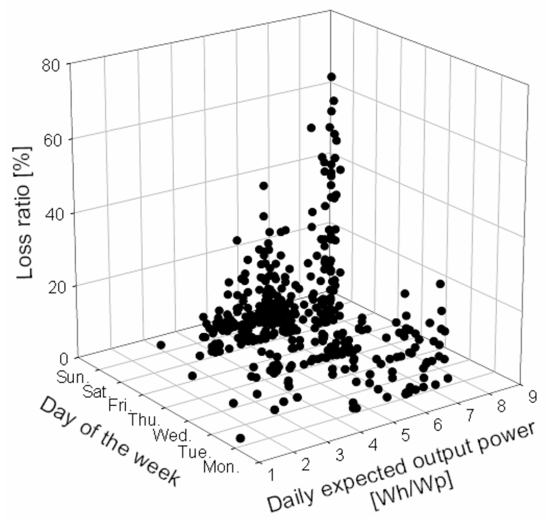

Figure 7: Loss ratios due to the grid voltage as a function of the day of the week and daily expected output power

Another factor to differentiate the amount of energy loss due to the grid voltage among the systems is the starting voltage of output regulation. Examples of the regulation methods, starting voltage and regulating speed are summarized in Table 1. Phase advance reactive power control will shift the phase of current and change the power factor between 1 and 0.85, active power control will regulate the output current in order to reduce the output power by shifting the operation point from MPP to the open circuit voltage. Since PCS is not monitoring the voltage at the connecting point but its own output terminal voltage and there is a voltage drop between PCS output terminal and connecting point due to the resistance of the drop wire, voltage at the connecting point might be lower than that at the PCS output terminal. Thus PCS may not need to start the regulation from 107V but can start from slightly higher voltage. This is one of the reasons why starting voltages of output regulation are not exactly the same among all the PCS. However, it is pointed out that this kind of variation may cause the concentration of output restriction in particular PCS so this variation should be minimized. [8]

PCS Types	Starting Voltage	Speed
Reactive power control		
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

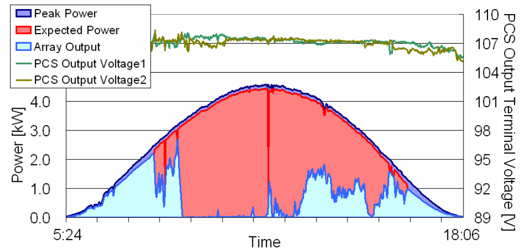

Figure 8: Example of output regulation due to the high grid voltage. System #1 with commercial PCS type A

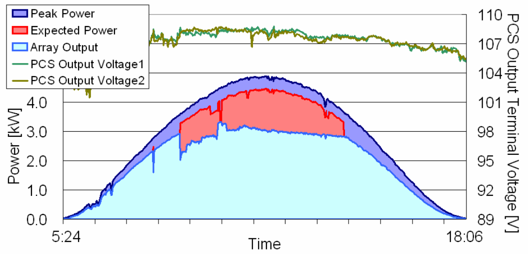

Figure 9: Example of output regulation due to the high grid voltage. System #2 with commercial PCS type B

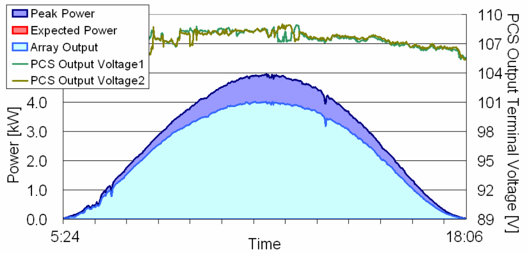

Figure 10: Example of output regulation due to the high grid voltage. System #3 with commercial PCS type C

Figures 8, 9 and 10 are examples of the output regulations due to the high grid voltage for three different commercial PCS. All the systems are connected under the same pole transformer, no battery are installed in these systems. Data are collected on April 9, 2005, Saturday. Peak power means expected system output power under the measured irradiation at the module temperature of 25 degree Celsius. Array output means actual output power from the PV array under the actual module temperature. Red area means lost energy mainly because of the restriction of the output power due to the high grid voltage. PCS output voltage1 and 2 are measured voltage at the single-phase three-wire PCS output terminals. Starting voltage of the active power regulation for system #1's PCS is around 107.5[V]. On the other hand, that of system #2's is around 109[V] and 110[V] for system #3's PCS. As a result, around 69% of the expected power was lost due to the high grid voltage in system #1 while system #2 lost around 15% and no loss was observed in system #3. PCS output terminal voltages of system #3 are slightly higher than those of the others because #3 has more reverse power flow to the grid. However, this result does not mean that system #3 was in over voltage condition because these voltages are not the voltages at the connecting point.

4.4 Effect of battery

Battery can be used as an output restriction avoidance system in grid connected PV systems. Charging battery with generated electricity can minimize the power fed to the grid in the daytime. Stored electricity will be used in the in-house load during the nighttime. Figures 11 and 12 are examples of the results how the battery worked as an output restriction avoidance system. Data are collected on March 25, 2006, Saturday. In addition to the data showed in Figures 8, 9 and 10, feeding power to the grid and charged power to the battery are plotted in these figures. Negative power of the feeding power means forward power flow from the grid to the in-house load, negative power of the battery power means charging battery. Bottom side of Figure 12 shows state of charge. (SOC)

System #4 in Figure 11 resulted out put energy loss due to the high grid voltage in afternoon and lost energy was approximately 20% of the daily expected energy out. On the other hand, system #5 started charging battery around 10 a.m. so there is no fed power when the voltage is high in the afternoon. As a result, no electric power was lost due to the high grid voltage.

Another example of battery integrated system is shown in Figure 13. The system started charging battery when the PV array started generation of electricity. Then battery was fully charged around noon so there was no more room to store the electric power when the voltage became high in the afternoon. The capacity of the battery should be minimized from the installation cost point of view, however, less capacity requires more intelligent method for charging and discharging battery. Further study will be continued to optimize the control pattern of the battery.

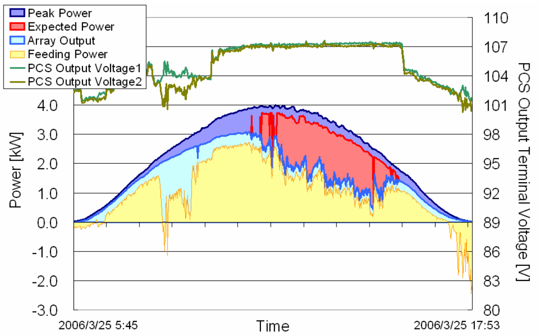

Figure 11: Example of output regulation due to the high grid voltage. System #4 with commercial PCS type A

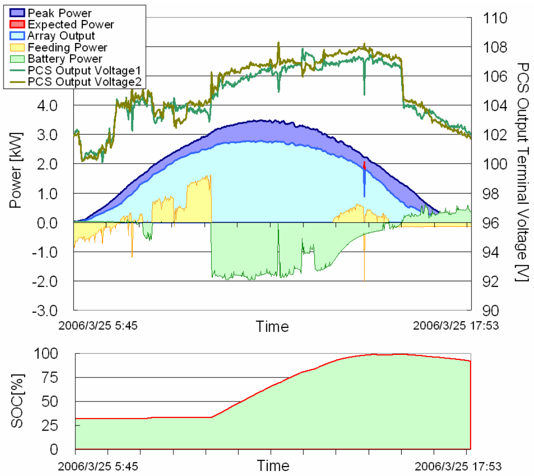

Figure 12: Example of output restriction avoidance. System #5 with unified PCS with battery

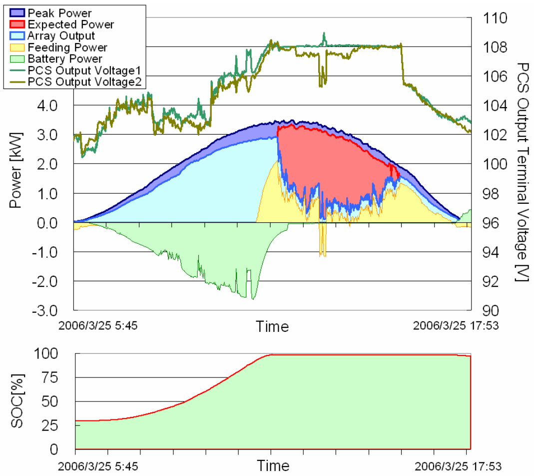

Figure 13: Example of the failure of output restriction avoidance. System #6 with unified PCS with battery

5 CONCLUSIONS

Output energy loss due to the high grid voltage is analyzed in this paper. Without the battery, PV system's output energy is restricted by the grid voltage. Since the reverse power flow from the PV system to the grid is one of the causes of high grid voltage, battery integration is one of the options to reduce the risk of over voltage and minimize the energy loss due to the high grid voltage for PV system's user side.

Although the frequency of the occurrence of active power regulation due to the high grid voltage is very low, some of the systems had significant amount of output energy loss in fewer load / more electricity generation condition such as weekend and sunny clear day. Different PCS have different starting voltage of the active power regulation so the amount of the lost energy is not the same among all the PCS. If the battery is appropriately operated, battery integrated PV system can avoid the output energy loss under the high grid voltage situation. However, battery integration results additional energy loss due to the charge controller and battery, saved energy should be larger than the additional loss in order to maximize the merit of PV system user. Amount of saved energy will be affected by the grid condition and battery operation. Further research will be continued in the "Demonstrative research on clustered PV systems."

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