STUDY ON THE OVER VOLTAGE PROBLEM AND BATTERY OPERATION FOR GRID-CONNECTED RESIDENTIAL PV SYSTEMS

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ABSTRACT: “Demonstrative research on clustered PV systems” has been conducted since December, 2002 in Ota, Japan. Approximately 2.1 [MW] of PV systems which are composed of 553 residential PV systems are installed with lead acid batteries and grid-connected in the demonstrative research area. Battery is used as an over voltage avoidance system which will prevent the over voltage at the power distribution line and avoid the output energy loss due to the high grid voltage. “Voltage control mode”, “Minimizing reverse power mode” and “Schedule mode” are tested in the real grid-connected condition, results are quantitatively summarized followed by the charge / discharge efficiency in this paper.

Keywords: Battery Storage and Control, Grid-Connected, PV System

1 INTRODUCTION

“Demonstrative research on clustered PV systems” has been conducted since December, 2002 in Ota, Japan. The main objective of the research is to investigate about the over voltage problem that is anticipated occurring in the clustered photovoltaic (PV) systems. [1]

In clustered PV systems, many of residential PV systems are intensively installed and grid-connected in the small urban area’s power distribution network. In this case, voltage at the power distribution line will rise because of the reverse power flow from each PV systems. [2] Thus PV system’s output needs to be regulated even with the enough irradiation if the grid voltage becomes high. To minimize the output energy loss due to the high grid voltage, newly developed battery integrated PV systems are installed in this research. Approximately 2.1 [MW] of PV systems which are composed of 553 residential PV systems are installed with batteries and grid-connected in the demonstrative research area. The purpose of this paper is to clarify the requirement of the battery operation to avoid the over voltage problem and to compare the different types of battery operation mode for grid-connected residential PV systems.

2 BATTERY INTEGRATED PV SYSTEMS

2.1 Overview of the battery integrated PV system

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. A capacity of the battery is approximately 9.6[kWh] which is chosen based on the simulation result and the regulation of the fire department. Only the power from PV arrays will be charged to the battery, charged electric energy will be used in the in-house load. Charge-controller monitors a power flow at the connecting point, more than 150[W] of a forward power flow is required for discharging in order to prevent the reverse power flow from battery to the grid. The maximum depth of discharge is set to 70 [%] in order to avoid the 100 [%] discharge condition which may cause the reduction of the battery’s capacity and affect the battery life. Periodic full charge is performed in order to recover the capacity of the battery. Batteries are fully charged every two weeks and judgment condition of the completion of recovery charge is that the charging current becomes less than 1 [A] and continue this condition for more than five hours.

Two types of charge-controller are developed in the demonstrative research. One is the additional charge controller for commercial PV systems and the other is the unified PCS which controls both PV and battery. Schematic drawing of the additional battery system is shown in Figure 1 and that of the unified PCS’s is shown in Figure 2.

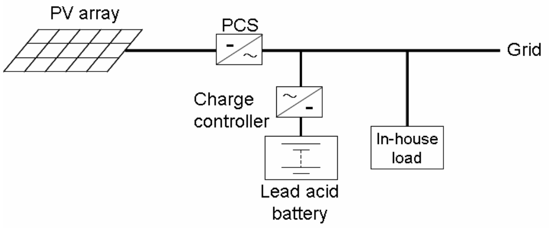

Figure 1: Schematic drawing of the battery integrated PV system with the additional charge controller

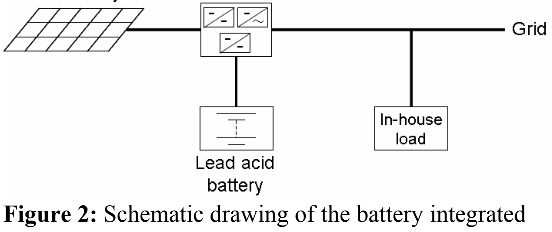

Figure 2: Schematic drawing of the battery integrated PV system with the unified PCS

2.2 Over voltage and energy loss

The voltage at the power distribution line needs to be controlled within 101[V] +- 6[V] or 202[V] +- 20[V] in Japan. If the voltage becomes higher than this limitation, PV systems need to reduce its output to prevent over voltage. Since this research is the demonstrative research and using commercial power distribution system, voltage is well managed by utility side so the energy loss due to the high grid voltage is not so severe so far.

Output energy loss due to the high grid voltage (over voltage) is calculated using SV method. [3][4] The maximum energy loss was recorded on March 25th, 2006. Total energy loss and daily total output on this day were 0.36 [MW] and 10.3 [MW] respectively. Summary of the output energy loss due to the high grid voltage is shown in Figure 3. Most of the energy losses are observed in spring and autumn which seasons relatively have nice clear sky and good weather thus electric load such as air conditioners are not in use. Figure 4 shows an output energy loss for each time in an increment of one minute. Most of the over voltage occurred in between 10:00 to 14:00.

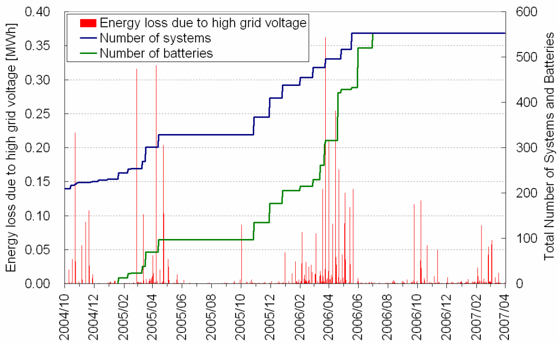

Figure 3: Summary of the output energy loss due to high grid voltage

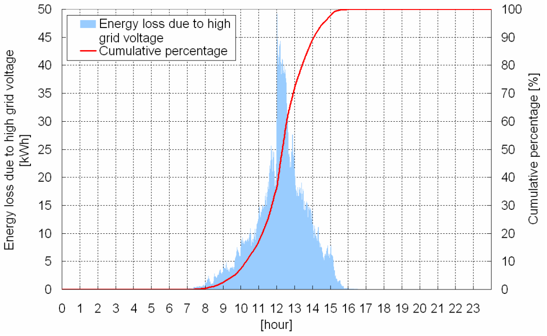

Figure 4: Output energy loss for each time in an increment of one minute

2.3 Battery operation mode

Basic concept of the battery integrated PV system is shown in Figure 5. In clear day, grid voltage becomes high due to the reverse power from PV systems. If the voltage reaches to the upper limit, PV system needs to regulate or stop outputting the power to the grid even with a lot of irradiation. This kind of output loss usually occurs not only because of the particular system's output but neighbors also raise the voltage around it. Thus some of the systems never output during this "high voltage" period while the other systems are feeding the power to the grid. This difference is strongly depending on the line impedance and type of PCS. Systems connected with low impedance experience less over voltage, systems which have low starting voltage of output regulation have more energy loss.

To avoid this energy loss, battery integrated PV system will charge the battery during the daytime and use that stored energy during the night. As long as the battery has enough capacity to charge the energy from PV, this system never experience the output energy loss due to the high grid voltage. More battery's capacity is better for this purpose.

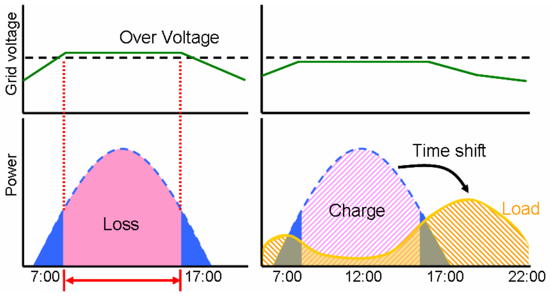

Figure 5: Illustration of the basic concept of the battery integrated PV systems

On the other hand, installing the battery adds extra cost for PV system so smaller capacity is better from the cost stand point. Preferable state of charge (SOC) have also inconsistent requirement, the higher SOC is better for lead-acid battery from the life time stand point but keeping lower SOC is better for the over voltage avoidance in order to maintain enough capacity to charge the reverse power flow from PV.

To find out the optimum battery operation mode to solve these conflicts of the requirements, several battery operation modes are tested in this research. Most of the operation mode can be classified into three operation mode, i.e. "Voltage control mode", "Minimizing reverse power mode" and "Schedule mode." Battery control using weather forecast and other intelligent control mode are also tested. Figure 6 illustrates the image of charging pattern for basic three operation modes.

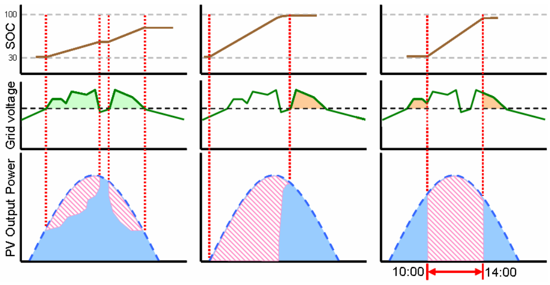

Figure 6: Illustration of the charging pattern of "Voltage control mode" (left), "Minimizing reverse power mode" (center) and "Schedule mode" (right)

"Voltage control mode" will charge the battery only when the PCS's output terminal voltage exceeds the set point. If the voltage is always lower than the set point battery will never be charged except the recovery charge. This situation may happen in rainy season or other "heavy load" seasons. This mode can minimize the charge / discharge loss and have a potential to reduce the capacity of the battery. However, if the voltage is always higher than the set point battery will be kept charging so it will be the same operation as the "Minimizing reverse power mode."

"Minimizing reverse power mode" will charge the battery anytime until the battery becomes full charge. An average nominal power of each PV systems is approximately 4 [kW], so most of the battery will be fully charged around noontime in clear day. As a result, this mode often fails to avoid output energy loss in afternoon due to the lack of the remaining capacity to charge. SOC will be kept high in this mode which may prevent degradation of the battery.

"Schedule mode" will charge the battery based on the schedule. For example, battery will be charged from 10:00 to 14:00 everyday regardless the voltage. Since most of the over voltage occurred in between 10:00 to 14:00, this mode can avoid most of the output energy loss. Charging current is also limited in this mode. 0.2 [CA] which is equivalent to 9.8 [A] and 0.1 [CA] are used in the schedule of 10:00 to 14:00 and 9:00 to 15:00 respectively. Both combination aims to avoid full charge situation until the end of the schedule time.

3 RESULTS AND DISCUSSIONS

3.1 Battery operation results

An actual operation data of each mode are summarized on two weeks basis which period starts right after the recovery charge and ends right before the next. One minute averages of secondly measured data are used for the analysis. Data from January 1st, 2007 to January 11th, 2007 which period includes sunny days and cloudy days are summarized in Figures 7, 8, 9, 10 and 11. Each figure shows 10 days average of PV array output, AC power at the connecting point (Positive=reverse (sell to the grid) / Negative=forward (buy from the grid)), load, Battery DC power (Positive=discharge / Negative=charge), PCS output terminal voltages and battery's SOC in an increment of one minute. Operation modes in Figures 7, 8, 9, 10 and 11 are "Voltage control mode" which start charging from 104.5 [V], "Voltage control mode" which start charging from 105 [V], "Minimizing reverse power mode", "Schedule mode" which charge from 10:00 to 14:00 with 0.2 [CA] and "Schedule mode" which charge from 9:00 to 15:00 with 0.1 [CA] respectively. Numbers of the PV systems assigned for each operation mode are 19, 22, 18, 27 and 26 in the same order with the explanation of operation modes.

Grid voltage was not so high in this period, average voltage at PCS's output terminal around noon is approximately 104 [V]. Thus 104.5 [V] and 105 [V] are chosen in "voltage control mode" to avoid "never charged" situation. Minimum SOC is not 30 [%] but around 40 [%] in each mode, this is mainly because of the few systems which don't have enough electric loads to discharge all the electric power in the battery during the night.

To review these operation results, percentages of the electric power charged to generated, 10 days averages of SOC at 12 o'clock and average daily peak SOC are summarized in Table 1. The first criterion is to compare the battery usage. The second criterion is to compare the remaining capacity of the battery which can be used for over voltage avoidance. The third criterion is to compare the possibility of battery degradation. Lower average SOC is better for the over voltage avoidance, higher peak SOC is better for the battery's life.

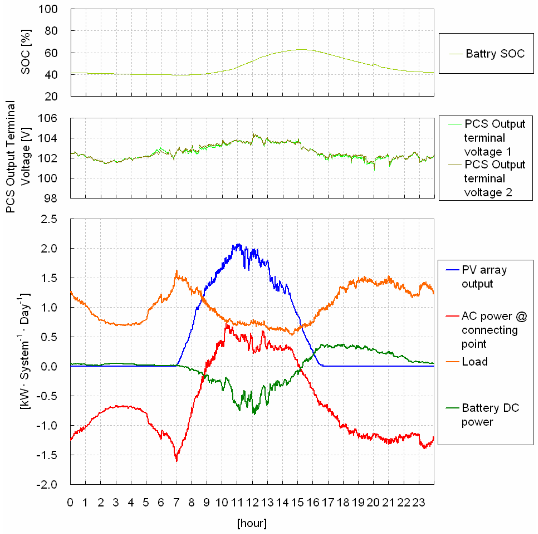

Figure 7: Battery operation results of "Voltage control mode" start charging from 104.5 [V]

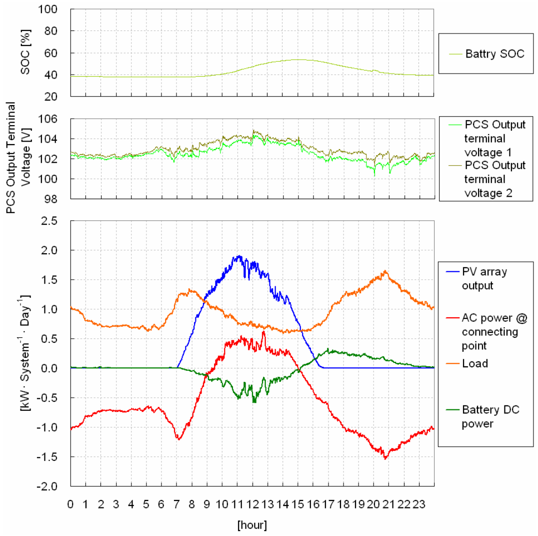

Figure 8: Battery operation results of "Voltage control mode" start charging from 105 [V]

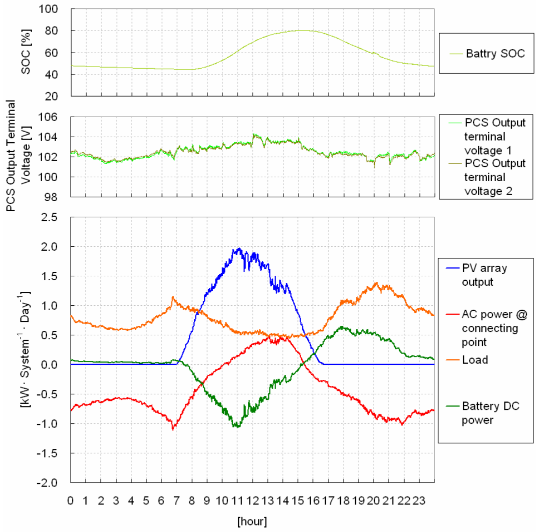

Figure 9: Battery operation results of "Minimizing reverse power mode"

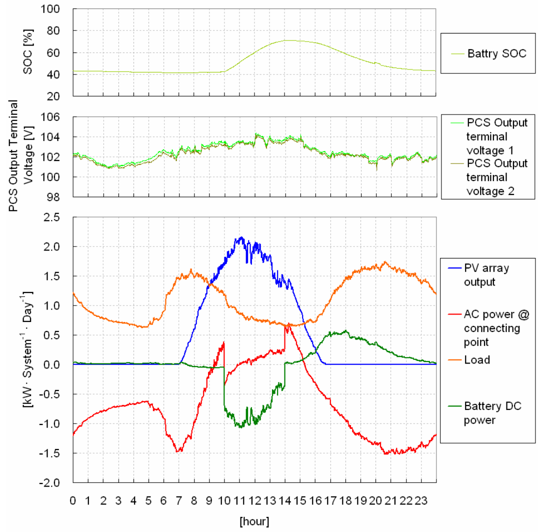

Figure 10: Battery operation results of "Schedule mode" charge from 10:00 to 14:00 with 0.2 [CA]

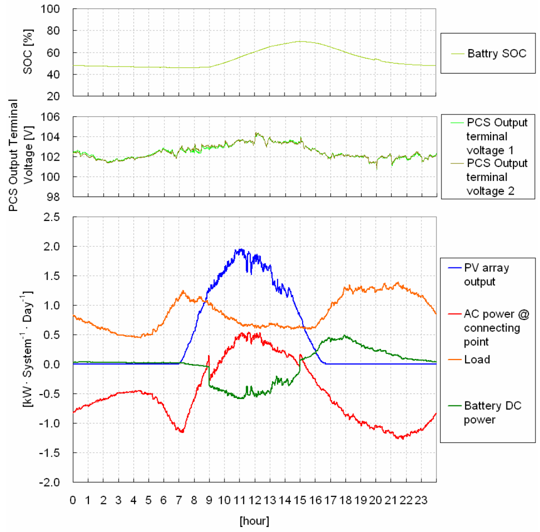

Figure 11: Battery operation results of "Schedule mode" charge from 9:00 to 15:00 with 0.1 [CA]

Table 1: Comparison of the battery operation results

	% of power (Charged/Generated)	SOC [%] @12:00	Daily Peak SOC [%]
Voltage (104.5V)	23.9	52.1	62.8
Voltage (105V)	20.7	47.0	53.6
Min. reverse power	38.1	69.3	80.1
Schedule (10-14)	29.4	59.9	71.1
Schedule (9-15)	27.6	60.4	70.2

As a result, both of the "voltage control mode" had lowest SOC through a day and the smallest battery usage. Only the 0.5 [V] difference of the charge-start voltage had enough impact to differentiate the results. "Minimizing reverse power mode" had the highest average SOC and the peak SOC, easily became high SOC during the day and had the highest usage of the battery. "Schedule mode" was in between these two modes. Both combinations of the time and current limitation controlled both an average and a peak SOC well.

3.2 Charge / Discharge efficiency

Charge / discharge efficiencies are calculated and summarized in Table 2. Evaluation period is the same as the period in section 3.1 but including post recovery charge because the state of charge need to be 100 [%] in the beginning and the end of the calculation period in order to correct the measurement error of the cumulative ampere hour. As a result, charge / discharge efficiencies are almost the same value regardless the operation mode. Although the ampere hour efficiency of the battery's DC output was around 96 [%] as expected, watt hour efficiency of the charge-controller's AC output was less than 70 [%] including the loss in the battery and the charge controller.

Table 2: Comparison of the battery charge / discharge efficiency

	kWh efficiency (DC) [%]	kWh efficiency (AC) [%]	Ah efficiency (DC) [%]
Voltage (104.5V)	85.8	68.9	96.2
Voltage (105V)	85.2	62.9	95.0
Min. reverse power	85.7	69.1	96.5
Schedule (10-14)	85.6	68.9	96.7
Schedule (9-15)	87.2	69.4	96.9

4 CONCLUSIONS

Actual operation results of battery integrated residential PV systems are summarized in this paper. Real grid-connected battery operations are successfully demonstrated, SOC changes and efficiencies are quantitatively analyzed. Due to the low efficiency of the current battery systems, small usage of the battery is better for total efficiency at this moment. Thus "voltage control mode" can be the first choice of the operation mode. Further research will be continued until the end of the project.

ACKNOWLEDGEMENT

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