DISTRIBUTION LINE STRUCTURE AND GENERATION EFFICIENCY IMPROVEMENT: A CLUSTERED RESIDENTIAL GRID-INTERCONNECTED PV

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Abstract – In Japan, the target capacity for installed photovoltaic power systems (PV) in 2020 has been set to 28 GW. The PV output (active power) must be suppressed to sustain adequate voltage (within 101 ± 6V), which was established by the Electricity Business Act in Japan, due to voltage increases by inverse power from PV when clustered residential PV systems are grid-interconnected on a distribution line, even if sufficient irradiance exists. Simulation software was developed to analyze voltage increases when clustered PV were grid-interconnected on a large-scale demonstrative research in Ota City, Japan. From the previous fiscal year, the authors started to research improving whole generation efficiency at a site. We are developing to balance it among all the residences through voltage control, including power conditioning systems of a clustered residential grid-interconnected PV with the developed simulation software. For the subject, we have already demonstrated that 25 percent of the output suppression loss was eliminated with reactive power control when 225 residential PV are grid-interconnected to a simple single distribution line. In this research, a complex single distribution line, where 2160 residential PV are grid-interconnected, is set. We develop suitable voltage control for both simple and complex distribution lines.

Keywords: distribution line, grid-interconnection, photovoltaic power systems, power conditioning systems, reactive power, voltage increase

1 INTRODUCTION

Installing zero-emission power sources is necessary to reduce greenhouse gas and fight global warming. In Japan, the target capacity for installed photovoltaic power systems (PV) in 2020 has been set to 28 GW, which is 20 times the 2005 capacity. The goal is to achieve a rate of zero-emission power source generated energy of over 50 percent of all generated energy, according to a long-term outlook in August 2009 for energy supply and demand.

Technical problems concerning power system stabilization were put together, a flow chart to create next-generation power transmission and distribution systems was developed, and the cost of stabilizing power systems was estimated when many PV would be grid-interconnected. The results showed three crucial issues for creating next-generation power transmission and distribution systems as follows: [1]

(a) Surplus power creation

Surplus power will be created because the summation of base supply power (summation of nuclear, hydraulic and thermal minimum power generation) and PV generation power will be larger than the demand during the off-peak term when grid-interconnection PV increases.

(b) Insufficient frequency control

PV generation power fluctuates largely due to irradiation fluctuation. Frequencies exceeding adequate values and an unstable power supply occurring when the short-term balance between supply and demand collapses is an issue.

(c) Voltage increases on distribution lines

PV output should be suppressed to sustain adequate voltage (within 101 ± 6V) when grid-interconnected PV are increased on distribution lines, even with sufficient irradiance.

Among these three problems, we selected voltage increases on distribution lines. Researchers have been trying to solve this problem, but issues still remain. Approaches to solving this problem should address both power systems and generation distribution. Solutions for power systems should be to install SVC or similar products on distribution lines to control the voltage within adequate values. Solutions for distributing the power generated should include controlling the voltage with voltage control systems of power conditioning systems (PCS) [2] such as reactive power control [3] and charging inverse power to batteries. For a typical example with batteries, a large-scale demonstrative research was conducted in Ota City, Japan with a NEDO project: “Demonstrative research on clustered PV systems.” [4] PV were installed in 553 residences and grid-interconnected to a single distribution line. In the research, simulation software was developed to analyze voltage increases when clustered PV are grid-interconnected. With this simulation software, increasing generation efficiency and economic efficiency were evaluated when batteries were installed for each residence. The PV output and load power, which were obtained for 553 residences for several years, were used for simulation.

From the previous fiscal year, the authors started to research improving generation efficiency at a site and balancing it among all the residences through voltage control, including PCS of a clustered residential grid-interconnected PV. For the subject we have already demonstrated that 25 percent of the output suppression loss was eliminated with reactive power control including PV voltage control when 225 residential PV were grid-interconnected to and balanced on a three-phase distribution line [5]. However, the efficiency was only certified for the defined simple distribution line structure.

In this paper, a complex single distribution line, where 2160 residential PV are grid-interconnected, is set. We develop appropriate voltage control for both simple and complex distribution lines.

2 SUMMARY OF SIMULATION

2.1 Factors of output suppression loss generation

The voltage on a distribution line increases due to inverse power from each residence when clustered PV are grid-interconnected to a single distribution line. The voltage will probably exceed the adequate voltage (101 ± 6V), which was established by the Electricity Business Act in Japan for when PV generates substantial energy and residences have little demand, especially on a holiday in spring or fall. PV must be sufficiently controllable to sustain adequate voltage in the worst case, in which PV output would be suppressed at some of the residences grid-interconnected to terminals of a distribution line as shown in Fig. 1.

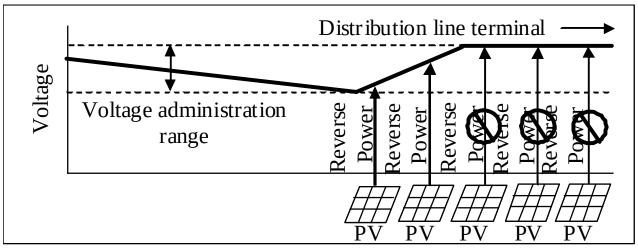


Figure 1: Output suppression

The basic method to calculate the voltage distribution on a distribution line is explained with the test circuit shown in Fig. 2. Four PV are grid-interconnected. The voltage at the terminal of the PV output is grid-interconnected to the terminal on a distribution line and calculated with Eq. 1.

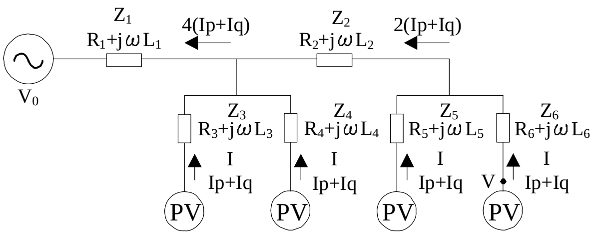


Figure 2: Circuit structure to calculate voltage distribution

$$V = V_0 + [4R_1 + 2R_2 + R_6 \quad j\omega \quad (4L_1 + 2L_2 + L_6)] \begin{bmatrix} I_p & jI_q \\ jI_q & I_p \end{bmatrix} \cdot \cdot \cdot (1)$$

Equation 1 shows that the voltage at the terminal of the PV output grid-interconnected to the terminal on a distribution line is calculated with three factors: impedance (Z_1, Z_2, Z_6), PV output (I) and sending voltage (V_0). In this case, current (I) from the four PV flows through Z_1; the value of Z_1 greatly influences the voltage increase.

2.2 Simulation parameter

2.2.1 Distribution line structure

(a) A simple distribution line structure

In the simple distribution line structure used for this simulation, 225 PV (75 PV in a single phase) were grid-interconnected to a single distribution line. The structure of the high voltage distribution line is shown in Fig. 3 and that of the low voltage distribution line in Fig. 4.

The pole transformers (Tr) were connected to divide the high voltage line into five equal lengths (Sec) of 2 km. The electric wire on the high voltage line was AL 120 mm^2, which was used in general distribution lines in the residential area. [6]

A pole transformer supplies fifteen residences in this low voltage structure. ALOC 120 mm^2 was used as low distribution line and SV 14 mm^2 as low voltage drop wire; the wire used from cabinet panel to PCS was CV 5.5 mm^2.

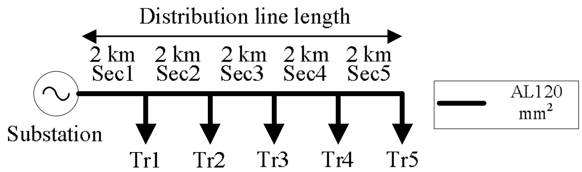


Figure 3: High-voltage distribution line structure

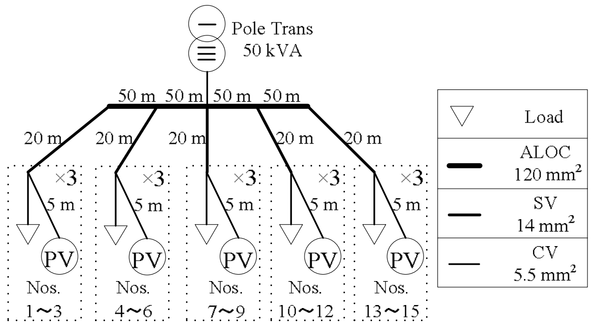


Figure 4: Low-voltage distribution line structure

(b) A complex distribution line structure

In the complex distribution line structure used for this simulation, 2160 PV (720 PV in a single phase) were grid-interconnected to a single distribution line. The structure of the high voltage distribution line, defined as a complex distribution line structure for residential areas, is shown in Fig. 5.

On the high-voltage distribution line, 48 pole transformers were grid-connected to a single phase and 10 three-phase balanced loads were grid-connected. The straight line length from substation to terminal was 3.26 km. The branch line length was 0.49 km.

The low-voltage line structure was the same as that on the simple distribution line structure.

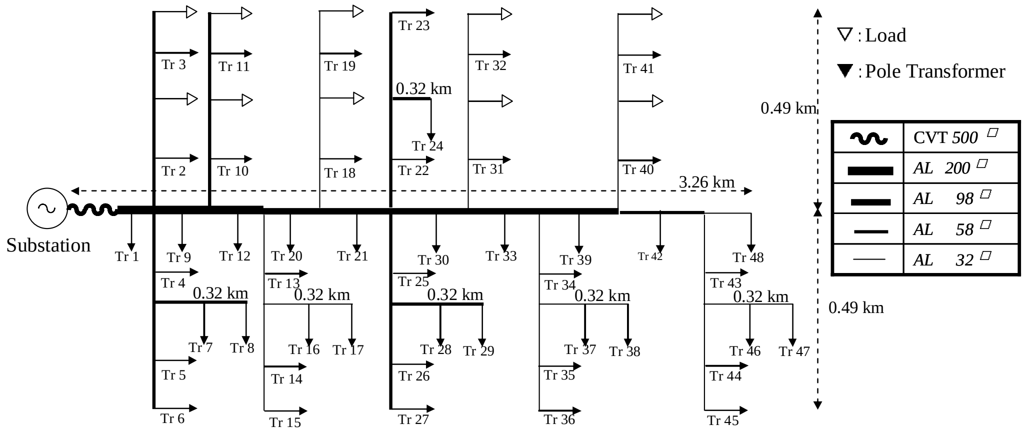


Figure 5: Complex distribution line

2.2.2 PV output and load power

The PV output and residential load power used for simulation were the average generation and load power. The simulation data were obtained at 553 residences in Ota City in Japan with a NEDO project: "Demonstrative research on clustered PV systems" [4]. April 29, 2007 was selected for typical data in the spring when PV generated substantial energy and residences consumed a limited portion. The PV output and load power for this date are shown in Fig. 6. The PV generated energy was 21.7 kWh; the electric energy consumed was 15.5 kWh.

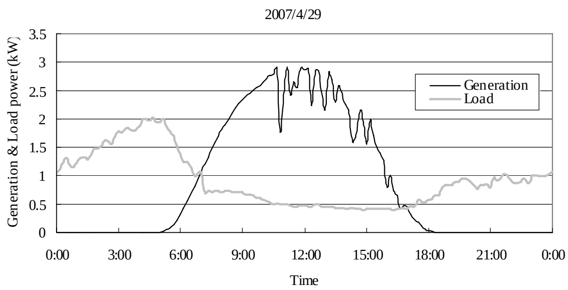


Figure 6: Generation and load power

The load power, which was consumed in a three-phase balanced load, was a constant 35 kW on a single phase from 8:00 to 17:00 and 10 kW before 8:00 and after 17:00. The consumed energy of 35 kW was energy for daytime operation. The consumed energy of 10 kW was standby energy.

2.2.3 Sending Voltage

In this research, sending voltage was fixed at a one time simulation from 6600 V to 6700 V to estimate the sending voltage, where output suppression loss on the simple distribution line structure was the same as on the complex line structure.

2.2.4 PCS Control

The basic control for the PCS model, which was developed to simulate the commercial PCS Control in the NEDO project, was revised and used in this research. The specifications to control reactive power and suppress the PV output are shown in Fig. 7, which shows the correlation between voltage and PCS output. The PCS controlled reactive power with reactive power control when voltage exceeded the reactive power control operating voltage. Active power was suppressed to adjust the apparent power to the previous active power. The PCS output was next suppressed by output suppression control when voltage was higher than the operating voltage output suppression control.

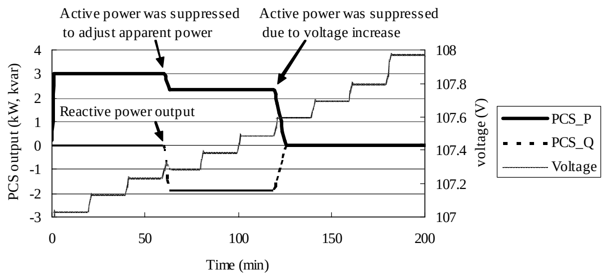


Figure 7: Correlation between voltage and PCS output

Standard operating and reset voltage are shown in Table 1. Setting phase factors are 100, 97.5, 95, 92.5, 90, 87.5 and 85 percent.

	Output suppression control	Reactive power control
Operating voltage	107.5 (V)	107.3 (V)
Reset voltage	107.3 (V)	107.1 (V)

Table 1: Standard voltage control specification in PCS

3 SIMULATION RESULTS

3.1 Influence of sending voltage upon PV generation rate

First, the influence of the sending voltage upon the PV generation rate, which was defined in Eq. 2, was estimated to search for the sending voltage of the complex distribution line. The PV generation rate was the same as for the simple distribution line structure. The results are shown in Fig. 8.

$$PV_{rate}(\%) = \frac{\sum_{n=1}^{N} P_{IDn} - \sum_{n=1}^{N} SUP_n}{\sum_{n=1}^{N} P_{IDn}} \times 100 \quad \cdot\cdot\cdot(2)$$

PV_{rate}: PV output rate
P_{IDn}: PV output at each residence without output suppression

loss due to voltage increase
SUP_n: Output suppression loss at each residence
N: Number of residences

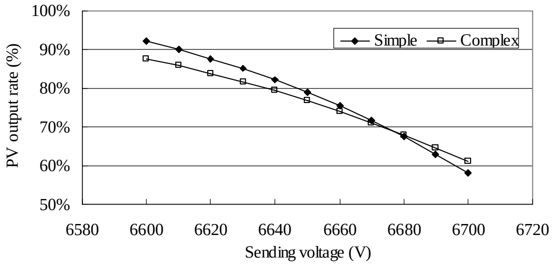


Figure 8: Correlation between sending voltage and PV output rate on the simple and complex distribution line structures

Sending voltages of 6660 V for the simple distribution line structure and 6655 V for the complex distribution line structure were selected. Because a PV generation rate of 75 percent on the simple distribution line structure with a sending voltage of 6660 V was the same as that on the complex distribution line structure with a sending voltage of 6655 V.

Output suppression loss distribution at each residence on the simple distribution line is shown in Fig. 9 and that on the complex distribution line in Fig. 10. Figures 9 and 10 show that output suppression loss at the high and low distribution line terminal residences was largest.

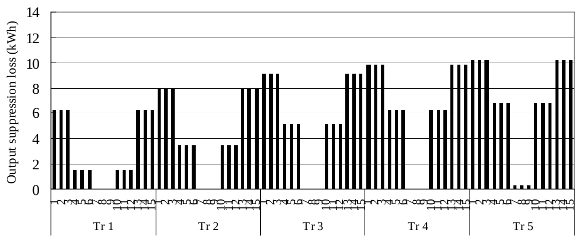


Figure 9: Output suppression loss distribution at each PCS on the simple distribution line

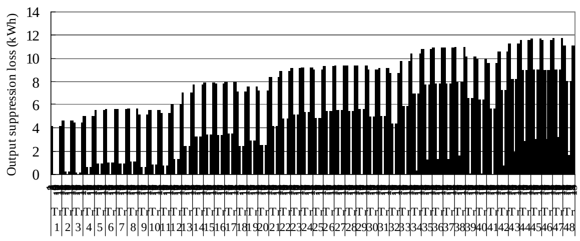


Figure 10: Output suppression loss distribution at each PCS on the complex distribution line

The output suppression loss at the residences near each transformer was much smaller than that at the terminal residences. Voltage increases at low voltage lines were large due to many (15) residences being connected to each transformer and the long low voltage distribution line (ALOC 120 mm^2). As a result output suppression loss fluctuated among all residences.

3.2 Evaluation of improved generation efficiency through residential PV normal reactive power control

The PV output rate on the simple and complex distribution line structures was calculated with residential PV reactive power control when all PCS operating and reset voltage was set at standard values. Reactive power control with the same operating and reset voltage among all residences was defined as normal reactive power control. The results in Fig. 11 show that the PV output rate exceeded 95 percent when the setting phase factor was less than 0.95. The rate was stable when the setting phase factor was between 0.925 and 0.85. The setting phase factor should be less than 0.925 to increase the PV output rate to the distribution line.

The PV output rate on the simple distribution line was the same as on the complex distribution line. The results show that the efficiency of residential PV reactive power control upon the PV output rate on the simple distribution line was the same as on the complex distribution line.

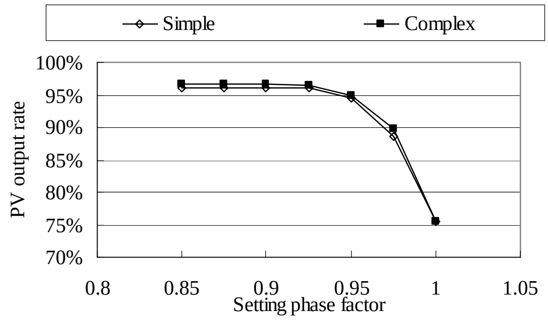


Figure 11: PV output rate with same operating and reset voltage at all PCS

Output suppression loss distribution at each PCS on the simple distribution line at the phase factor of 0.925 is shown in Fig. 12 and that on the complex distribution line in Fig. 13.

Normal reactive power control on both distribution lines clearly did not suppress output suppression loss fluctuation among all residences. Figures 14 and 15 show trend curves at the residences with the largest and smallest output suppression losses on the complex distribution line at the phase factor of 0.925. Reactive power output from 7:30 to 16:00 at the residence with the largest output suppression loss is due to voltage excess beyond reactive power operating voltage. However, at the same time reactive power was not output at the residence with the smallest output suppression loss due to lower voltage than reactive power control operating voltage. As shown in Fig. 7, active power was suppressed to adjust the apparent power to the active power without reactive power output when PCS controlled reactive power due to voltage excess beyond reactive power control operating voltage. So it is necessary to smooth reactive power among all residences in order to reduce output suppression fluctuation among all residences.

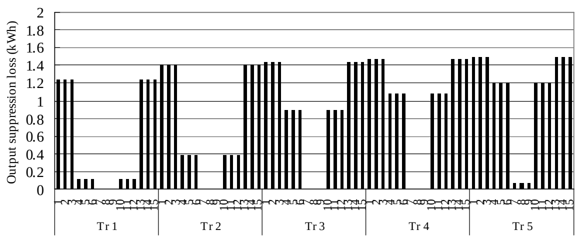


Figure 12: Output suppression loss distribution at each PCS on the simple distribution line at the phase factor of 0.925

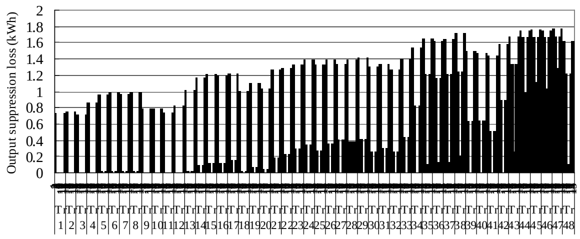
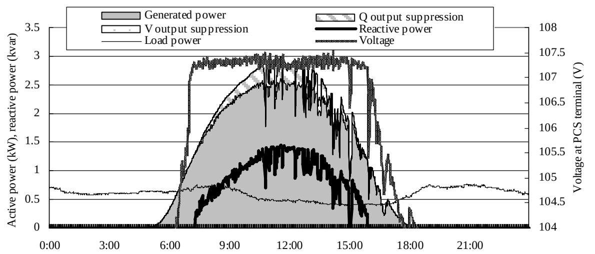


Figure 13: Output suppression loss distribution at each PCS on the complex distribution line at the phase factor of 0.925



Q output suppression: Output suppression loss due to reactive power output

V output suppression: Output suppression loss due to voltage increase

Figure 14: Trend curve at the residence with the largest output suppression loss on the complex distribution line at a phase factor of 0.9

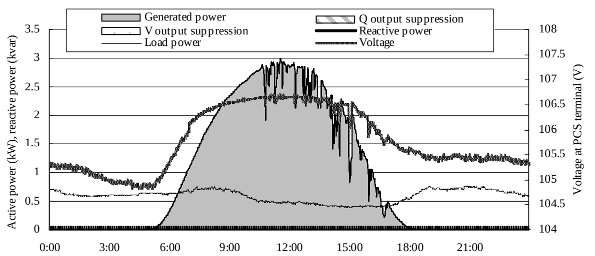


Figure 15: Trend curve at the residence with the smallest output suppression loss on the complex distribution line at the phase factor of 0.9

3.3 Efficiency of reducing the PV output rate fluctuation among all residences with advanced reactive power control

3.3.1 Calculation method of operating and reset voltage of advanced reactive power control

In this research, we explore using advanced reactive control to smooth reactive power. The operating voltage for advanced reactive power control was determined as follows:

1) Potential was measured at each PCS terminal with low sending voltage to avoid activating PCS control. Inverse power from all residences was between 100 W and 1000 W at intervals of 100 W.
2) The residence where voltage peaked among all residences was selected; the reactive power control operating voltage was set at 107.3 V.
3) The potential between each PCS terminal and maximum voltage was calculated; the reactive power control operating voltage was set by subtracting the potential from 107.3 V.
4) Reset voltage was set by subtracting 0.2 V from the operating voltage.

The maximum operating voltage at each pole transformer on the simple distribution line is shown in Fig. 16 and on the complex distribution line in Fig. 17.

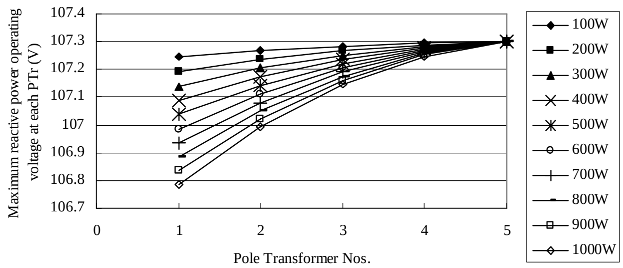


Figure 16: Maximum reactive power operating voltage at each PTr on the simple distribution line

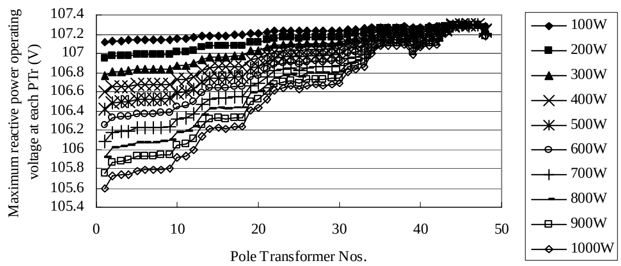


Figure 17: Maximum reactive power operating voltage at each PTr on the complex distribution line

3.3.2 Efficiency of reducing the output suppression loss fluctuation among all residences

In this section, the efficiency of reducing output suppression fluctuation among all residences by advanced reactive power control is evaluated. First, PV output rate was calculated with advanced reactive power control. PV output rate on the simple distribution line is shown in Fig. 18 and on the complex line in Fig. 19.

Figures 18 and 19 show that the PV output rate exceeded 95 percent when the setting phase factor was less than 0.95. The rate was stable when the setting phase factor was between 0.925 and 0.85. The PV output rate with inverse power of 500 W was same as with 0 W, which was defined as normal reactive power control.

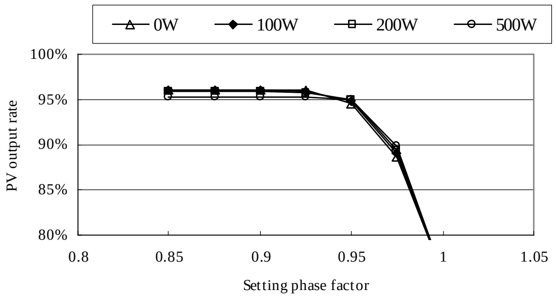


Figure 18: PV output rate on the simple distribution line structure with different operating and reset voltage at each PCS

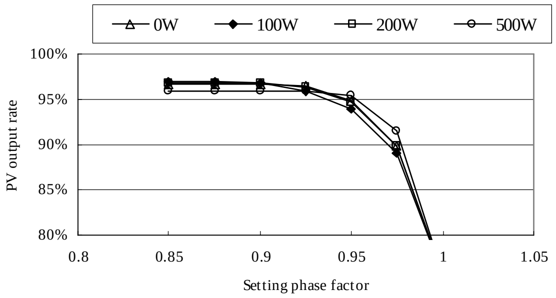


Figure 19: PV output rate on the complex distribution line structure with different operating and reset voltage at each PCS

Next, efficiency of reducing output suppression loss fluctuation among all residences with advanced reactive power control was evaluated with difference between maximum and minimum output suppression loss. It would be used for the evaluation because output suppression loss distribution among all residences did not show normal distribution.

The difference between maximum and minimum output suppression loss is shown in Fig. 20 for the simple distribution line and in Fig. 21 for the complex distribution line.

Fig. 20 shows that the output suppression loss fluctuation was smaller with the greater efficiency of advanced reactive power control. The difference between maximum and minimum output suppression loss with inverse power of 500 W and a setting phase factor of 0.925 was 0.9 kWh smaller than with the same operating and reset voltage at all PCS and a setting phase factor of 0.925.

However, Fig. 21 shows that the output suppression loss fluctuation with normal reactive power control was the same or smaller than that with advanced reactive power control when the setting phase factor was less than 0.9. Figures 22 and 23 show that the output suppression loss fluctuations with advanced reactive power control were improved more than those with normal control. (Figure 13 shows an example of normal control at the phase factor of 0.925.) However, reactive power was too large around some of the terminal residences on the high and low voltage distribution line at the phase factor of 0.9. The resulting reactive power output reduced the other residences to little voltage excess beyond reactive power control operating voltage by too great a reactive power at around some of the terminal residences on the high and low voltage distribution line. At the phase factor of 0.925, limitation of reactive power was appropriate for smoothing output suppression loss.

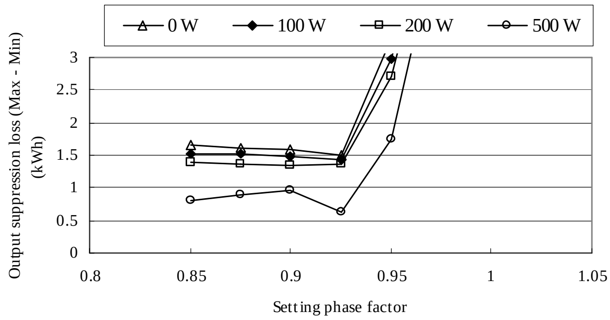


Figure 20: The difference between maximum and minimum output suppression loss on the simple distribution line

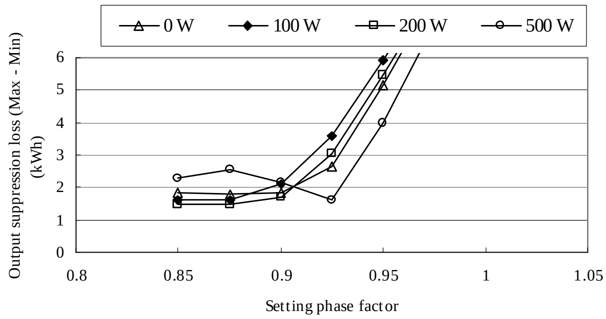


Figure 21: The difference between maximum and minimum output suppression loss on the complex distribution line

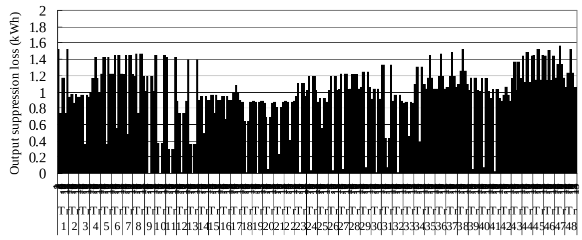


Figure 22: Output suppression loss distribution on the simple distribution line at the phase factor of 0.925 and at inverse power of 500 W

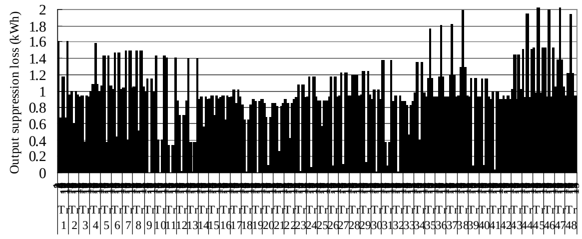


Figure 23: Output suppression loss distribution on the complex distribution line at the phase factor of 0.9 and at inverse power of 500 W

The results above show that advanced reactive power control was effective to smooth output suppression loss fluctuation without reducing the PV output rate on simple and complex distribution lines. Advanced reactive power control may become the general measure for smoothing output suppression loss fluctuation. However, advanced reactive power control might be improved to smooth output suppression loss more as follows:

1) The limits of reactive power output should be decreased at residences where reactive power output is too great.

2) Reactive power control operating voltage should be decreased at the residences where reactive power cannot be output.

4 CONCLUSION

This paper discussed a distribution line with clustered grid-interconnected PV that was made to examine the problem of voltage increases on distribution lines in order to develop next-generation power transmission and distribution systems. The influence of the distribution line structure on output suppression loss was analyzed using simulation.

First, we searched for the sending voltage of the complex distribution line, on which the PV generation rate was the same as the simple distribution line structure. The PV generation rate was 75 percent when the sending voltage was 6660 V on the simple distribution line structure and 6655 V on the complex distribution line structure. Both sending voltages were used following their evaluation.

Next, the PV output rate was calculated with normal reactive power control at all residences. The PV output rate exceeded 95 percent when the setting phase factor was less than 0.95; the rate was stable when the setting phase factor was between 0.925 and 0.85. The efficiency of residential PV reactive power control upon the PV output rate on the complex distribution line was the same as on the simple distribution line.

Finally, the efficiency of smoothing the output suppression loss fluctuation among all residences with advanced reactive power control was evaluated. The operating and reset voltage were set at the potential of every residence, which was calculated with low sending voltage not to generate output suppression loss and with inverse power between 100 W and 1000 W at intervals of 100 W.

The PV output rate was calculated with advanced reactive power control. The PV output rate with advanced reactive power control was almost the same with normal reactive power control on the simple and complex distribution lines.

The output suppression loss fluctuation was smaller with advanced reactive power control on the simple distribution line. The difference between maximum and minimum output suppression loss with inverse power of 500 W and the setting phase factor of 0.925 was 0.9 kWh smaller than with the normal reactive power control and the setting phase factor of 0.925.

The output suppression loss fluctuation with the normal reactive power control was almost the same or smaller than with the advanced reactive power control when the setting phase factor was less than 0.9 on the complex distribution line. However, output suppression loss distribution on the complex distribution line show that with advanced reactive power control was improved more smoothly than with normal reactive power control excluding too much reactive power output at some of around the terminal residences.

Advanced reactive power control could become the standard control for smoothing output suppression loss fluctuation. However, improving it could smooth output suppression loss more, so case studies need to be conducted to establish the most appropriate reactive power control.

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