# Avoided Cost and Effects of Voltage Control by Demand Response in a Distribution Network with High Integration of Rooftop PV

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***Abstract*— The capacity of installed photovoltaic (PV) generation in Japan has been expanding rapidly due to the governmental subsidy and feed-in tariff programs and then it has reached to 3.62 million kW as of 2010. This rapid increase in PV installation drives utilities to problems on how to operate stably the electric power systems. Therefore, electric power companies have to invest heavily in the systems. Our concern is to consider the possibility of implementing a demand response (DR) program as an alternative measure to the conventional power supply investment. This paper shows new findings from our simulations of voltage control by DR in distribution systems with high integration of rooftop PV. By our simulations based on the realistic input data, we clarified the economical efficiency of implementing the DR program as an alternative measure to the conventional investment in power supply against the voltage rise problem in distribution systems with PV.**

***Index Terms*—Demand response, Distribution system, Economical efficiency, Photovoltaic generation, Voltage rise problem**

## I. Introduction

The capacity of installed photovoltaic (PV) generation in Japan has been expanding due to the governmental subsidy and then it has reached to 3.6 million kW as of 2010, which is the world's 3rd largest capacity. In addition, it is expected that the capacity of PV will increase sharply in the future because a new feed-in tariff (FIT) program was started in July, 2012. However, the rapid increase in PV installation drives electric utilities to various problems on how to operate the electric power systems stably. Especially, many PV systems have been introduced onto the roofs of residences in Japan and then the reverse power flow from PVs has already been brought about the voltage rise problem in distribution systems. By a Japanese law, the customer voltage must be maintained within a range of 95 V to 107 V, but in actuality the voltage exceeds 107 V due to the reverse power flow from PVs (Fig.1). Therefore, electric utilities have to invest heavily in distribution systems, such as installing voltage regulators, in order to maintain an adequate voltage level.

On the other hand, the problem of power supply shortage has arisen after the Great East Japan Earthquake which occurred in March, 2011. Under this influence, the attention to a Demand Response (DR) program has been increasing gradually in Japan recently. The demonstration experiments using the DR program as a measure for controlling electricity demands are carried out in various parts of Japan. In addition to controlling electricity demands by DR, we are researching the possibility of a new DR program which may be materialized in Japan. This time we paid attention to the possibility of implementing the new DR program as an alternative measure to the conventional power supply investment against the voltage rise problem. This paper shows new findings from our simulations on the economy of voltage control by DR in distribution systems with high PV penetration.

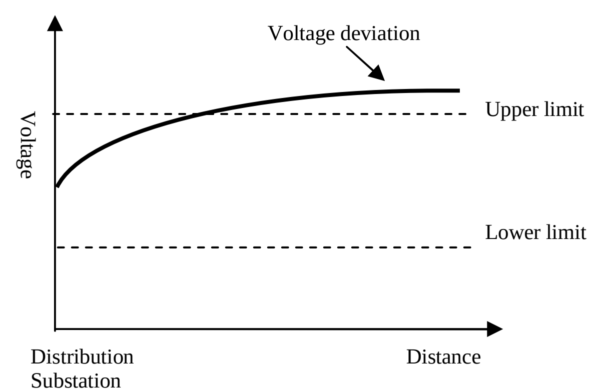


Fig.1 Voltage rise problem in a distribution line

## II. The Target of Simulations

By introducing DR as a new solution of the voltage rise problem in a distribution system, a large sum of the conventional power supply investment may be avoided and we may be able to find a more economical measure. Therefore, we simulated based on actual measured data of over 500 residential loads and solar power output in Japan and had a quantitative understanding of the DR installation. Then we aimed at clarifying economical efficiency in the case of implementing DR as an alternative measure to the conventional power supply investment. To be concrete, we grasped how long in days and time DR must be put into motion and the amount of reverse power flow which must be reduced by DR when we install DR against voltage rise problems. Moreover, we clarified the expense which can be invested in DR and the cost which can be avoided by implementing DR as the alternative measure to the conventional power supply investment. We also analyzed changes of the DR effect by the arrangement of residences and PVs in a distribution system.

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## III. THE METHOD OF SIMULATIONS

We set up a distribution system model with difficult voltage management, and simulated the fluctuations of voltage in the distribution system model over one year (Fig.2, Table I). In the simulations, the PV penetration rate was 10% - 30%. The rate shows the number of PV holders to the total number of residences connected to the distribution system model. [1][2]

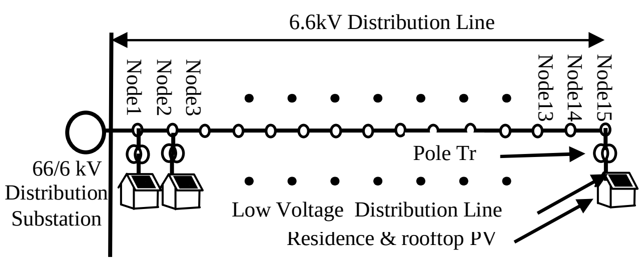


Fig.2 Distribution System Model

TABLE I Conditions of the Distribution System Model

| Item | Setting Value |
|---|---|
| Length of 6.6 kV distribution line | 3.7 km |
| The number of Pole Tr | 150 |
| The number of residences | 2250 |
| Load peak | 3.9 MW |
| Installed capacity of PV | 3.9 kW per unit |

We set up two cases based on the arrangement of residences and PVs (Fig.3). Case 1 is a precondition that they are arranged equally at the whole distribution line. Case 2 is a precondition that they exist only in the second half of the distribution line, and are arranged equally in that area. The data used for simulations is based on the actual measurement of the loads and rooftop PVs of over 500 residences acquired by the demonstrations of New Energy and Industrial Technology Department Organization in 2007 [3]. Based on such conditions, we simulated the degree of the voltage fluctuations every 30 minutes over one year. Based on the simulation results, we investigated the number of days and time DR must be put into motion and the amount of reverse power flow which must be reduced by DR when we installed DR against voltage rise problems. On the other hand, we simulated the conventional power supply investment which is needed under the same conditions as the DR installation and calculated the costs of the conventional power supply investment. Thus, we compared the DR effects by the arrangement of residences and PVs based on the results of case 1 and case 2. Also, the simulations clarified the expense which can be invested in DR and the cost which can be avoided by implementing DR as an alternative measure to the conventional power supply investment.

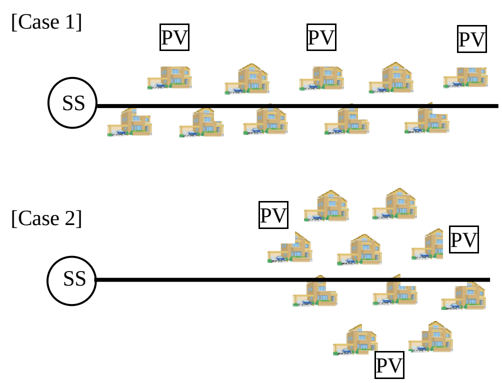


Fig.3 Arrangement of Residences and PVs
in case 1 and case 2

## IV. THE RESULTS OF SIMULATIONS

First, a simulation result showed the voltage rise problem did not occur over one year in the distribution system model with the PV penetration rate of less than 20%. The reverse power flow was brought in the case of 20%, but electric utilities could maintain a proper voltage by operating their distribution systems accurately. However, the amount of reverse power flow in the case of 30% increased and electric utilities could not maintain a proper voltage (Table II). Then, they will be required to invest heavily against voltage rise problems. Therefore, we simulated in detail the case of PV penetration of 30% and obtained new knowledge. We will report our various findings as follows.

- Fluctuations of voltage in case 1
- Fluctuations of voltage in case 2
- Conditions required when the DR is installed in case 1
- Conditions required when the DR is installed in case 2

TABLE II Necessity of the measure against voltage problem in case 1

| PV penetration rate | 10% | 20% | 30% |
|---|---|---|---|
| Availability of reverse power flow | Non-existence | Existence | |
| Maintenance of proper voltage | O | O | X |
| Necessity of the measure against voltage problem | Unnecessary | | Necessary |

### A. *Fluctuations of voltage in case 1*

We describe the simulation results of case1 which the residences and PVs are arranged equally at the whole distribution line. Fig.4 shows the simulation result of the voltage fluctuation every 30 minutes of the day which voltage deviation was the largest over a year. The vertical line of Fig.4 shows voltage values of each node, that is, each position of the pole transformers installed between the high-tension distribution line and the low-tension distribution line. In addition, the pole transformers from node 1 to node 9 change 6750 V into 105 V and the pole transformers to node 15 change 6600 V into 105 V. Fig.5 shows the time course of the voltage in each node and the voltage over the upper limit of proper voltage between 9:00 and 13:30 in the area after node 9. The voltage exceeds the upper limit most greatly by 0.6 V at 10:00. The upper limit and lower limit in Fig.5 mean the limits of voltage in the pole transformer points.

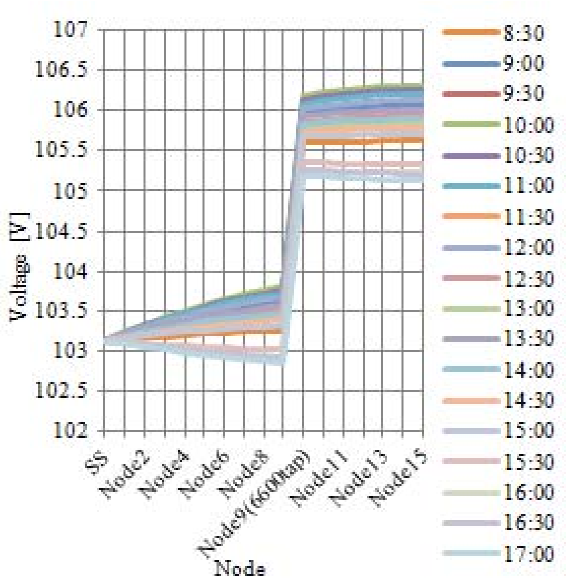


Fig.4 A simulation result of voltage fluctuation in case1

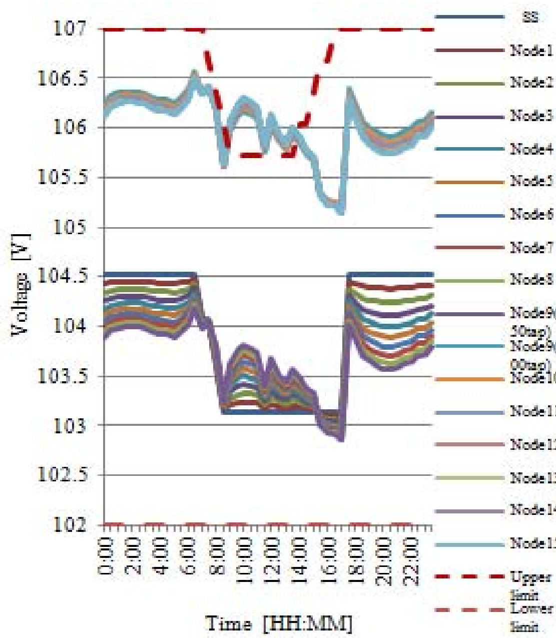


Fig.5 The time transition of each node voltage in case1

### B. *Fluctuations of voltage in case 2*

We describe the simulation results of case2. Case 2 is a precondition that the residences and PVs exist only in the second half of the distribution line. The pole transformers from node 1 to node 5 change 6750 V into 105 V and the pole transformers to node 15 change 6600 V into 105V. Other conditions are the same as that of case 1. Fig.6 and Fig.7 show the simulation results of the voltage fluctuation every 30 minutes of the day which voltage deviation was the largest over a year. The voltage is over the upper limit of proper voltage between 9:00 and 14:00. The voltage deviation occurs in the area after node 5. The voltage exceeds the upper limit by 1.0 V at 10:00. The upper limit and lower limit in Fig.7 mean the limits of voltage in the pole transformer points.

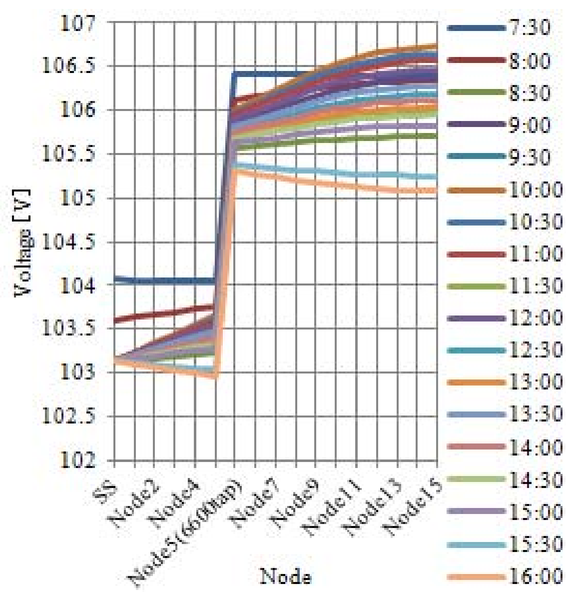


Fig.6 A simulation result of voltage fluctuation in case2

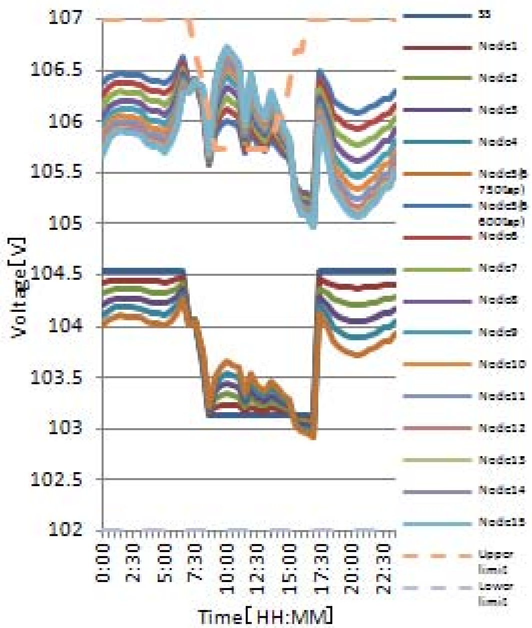


Fig.7 The time transition of each node voltage in case2

### C. *Conditions recquired when the DR is installed in case 1*

We found that we needed to carry out the following DR when we implement the new DR program as an alternative measure to the conventional power supply investment against the voltage rise problem in case 1 (Table III, Table IV).

- The number of days by which DR should be exercised is 23 days a year.
- The total number of hours by which DR should be exercised is 55 hours a year.
- The time zone for which DR is especially needed is between around 11:30 and 12:00.
- The amount of reverse power flow which must be reduced by DR is about 16,000 kWh per year, which is about 2 % of the annual amount of reverse power flow.

### D. *Conditions recquired when the DR is installed in case 2*

Similarly, we found that we needed to carry out the following DR in case 2.

- The number of days by which DR should be exercised is 50 days a year.
- The total number of hours by which DR should be exercised is 151 hours a year.
- The time zone for which DR is especially needed is between around 11:00 and 12:00.
- The amount of reverse power flow which must be reduced by DR is about 42,000 kWh per year, which is about 6 % of the annual amount of reverse power flow.

According to the simulation results, in case 2, the days which need DR are more than twice the days as in case 1 and the amount of reverse power flow which must be reduced by DR is also about three times of that in the case 1. It was shown clearly that the frequency of DR in case 1 was lower than that in case 2. We found that a burden of DR in case 1 was smaller.

TABLE III The number of days and hours by DR

| PV penetration rate of 30% | Case 1 | Case 2 |
|---|---|---|
| The number of days by DR (a) | 23 days | 50 days |
| The total number of hours by DR (b) | 55 hours | 151 hours |
| b/a | 2.4 hours per day | 3.0 hours per day |

TABLE IV The reverse power flow which must be reduced by DR

| The reverse power flow reduced by DR [kWh] | Case 1 | | Case 2 | |
|---|---|---|---|---|
| | kWh | Percent of total | kWh | Percent of total |
| 9:00 | 297 | 2% | 490 | 1% |
| 9:30 | 826 | 5% | 1321 | 3% |
| 10:00 | 1542 | 9% | 3062 | 7% |
| 10:30 | 2092 | 13% | 5485 | 13% |
| 11:00 | 2186 | 13% | 5989 | 14% |
| 11:30 | 2313 | 14% | 6617 | 16% |
| 12:00 | 2265 | 14% | 6097 | 14% |
| 12:30 | 1942 | 12% | 5411 | 13% |
| 13:00 | 1553 | 10% | 4253 | 10% |
| 13:30 | 1273 | 8% | 3002 | 7% |
| 14:00 | - | - | 313 | 1% |
| 14:30 | - | - | 18 | 0.04% |
| Total | 16291 | 100% | 42058 | 100% |
| Ratio to the annual amount of reverse power flow | 2 % | - | 6 % | - |

Even if it is a day which deviates from proper voltage most, voltage is always maintained properly by introducing DR in case 1 (Fig.8). Also, the same can be said of case 2 (Fig.9).

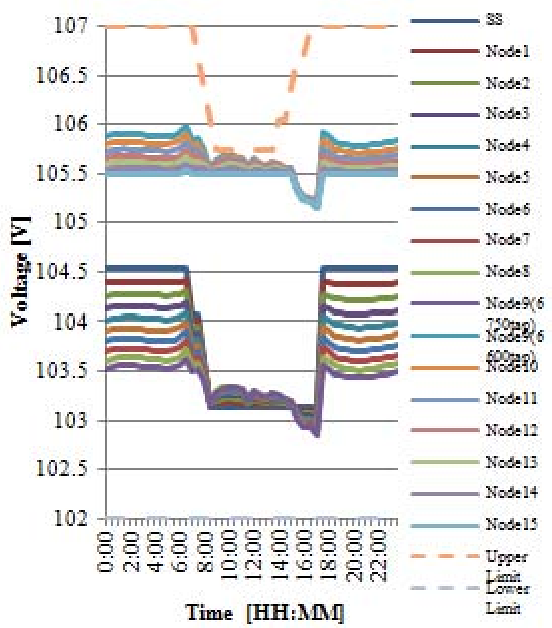


Fig.8 A simulation result of voltage fluctuation with DR in case1

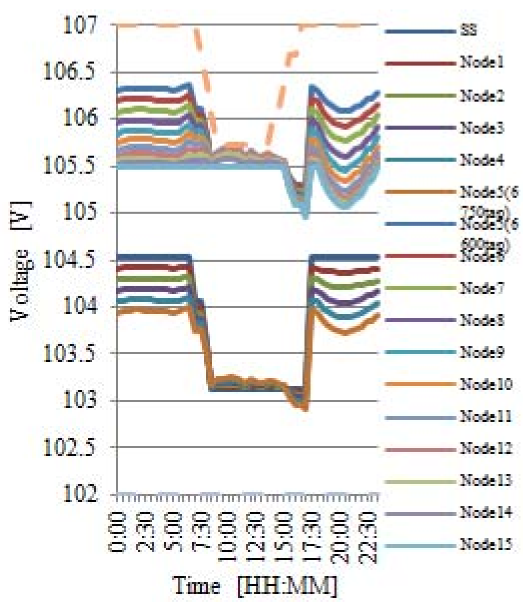


Fig.9 A simulation result of voltage fluctuation with DR in case2

## V. THE COST WHICH CAN BE AVOIDED BY DR

By implementing DR as an alternative measure to the conventional power supply investment, we can avoid the conventional investment in distribution systems, such as installing voltage regulators. Then, we clarified the avoided costs based on our simulation results. Table V shows the avoided cost by implementing DR. The avoided cost in case 1 is about 1.6 million yen per year and that of case 2 is about 3 million yen per year.

TABLE V Avoided cost by DR

| PV penetration rate of 30% | Case 1 | Case 2 |
|---|---|---|
| Avoided cost [million yen per year] | 1.6 | 3.2 |

## VI. THE EXPENSE WHICH CAN BE INVESTED IN DR

When we introduce DR as a new solution to the voltage rise problem in a distribution system, we computed the expense which can be invested. Then, we compared the expense of case 1 and case 2 based on the mentioned amount of reverse power flow which must be reduced and the cost which can be avoided by DR. As a result, the expense of case1 is higher than that of case2. That means the investment effect of case 1 by DR is higher than that of case 2 (Fig.10).

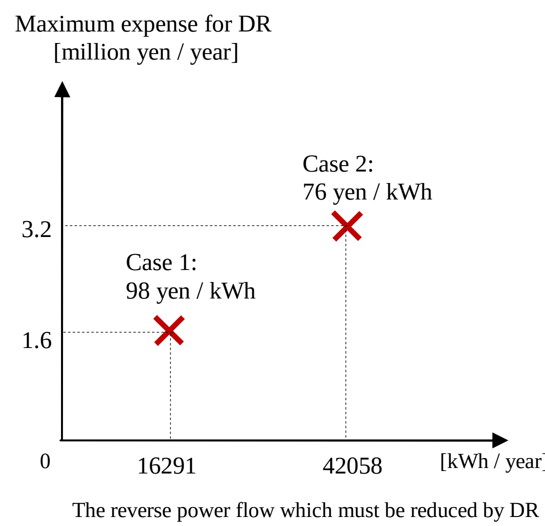


Fig.10 Maximum expense for DR

## VII. CONCLUSION

We investigated the economical efficiency on the possibility of implementing the new DR against the voltage rise problem in the distribution systems with high integration of rooftop PVs. We were able to acquire various new findings based on our simulation results. We got the number of days and the total number of hours by which DR should be exercised in the distribution system model with the PVs' penetration rate of 30%. Also, we clarified the amount of reverse power flow which must be reduced by DR. We obtained knowledge of the cost which can be avoided by DR and the expense which can be invested in DR, too. Furthermore, we could find out that it is higher for the economic effect to apply the DR program to the distribution line of case 1 rather than the distribution line of case 2. These new findings acquired by our simulation results are greatly useful when the electric utilities choose the more economical measure against the voltage rise problem in the distribution systems.

## ACKNOWLEDGMENT

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