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Study on Voltage Control of Distribution Network Using PV Generation Forecasting

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Abstract. With the expected spread of photovoltaic (PV) systems, high power generation in spring and summer is expected to cause abnormally high voltage in distribution systems. As described in herein, we propose a method to improve the utilization efficiency of a small-scale PV generator connected to a distribution system by short-term (30 min) forecasting of solar power generation output in a small area of a few kilometers. As a countermeasure against abnormally high voltage, a method exists to adjust the voltage by switching a tap of the substation transformer. However, the switching frequency of the tap with mechanical contact is limited to once or twice per hour. Under these conditions, if short-term forecasting of solar power generation were possible, then tap changing of a substation transformer efficiently could maintain voltage within an appropriate range, which enables effective use of solar power. This paper is organized as follows. After a short-term forecast method of solar power is proposed. The method of adjusting the sending end voltage of a distribution substation based on the PV output forecast data is proposed. Finally, reduction of the PV disconnection frequency is verified numerically.

Key words

forecast, disconnection, distribution line, smoothing effect.

1. Introduction

Solar power generating systems provide renewable energy, but they have the shortcoming of providing little power generation per unit of area. In Japan, because of a nuclear accident caused by the 2011 earthquake and tsunami, interest in renewable energy is increasing, especially in photovoltaic (PV) power generation. However, Japan has few flat areas. The spread of so-called mega-solar projects is constrained by the scarcity of useful land.

Generally, PV arrays installed on residential rooftops are of small scale, less than 10 kW, but most are about 3-5 kW. The daily electricity usage of a typical Japanese house is 20-25 kWh, depending on the roof size, the electricity demand during the day, the installation cost, etc. Surplus electricity generated during the day can be sold through PCS and the distribution grid, but these arrays are not intended to provide electricity to a wide area administered by electric power companies. Still the arrays can assist in augmenting the electricity supply to residential areas. In Japan, for reasons of network protection, distribution lines from the substation are connected radially: surplus power must be consumed within the same power distribution line.

For these reasons, the power generated in the distribution system is assumed to be consumed within the distribution system. However, considering the characteristic that PV power generation fluctuates even during the day and does not generate electricity at night, the power supply from the power utility remains indispensable.Although the use of a power storage device (storage battery, etc.) is effective [1], at present, it is not popular in terms of price, installation location, safety assurance, etc.

Generally in Japan, three-phase 6,600 V is supplied to each node over lines extending several kilometers. Voltage is changed to 202 ± 20 V and 101 ± 6 V by pole transformers. The voltage on the distribution line must be adjusted in consideration of the whole voltage balance because of the electric resistance of the distribution line. Because of such circumstances, changes in system power demand and changes in PV generation tend to cause large changes in voltage, particularly at the ends of distribution lines.

On rainy or cloudy days, the distribution system receives most of the demanded electricity from electric power companies. In such situations, if the PV-generated power increases rapidly, the voltage rises, causing a risk of deviating from the specified value. As a countermeasure, a Power Conditioning System (PCS) temporarily reduces the output power or disconnects it using a voltage monitoring function, thereby keeping the voltage within the specified value. As a result, solar power is used ineffectively.

Over the long term, a pole transformer tap can adjust the voltage. In the short term, it can be adjusted by switching a tap of the substation transformer. However, the PV power is affected strongly by the weather: the generated power changes drastically within several minutes. Therefore, the mechanical tap change method cannot be used. The system is forced to disconnect the PV system.

Conventional solar radiation forecasting is often used as a method for power utilities to obtain maximum electric power and maximum profit in operations using large-scale photovoltaic power generation [2]–[15]. In the case of so-called mega-solar and large-scale PV systems, the effects of local cloud motion can be reduced by smoothing [16]–[20]. Forecasting information is effective for methods using wide area weather forecasting or meteorological satellites. However, they have remained unsuitable for application to distribution systems in the range of several kilometers. Adjustment of the feed voltage from the substation could be run efficiently, and the probability of PV disconnection could be reduced, if PV power generation forecasting of several tens of minutes ahead were possible.

This paper proposes a short-term forecasting method, describes application of the forecasted results to a distribution system, and presents verification of the results.

2. Forecasting Method of Solar Irradiation and PV Generation

PV generation forecasting methods have been variously proposed. This study examines stabilization of a distribution system's voltage to increase PV power generation efficiency. To do so, it is necessary to forecast the temporal change of solar irradiance value and PV power generation value in a target area. The length of one power distribution system is several kilometers. The switching frequency of the tap of a substation is about once or twice per hour.

The conditions necessary for forecast in this study are as follows.
<Condition 1> The target area is narrow.
<Condition 2> The forecasted time is short.
<Condition 3> The forecasted data must be sufficient to calculate the PV generation value [21]

Forecasting methods proposed in earlier reports use a numerical weather model for weather forecasting, meteorological observation data applied for solar radiation forecasting, solar radiation forecasting using cloud image data observed from the ground, and solar radiation forecasting using satellite images [22]-[24], or a combination of these methods.

The method using a numerical model for weather and the method using satellite images are useful for wide areas, with forecasted time as long as several hours to several days. Cloud images observed from the ground are useful for a radius several kilometers, with forecasting time of several minutes to about 15 min. The method is useful for forecasting on a local system scale. However, special equipment installation and image processing are required.

PV generation forecasting methods have been variously proposed. Our study applies a method using the amount of PV generation or solar irradiance in a nearby area. The solar radiation intensities of the near multipoint distribution system are measured. Then short-term forecasts are made through inference from correlation. A strong positive correlation is known to exist between solar irradiance and PV generation. The solar radiation intensity depends on weather conditions at each point. Solar radiation intensity is greatly affected by cloud movement. In general, clouds move while changing shape. Therefore, time-series data at each observation point tend to present mutually similar waveforms at different times. By analyzing nearby solar radiation irradiance information and considering of movement speed and direction of clouds, one can forecast the short-term solar radiation intensity of a given location.

Smart meter systems, which automatically collect grid data, are becoming more common with automated meter reading systems, and are expected to become increasingly popular. In this study, PV power generation data of five measurement points were used as presented in Fig. 1. Fig. 2 shows the measurement equipment using PV.

As shown in Fig. 3, to approximate the solar radiation irradiance at two points, a cut-out of the time series data in the time zone window is done first. Then, correlation coefficients of other time-series data are calculated while moving the time axis of the series data [25].

By determining the time difference at which the correlation is the strongest, the cloud movement time can be estimated. From movement of the clouds measured at multiple points, the moving directions and moving distance are estimated. Then the time series of solar radiation intensity at the forecasting point can be estimated. Because the major cause of solar radiation irradiance can be assumed to be cloud influence, the amount of power generation at the windward point from the forecast point appears after some time lag. This time lag represents moving time of clouds.

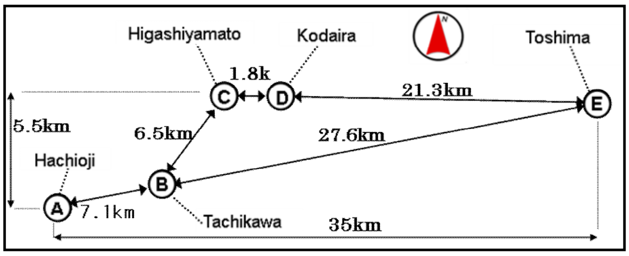


Fig. 1. Location of measuring point (Tokyo, Japan).

Fig. 2. Measurement Equipment using PV.

Correlation coefficients of solar radiation irradiance obtained from multiple points includes cloud movement information. Furthermore, it is possible to forecast solar irradiance time series data using distance data between the forecast point and measured points using the following method. Solar irradiance of the forecast point is determined using equation (1). This equation uses the weighting factor on the windward data to move the time axis. The result is determined by adding them together. With movement of the time axis, using the time lag obtained using the method described previously, the weighting coefficients are determined as a function of the distance to be closer to the destination point. Fig. 4 shows the result of forecast using data of two points.

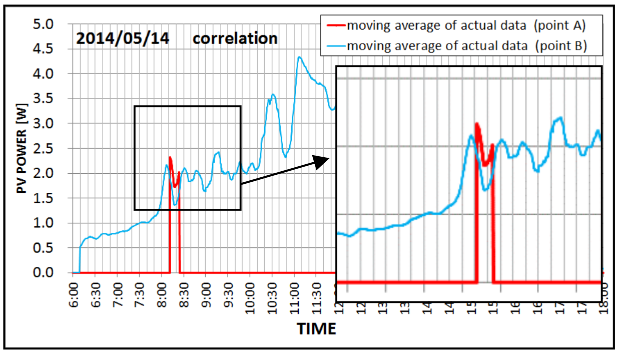
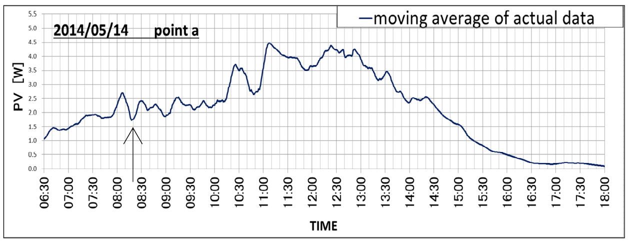
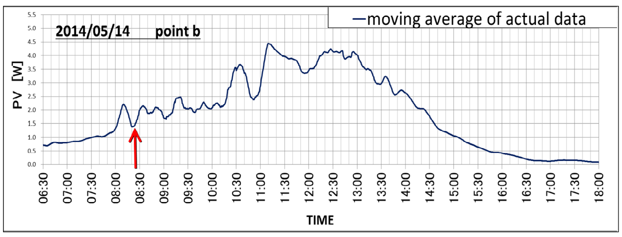


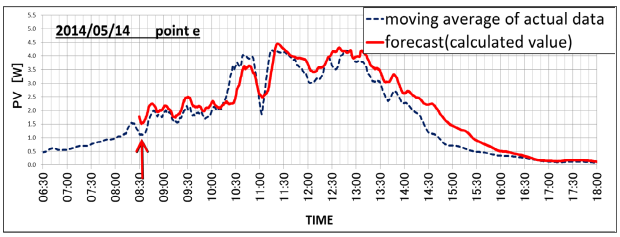
Fig. 3. Comparison of Two Point Data.



(a) Power Generation of PV at point A



(b) Power Generation of PV at point B



(c) Power Generation of PV at point E
(actual data and forecasted data)

Fig. 4. Forecast of Power generation using two point data.

$$P_E(t) = K_A P_A(t + \tau_{AE}) + K_B P_B(t + \tau_{BE}) \quad (1)$$

$P_E(t)$: Amount of power generated at the forecast point E
K_A, K_B: weighting factor at points A, B

τ_{AE}, τ_{BE}: time lag between forecast point E and point A or B
$P_A(t)$: power generation at time t at Point A
$P_B(t)$: power generation at time t at Point B

Using the same method, Fig. 5 is the result of forecast using data of four points by equation (2).

$$P_E(t) = K_A P_A(t + \tau_{AE}) + K_B P_B(t + \tau_{BE}) + K_C P_C(t + \tau_{CE}) + K_D P_D(t + \tau_{DE}) \quad (2)$$

In that equation, the following variables are used.

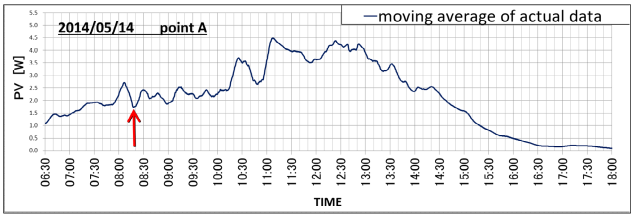
K_A, K_B, K_C, K_D: weighting factor at point A, B, C, D
τ_{AE}, τ_{BE}, τ_{CE}, τ_{DE}: time lag between the forecast point E and point A, B, C, or D

where $K_A + K_B + K_C + K_D = 1$

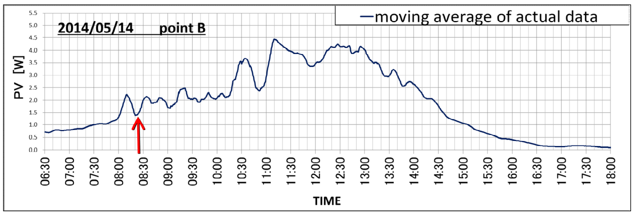
$P_A(t)$: power generation at time t at Point A
$P_B(t)$: power generation at time t at Point B
$P_C(t)$: power generation at time t at Point C
$P_D(t)$: power generation at time t at Point D

Fig. 6 shows the error rate between the actual value and the forecasted value in two ways. In this example, in the time lag calculation, the sudden drop at 8:30 occurs only once. The same parameters are used continuously for the afternoon forecasting calculation. However, if the sequential time lag calculation is performed, the accuracy is improved.

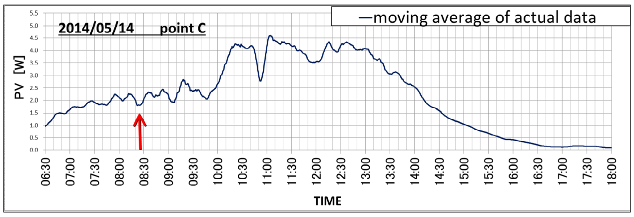
As presented in Fig. 1, the arrangement on the map is not strictly straight, but forecasting is made using weighting coefficients according to each distance. As shown in Table 1, the four-point method provides high accuracy. However, the time margin from the forecast completed to the actual time is small.



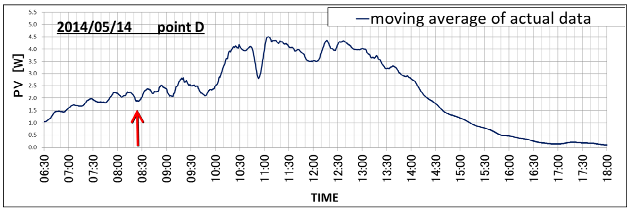
(a) Power Generation of PV at point A



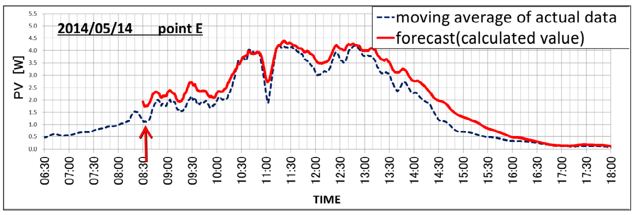
(a) Power Generation of PV at point B



(c) Power Generation of PV at point C



(d) Power Generation of PV at point D



(e) Power Generation of PV at point E
(actual data and forecasted data)

Fig. 5. Forecast of Power generation using four point data.

Fig. 6. Error Rate.

3. Application for Voltage Assessment of Distribution Network

A. Simulation

The resulting solar radiation forecast data are applied to voltage control of a distribution network [26]. For this study, five nodes are placed in the distribution system. Then voltage analysis by simulating the power distribution line is performed based on demand and PV generation. Generally in Japan, three-phase 6,600 V is supplied to each node over lines extending several kilometers. The voltage is changed to 200 V / 100 V by pole transformers. The simulation model has a distribution line with total length of 5 km. It is assumed that each of the five nodes supplies customers with up to 600 kW and that each is connected to PV rated as 400 kW. For the PV output at each node and for sending end voltage at the substation, a power flow calculation is performed at a fixed time interval. The sending end voltage at the substation is increased or decreased according to the power supplied from the substation. Furthermore, PV output forecast values are also considered in calculations. In Japan, voltage must be maintained within the range of 95-107 V by law. Each node voltage of the distribution line is calculated for the time intervals based on sending end voltage conditions. Fig. 7 shows the model used for the simulation. Table 2 presents conditions of the simulation.

Table 1. RMSE and Time Margin of Forecasting

Number of measuring points	Root Mean Squared Error (RMSE)	Time margin
Two points	13.20	15 min
Four points	11.63	9 min

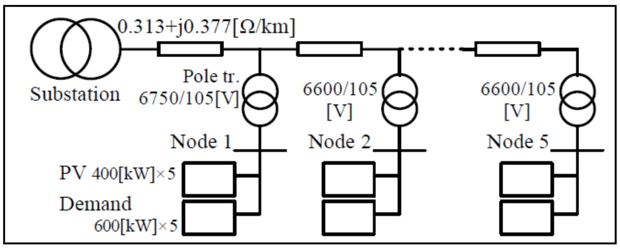


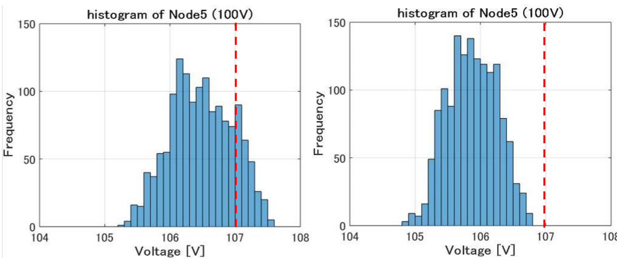
Fig. 7. Simulation Model for Distribution Network.

Table 2. Simulation Conditions

Number of nodes	5
Demand power	600 kW/node (fixed value)
PV generation	400 kW/node (time series value)
Time zone for simulation	6 hr (9:00–15:00, every 10 s)
Input data (PV)	2160 values/node
Input data (demand)	2160 values/node (fixed value)
Substation output voltage	6550, 6500, 6450, 6400, 6350, 6300, 6250, 6200 [V]
Output data	2160 values (voltage value of 100 V line)

B. Numerical Results

Forecast results are used to assess voltage at five nodes. After fixing the sending end voltage based on the power supplied by the substation transformer, many time series of PV output data are prepared. These time series data correspond to the PV output forecast. Although the PV output varies, the sending end voltage is fixed, so voltage deviation from the permissible range might occur. For simplicity, the PV output forecast is assumed here to be accurate. Fig. 8 presents an application example for May 8, 2014, representing the voltage at Node 5. For comparison, a fixed voltage case irrespective of supply power from a distribution transformer is studied as Case (a). Case (b) employs sending end voltage control as described earlier. No voltage violation occurs in the case of the sending end voltage control, although a large probability of voltage violation occurs in the fixed voltage case.



Case (a) Case (b)

Fig. 8. Frequency distribution of Voltage at Node 5.

4. Conclusion

As described in this paper, a novel voltage control method is proposed using a short-term forecast of PV output. The sending end voltage control by tap changing at the distribution substation based on the forecast data has been proven to be effective. Results show that the voltage is maintained in the power distribution system within a specified value using these methods. Furthermore, the disconnection frequency of the PCS can be decreased. Future studies should assess the risks of forecast error using probabilistic analysis.

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