Photovoltaic Power Generation Forecasting Technology for Supporting Energy Management Systems

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ABSTRACT

With the aim of realizing a low-carbon society, photovoltaic power generation is being promoted worldwide. The amount of photovoltaic power generation will fluctuate dramatically according to the weather conditions, and may adversely affect the power system if introduced in large quantities. Therefore, it is necessary to forecast the amount of power generation and to control the supply and demand. In order to achieve supply and demand control that is stable, Fuji Electric has developed technology for forecasting the amount of power generation. By predicting the amount of insolation from numerical weather forecast data, and converting that prediction into an amount of power generation based on the properties of photovoltaic modules, the amount of power generation can be forecasted for up to several days in the future in any region of the world.

1. Introduction

Recently, the implementation of a large amount of photovoltaic power generation to electric power systems is planned in response to ongoing efforts toward the realization of a low-carbon society and the experience of electric power shortages after the Great East Japan Earthquake. However, there is fear that photovoltaic power generation affects electric power systems adversely because its output electric power greatly fluctuates depending on meteorological conditions. It is, therefore, important to predict the output electric power of photovoltaic power generation and apply an energy management system (EMS) to the planning and control of generators and storage batteries in order to achieve stable supply and demand control of electric power systems.

This paper describes an output electric power prediction approach developed by Fuji Electric Co., Ltd. and the simulation results of its effectiveness.

2. Overview of Output Electric Power Prediction Technology

Two methods are used to predict the output electric power of photovoltaic power generation: direct prediction, which directly predicts output electric power, and indirect prediction, which predicts the amount of insolation and converts it into output electric power. Direct prediction requires modelling the relationship between output electric power and various factors for each photovoltaic power generation module.

Indirect prediction, on the other hand, has recently become the mainstream of output electric power prediction as a versatile approach. This approach needs to model the relationship between meteorological information and the amount of insolation, and can be classified into the following three methods according to the meteorological information to use:

(1) Method using weather forecasts

This method predicts output electric power based on the weather conditions such as fair and cloudy. It has the drawback of not being able to provide high prediction accuracy because forecasting can be performed only discretely in weather forecasts.

(2) Method using numerical weather forecast data

The Japan Meteorological Agency calculates detailed numerical weather forecast data by dividing the horizontal surface of the Earth into grids at intervals of several kilometers in several dozen layers above the ground. This method uses such numerical weather forecast data to predict output electric power. It is characterized by the advantage that diverse meteorological elements are available for the prediction of output electric power and high prediction accuracy can be thus expected. On the other hand, many meteorological elements must be processed in properly, and advanced statistical processing technology is required.

(3) Method using meteorological numerical simulation

This method calculates the intervals between calculation grids more minutely with numerical weather forecast data as initial values. Although this method has the advantage of being able to predict detailed output electric power, in the unit of several minutes for example, it incurs an enormous cost. It is reported that it takes 2 to 20 hours to calculate output electric power, depending on the calculation conditions, which is far beyond the EMS's calculation updating cycle of 30 minutes.

Since the EMS must control the supply and demand balance, high accuracy and quick calculations

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are indispensable for predicting the output electric power of photovoltaic power generation. Fuji Electric, possessing advanced statistical process technology, developed a photovoltaic power generation prediction function using numerical weather forecast data described in (2) above.

The functional configuration of the output electric power prediction system is shown in Fig. 1. It receives numerical weather forecast data released by the Japan Meteorological Agency and extracts weather forecasts for the target forecast area. These weather forecasts do not include the amount of insolation. Thus, the output electric power prediction system predicts the amount of insolation from weather forecast values and finally converts it into output electric power using the characteristics of the photovoltaic power generation module installed at the target forecast area.

The features of this system are shown below.

(a) The system is applicable in any area of the world.
(b) The system is capable of predicting output electric power up to 192 hours ahead.
(c) The system is capable of predicting output electric power with high accuracy because it uses multiple meteorological elements.
(d) It calculates within one minute, which is faster than the EMS's calculation update cycle of 30 minutes, and therefore the burden on the system is small.

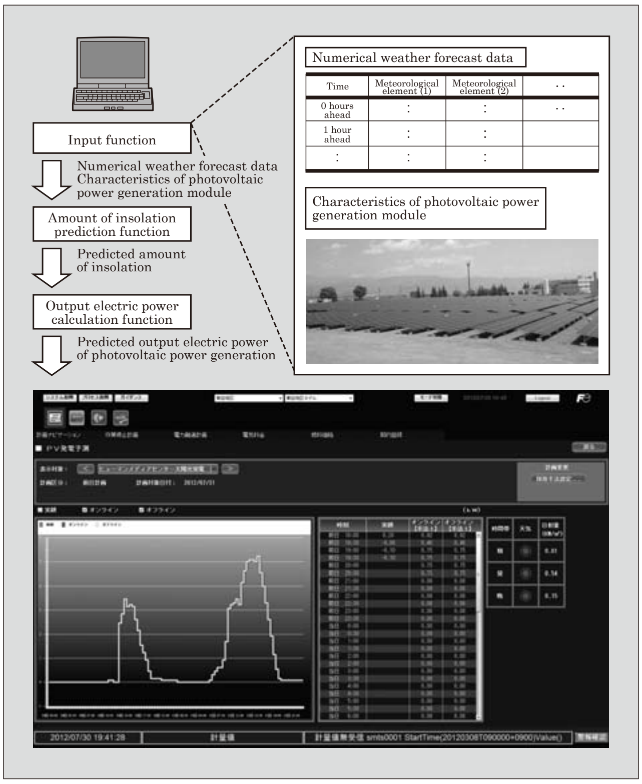

Fig.1 Functional configuration of output electric power prediction system

3. Output Electric Power Prediction Approach

3.1 Numerical weather forecast

Numerical weather forecasts require a huge volume of observation data and calculation capability because the air is covered with a three-dimensional grid of several-kilometer intervals and changes in meteorological elements on grid points, such as the air (temperature, wind velocity, wind direction, atmospheric pressure) and water vapor (relative humidity, amount of precipitation, amount of cloud), are numerically resolved over time. For this reason, numerical weather forecasts are carried out only by the meteorological agencies of major countries. The Japan Meteorological Agency calculates three types of weather forecasts — GSM (global area), GSM (area of Japan), and MSM (area of Japan). As shown in Table 1, the range of forecast, the grid interval, the distribution interval, and the forecast period are different among these types of forecasts. Numerical weather forecasts predict various meteorological elements but do not include the amount of insolation, which is required to predict output electric power.

The output electric power prediction approach developed by Fuji Electric is compatible with all three types of numerical weather forecast data.

3.2 Amount of insolation prediction method

The amount of insolation on the ground is the amount of insolation from the sun attenuated by the air. To predict the amount of insolation with this physical characteristic taken into account, the three steps described in (1) to (3) below were used, as shown in Fig. 2.

(1) Calculation of amount of extraterrestrial insolation

The amount of extraterrestrial isolation means the amount of solar radiation energy before it enters the atmosphere and it can be calculated from the location of the area and the orientation of the sun, as expressed by the equation shown below.

Table 1 Details of numerical weather forecasts

Type of forecast	Range of forecast	Grating interval	Distribution interval	Maximum forecast period
GSM (global area)	Whole world	East to west: 0.5° North to south: 0.5° 17 vertical layers	6 hours	192 hours
GSM (area of Japan)	North latitude: 20 to 50° East longitude: 120 to 150°	East to west: 0.25° North to south: 0.2° 17 vertical layers	6 hours	192 hours
MSM (area of Japan)	North latitude: 22.4 to 47.6° East longitude: 120 to 150°	East to west: 0.05° North to south: 0.0625° 16 vertical layers	3 hours	33 hours

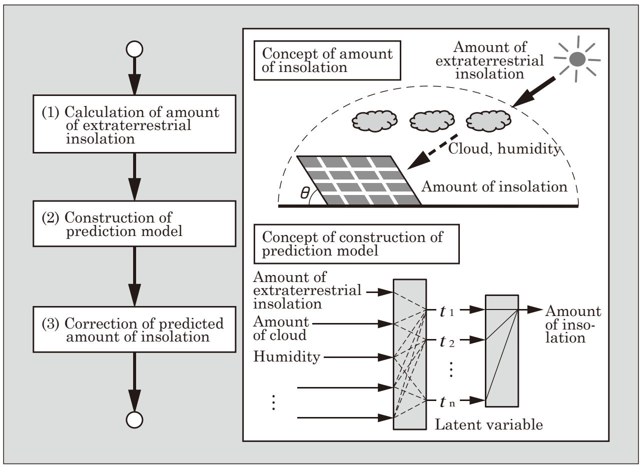

Fig.2 Flowchart for predicting amount of insolation

$$H_0 = I_0 \sin(h) \quad (1)$$

$$\sin(h) = \sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(\omega) \quad (2)$$

(When $\sin(h) < 0$, then $\sin(h) = 0$.)

H_0 : Amount of extraterrestrial insolation
I_0 : Solar constant
h : Solar altitude
δ : Celestial declination
ϕ : Latitude
ω : Hour angle

(2) Construction of a model for predicting the amount of insolation on the ground

The amount of extraterrestrial insolation in the air is affected by many meteorological elements, such as moisture in the air and the amount of cloud. Thus, it is desirable that these many elements be used to predict the amount of insolation on the ground with high accuracy.

Table 2 shows the input and output data used for prediction. The multiple regression method has been the most widely used prediction model, but its prediction accuracy may deteriorate due to the problem of multicollinearity. Multicollinearity is the phenomenon in which a proper model cannot be constructed if a strong correlation occurs between the items of input data. When there are many items of input data, as shown in Table 2, the problem of multicollinearity sometimes occurs, resulting in a failure to create a proper model with the multiple regression method. To prevent this problem, we constructed a model using a statistical approach called partial least squares (PLS). PLS has the advantage of being able to handle multicollinearity between explanatory variables and calculate a stable regression coefficient. As PLS deals with multicollinearity, explanatory variables are aggregated into an intermediate variable called a latent variable, and the output variable is expressed by the equation shown below.

Table 2 Input and output information for model for predicting amount of insolation

Input/ Output	Major Item	Detailed item
Input	Amount of cloud	Total amount of cloud Amount of cloud (upper layer) Amount of cloud (middle layer) Amount of cloud (lower layer)
	Humidity	1,000 hPa surface humidity 925 hPa surface humidity 850 hPa surface humidity 700 hPa surface humidity 600 hPa surface humidity 500 hPa surface humidity 400 hPa surface humidity 300 hPa surface humidity
	Amount of insolation	Amount of extraterrestrial insolation
Output	Amount of insolation	Amount of insolation

$$t = (W^{T} P_{C})^{-1} W^{T} x \quad (3)$$

$$y = Q_{C}\, t = Q_{C} (W^{T} P_{C})^{-1} W^{T} x \quad (4)$$

x : Input variable
t : Latent variable
y : Estimated output variable
W : Weighting matrix
P_C : Coefficient matrix relating to input variable
Q_C : Coefficient matrix relating to output variable

(3) Correction of predicted amount of insolation

The predicted amount of insolation on the ground calculated in (2) may deviate from a physical value, although slightly, because of the effect of variation in the data used for the construction of the model. If the predicted amount of insolation deviates from the physically allowable range, correct it to the maximum or minimum amount of insolation. In addition, since the amount of insolation in rainy weather is minimal, whenever rainy weather is expected from the predicted amount of precipitation, correct the predicted amount of insolation to the minimum value.

3.3 Output electric power prediction method

Output electric power can be calculated from the amount of insolation and the efficiency of the solar panels using the following equation:

$$P_{out} = y P_{rate} E_{trans} E_{temp} \quad (5)$$

P_{out} : Output electric power
y : Amount of insolation
P_{rate} : Rated output
E_{trans} : Transformation efficiency
E_{temp} : Coefficient of transformation efficiency of module at each temperature (module temperature efficiency)

The module temperature efficiency of the solar panels, however, shows a different degree of change depending on the type of solar panel, as shown in Fig. 3. Therefore, the model was made compatible with various types of solar panels by providing a table of module temperature efficiency.

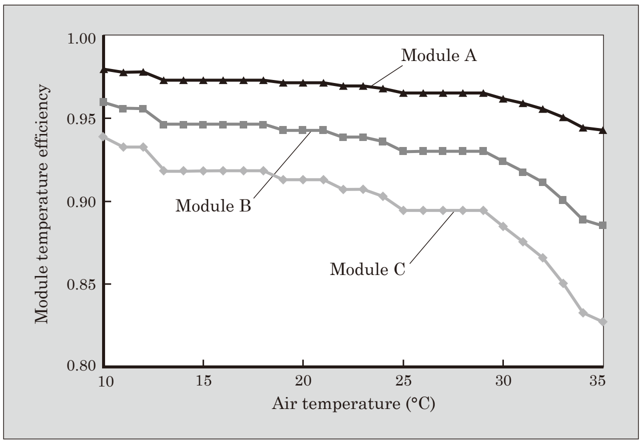

Fig.3 Relationship between air temperature and module temperature efficiency

4. Simulation Example

We conducted a simulation based on the developed output electric power prediction approach. Figure 4 shows a comparison between predicted amounts of insolation and actual values, and Fig. 5 makes a comparison between predicted output electric power generated by photovoltaic power generation and actual values. We used GSM (area of Japan) released at 3 a.m. before sunrise for numerical weather forecast data, and predicted the amount of insolation and output electric power for 24 hours from 4 a.m. to 3 a.m. on the following day. We evaluated them for a full month in April and July, respectively.

The predicted results analyzed were satisfactory on the whole. There was a gap between some predicted values and the corresponding actual values, but we found that it resulted from errors in the distributed numerical weather forecasts themselves. In addition, the prediction accuracy of photovoltaic power generation is shown in Table 3. The prediction accuracy required of photovoltaic power generation is equal to or less than the rated capacity of one generator in terms of preventing adverse effects on the startup and stop of generators. Assuming that the number of generators controlled by the EMS is 10 (number of generators used on a large-size isolated island) and photovoltaic power generation is 30% of the system capacity (implementation target in Japan in 2030), the required prediction accuracy of photovoltaic power generation is 0.33 p.u. (rated capacity of one generator) when the rated output electric power by photovoltaic power generation is 1.0 p.u. Judging from Table 3, this approach is capable of predicting output electric power with an accuracy of 0.2 p.u. at all times, proving its effectiveness in predicting output electric power.

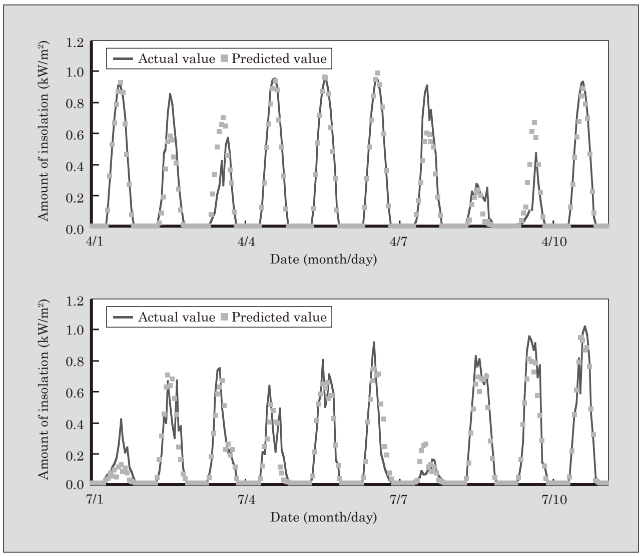

Fig.4 Prediction results of amounts of insolation

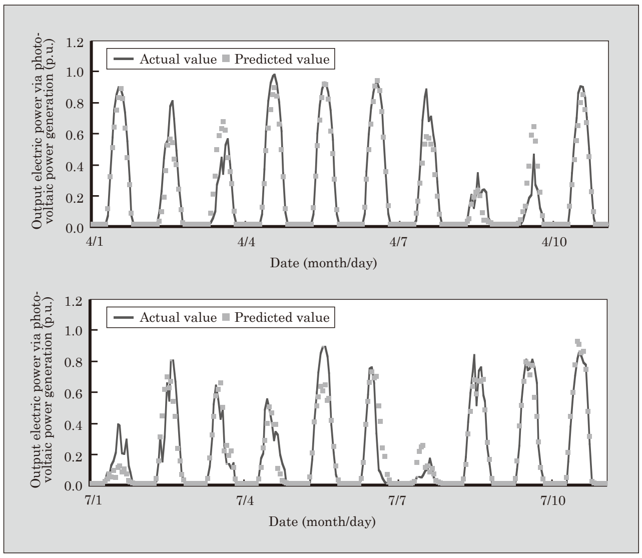

Fig.5 Prediction results of output electric power via photovoltaic power generation

Table 3 Prediction accuracy of photovoltaic power generation

Calculation method	6:00	7:00	8:00	9:00	10:00	11:00	12:00
RMSE (p.u.)	0.01	0.04	0.07	0.12	0.15	0.18	0.20
MAE (p.u.)	0.01	0.03	0.06	0.09	0.12	0.15	0.15

Calculation method	13:00	14:00	15:00	16:00	17:00	18:00	Average
RMSE (p.u.)	0.18	0.16	0.16	0.12	0.08	0.04	0.12
MAE (p.u.)	0.14	0.12	0.12	0.09	0.06	0.03	0.09

RMSE: Root mean square error
MAE: Mean absolute error
p.u.: Per unit method

5. Postscript

In this paper, we described photovoltaic power generation prediction technology that is indispensable for planning the starting and stopping of generators under the control of the EMS. This technology is characterized by a high level of prediction accuracy because it predicts output electric power using many pieces of weather forecast data distributed by numerical weather forecasts, such as the amount of cloud and humidity. It is also applicable in any area of the world as numerical weather forecasts cover the whole world.

This technology, together with technology for predicting output electric power by wind power generation, is undergoing a demonstration test as technology for predicting renewable energy in the "Kitakyushu Smart Community Creation Project." We will strive to improve its prediction accuracy and expand the times covered by its prediction.

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