Power Stabilization by Windfarm Applied Statistical Model and Pumped Storage Generation Using Archimedean Screw

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Abstract: In this paper, a method of stabilizing electric power by a system which is a combination of wind power generation and pumped storage power generation is proposed. The system operates based on the output predicted value of the windfarm. When the measured windfarm output is larger than the predicted value, the system is pumping up water with surplus power. When the windfarm output is smaller than the predicted value, the system is filling up lack power by hydro generator. Also, since hydro generator works with a start-up delay time, output shortage occurs at this time. To improve output shortage at the time, we estimate the time below the predicted value by a statistical model. As the result, the system succeeded in stabilizing the power and improving the start-up delay time of the hydro generator.

Key words: Windfarm, pumped storage power generation, Archimedean screw, statistical model.

1. Introduction

In recent years, power generation methods of using natural energy have become popular in order to realize a low-carbon society. Wind power generation is one of these methods. But its output changes irregularly and leads to the instability of power system while wind power connects it directly [1]. Therefore, the wind power generation system generally stores energy in a battery, etc. [2]. However, the quantity of the stored energy in a battery has a limit, and the lifetime of the store equipment is not so long.

We propose a method of using a pumped storage power station for regulating power supply of 1,000 MW class windfarm [3, 4]. Pumped storage power station has advantages about the maximum amount of regulated power supply and lifetime of the facility. Moreover, it works from the start of power generation to the rating in short time of about 6 min, and the output adjustment is easy.

In this paper, it is assumed that the combination of a seawater pumped storage power station and offshore wind power generations, because there are many places where mountains of several hundred meters height are along the coast in Japan. Seawater pumped storage power can be reduced the construction cost of the lower reservoir. Also, offshore wind power generation can obtain large and stable electric power compared with land wind power.

In this paper, power generation system that combines offshore wind power and sea water pumped storage power is simulated.

There are many ways of short-term (a few minutes) of windfarm output. For example, An et al. [5] use Chaotic-Time-Series method and GM (1,1) method, Zhu et al. [6] use Fuzzy Modeling method, and Peng et al. [7] use ANN (artificial neural network) method.

We need to predict the output after about 6 min to 20 min in order to determine the starting time of the hydro generator. Therefore, we predict short-term predictive value of windfarm and determine the starting time of the hydro generator using a statistical model.

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2. Outline of This System

2.1 Wind and Pumped Storage Power System

The schematic drawing of this system is shown in Fig. 1. This system shall be placed on a mountain close to the sea. A windfarm of 1,000 MW is installed on the mountain and/or offshore. In addition, an upper reservoir is installed in the slope of the mountain. The electricity of the wind power generations is sent to an electric power system. And the redundant electricity of the wind power generations is used for pumping.

The wind power generations and pumped storage power plant are connected to the power system. The pumped storage power system is constituted by the Archimedean screw that is pumping from lower reservoir to the upper pond and the hydro generator that is driven using the upper pond water.

2.2 Archimedean Screw

In this paper, we use the Archimedean screw as a water pump. When the wind stops, the wind turbines cannot generate electricity. Therefore, conventional water pumps cannot pump up water stably. On the other hand, the Archimedean screw can hold water inside the screws when the power is stopped and can pump up water immediately when the power is supplied. So, it is suitable for intermittent operation as this system.

A model of the Archimedean screw is shown in Fig. 2. And, specifications of the Archimedean screw in this research are shown in Table 1. We consider that the Archimedean screw is not only rotating the screw, but

Fig. 2 Schematic drawing of the Archimedean screw.

Table 1 Specifications of the Archimedean screw in this research.

Number of screw period	455 cycle
Screw diameter	3 m
Screw length	400 m
Screw angle	30 deg
Screw mass	250.7 t
Rated speed	25 rpm
Effective head	200 m
Pumping amount	3.17 m ³ /s
Moment of inertia	282,000 kg·m ²

the screw with the cylinder, outer frame of the screw. It is a costly, but it is possible to prevent deterioration due to friction between the trough and the screw and to smoothly rotate by outside fixed trough and bearings.

2.3 Operating Method of This System

This system operates based on the output predicted value of the windfarm. When the measured windfarm output is larger than the predicted value, the system is pumping up water with surplus power. When the measured value is smaller than the predicted value, the system is filling up lack power by hydro generator. The outline of the operating method is shown in Fig. 3.

3. Simulation

3.1 Simulation Method

Sample output data of a 2 MW wind turbine at intervals of one second from 13:00 to 16:00 on September 20, 2011 are shown in Fig. 4. Also, the outline of windfarm in this paper is shown in Fig. 5. It is assumed to be placed 20 turbines in vertical to the wind

Fig. 1 Schematic drawing of wind and pumped storage power system.

Fig. 3 Outline of operating method.

Fig. 4 Output data of the 2 MW wind power generator.

Fig. 5 Diagram of the windfarm.

direction and 25 turbines in parallel. We calculate the windfarm output from single wind power output data of Fig. 4.

We suppose that wind blows vertical to the line from A1 to A20. The average wind velocity from 13:00 to

Fig. 6 Output of the windfarm.

16:00 is 6.3 m/s. The wind which has observed at line A will reach line B 78 seconds later because the distance between line A and B is 500 m. As a result, the output of the windfarm is shown in Fig. 6.

3.2 Simulation Model

In this simulation, it is assumed to take 350 s to start the hydro generator. So, lack power occurs for the start-up delay time of the hydro generator, because after the measured value of the windfarm output is below the predicted value, the hydro generator starts.

In this paper, we predict the windfarm output using a statistical model, and the hydro power generator starts up before the windfarm output is below the predicted value. In particular, we calculate the correlation coefficient in order to determine the state of the correlation of windfarm output. The correlation coefficient takes a value from -1 to +1; it indicates positive correlation or negative one when the value is positive or negative, respectively. Therefore, if it shows the negative correlation coefficient, the output is lowered, it is estimated that the future of the output is also down. In this case, by using the least squares method, the time below the predicted value is estimated, then the starting time of the hydro generator is set at minus 350 s from the estimated time. The correlation coefficient is given by the following equation.

$$r = \frac{s_{xy}}{s_x s_y} \quad (1)$$

where, s_x and s_y show a standard deviation, s_{xy} shows a covariance.

$$s_x = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

$$s_y = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (y_i - \bar{y})^2} \quad (3)$$

$$s_{xy} = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}) \quad (4)$$

where, $\bar{x}$ and $\bar{y}$ show the average value of data x and y , respectively. In this calculation, x and y are calculated as time and output of windfarm, respectively.

3.3 Fourier Transform

Because windfarm output is a vibrating waveform, it may not be obtained an appropriate correlation coefficient affected by detail variation component of the output, if number of data n is small. In this paper, the output waveform is approximated by using Fourier transform. The Fourier transform of the windfarm output is shown in Fig. 7.

3.4 Simulation Conditions

Table 2 shows conditions for the simulation. It is assumed that the windfarm output is rating of 1,000 MW, i.e., arranged as Fig. 5 for 500 wind turbines of the rating of 2 MW, and the average prediction value of windfarm output is 455 MW. Three hydro generators of 30 MW, the total rating of 90 MW, and five the Archimedean screws of the rating of 11 MW and the maximum consumption are assumed. The model of pumped hydro power station is Okinawa Yanbaru Seawater Pumped Storage Power Station.

3.5 Simulation Result

First, Fig. 8 shows calculation result of the correlation coefficient of the windfarm output.

Fig. 7 Fourier transform of the windfarm output.

Table 2 Conditions for the simulation.

Wind power generators	Rated: 2 MW × 500 Units = 1,000 MW
Predicted value of windfarm output	455 MW
Hydro power generators	Rated: 30 MW × 3 Units = 90 MW Start-up time: 350 s
Archimedean screws power consumption	Rated: 11 MW × 5 Units = 55 MW Max: 21 MW × 5 Units = 105 MW

Fig. 8 Calculation of correlation coefficient of the windfarm output.

In this paper, we calculate the correlation coefficient for the past 60 s based on the certain time. Therefore, n is 60 in Eqs. (2)-(4).

As the result, it can be confirmed that the appropriate correlation coefficient is obtained by using Fourier transform to windfarm output.

Fig. 9 Simulation result.

Next, Fig. 9 shows a result of the simulation of the system. It is found to stabilize the system output, because it can be adjusted the excess and deficiency of output by pumped storage power.

Also, for this result, we consider the frequency variation value. Frequency variation of a power system can be obtained from power fluctuation value and total amount of the power system as follows [8].

$$\Delta f = \frac{\frac{\Delta P}{P} \times 100}{K_G + K_L} [Hz] \quad (5)$$

where, ΔP is power fluctuation value (MW), P is total amount of the power system (MW), K_G and K_L are frequency characteristics of power and load, respectively. P is a value of 6,440-13,950 MW referring the total amount of power generation by the Tohoku-Electric Power Co., Inc. in 2014. $K_G + K_L$ is a value 7-10, generally. In this calculation, by assuming the worst-case, we select that P is 6,440 MW and $K_G + K_L$ is 7. Table 3 shows this calculation result.

As the result, in the case of wind power generation only, power fluctuation value is -88:+123 MW, frequency variation of power system is -0.137:+0.191 Hz. On the other hand, in the case of wind and pumped storage power generation, power fluctuation value is

Table 3 Conditions for the simulation.

	Wind power	Wind and pumped storage power
Power fluctuation value (MW)	-88 : +123	-45 : +76
Frequency variation (Hz)	-0.137 : +0.191	-0.070 : +0.118

Table 4 The results of hydro power generator start-up.

Start-up time: 350s

	Time below the predicted windfarm output	Time obtained hydro power generator output	Delay time
(1)	13:19:03	13:17:52	None
(2)	15:21:52	15:17:12	None
(3)	15:41:54	15:45:40	226 s

-45:+76 MW, frequency variation of power is -0.070:+0.118 Hz.

Therefore, it is possible to stabilize power by wind and pumped storage power system. The Tohoku-Electric Power Co., Inc. sets a target value of frequency variation within ± 0.2 Hz, possibility to deviate from the target increases if wind power only is connected to the power system. Thus, it can be seen that this combined system of the large windfarm and pumped storage hydro power generation greatly improves the situation.

Also, Table 4 shows the results of hydro power generator start-up.

As the result, for time (1) and (2), the start-up delay time of hydro power generator is eliminated, and for the time (3), it is succeeded that the start-up time is reduced approximately 30% compared with 350 s. However, the start-up delay time at the time (3) cannot be eliminated, because the windfarm output is below the predicted output within 350 s after the negative correlation is detected. To deal with the case of time (3), it is necessary to consider how to set the appropriate output predicted value.

4. Conclusions

In this paper, we proposed a method of stabilizing by the power system which was a combination of wind power generation and pumped storage power

generation with the Archimedean screw, and simulated about the stability of the power system. As the result, it was found that the power system was stabilized and the requirement in the Tohoku-Electric Power Co, Inc. was achieved.

In addition, we succeeded in improving the start-up delay time of the hydro-generator by using the statistical model for the system. However, delay time always occurred in the cases that the windfarm output was below the predicted output within 350 s after the negative correlation was detected. So, it will be necessary to consider how to set the appropriate output predicted value.

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