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INVESTIGATION OF WIND POWER GENERATION IN LITHUANIA

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New Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources leads to rapid increase in the number of wind power plants and penetration of wind power into power systems. Highly variable and poorly predictable generation of wind power leads to serious concerns for power systems regarding control of their operation regimes and power generation balancing. Solution to these and other issues requires knowledge of potential and likely deviations of probabilistic variations in wind power generation, interdependencies of wind power generation variances between wind power parks and power system loads, parameters of wind speed and direction, etc. Successful integration of wind power plants into power systems demands appropriate assessment of all the types of required power generation reserves, research of wind power generation balancing by distributed power plants, possibilities for energy accumulation and variable load. For the purpose of solving these tasks it is necessary to determine probability parameters and interdependencies characteristic of power plants utilizing renewable energy as precisely as possible.

Introduction

Accomplished research and review of wind power plants operating in power systems of EU countries, studies performed by different companies and international organizations as well as public statistical data suggest that in Europe, development of wind power plants is gaining pace. In view of increasing number of wind power plants, a highly-variable and only partially predictable power generation by wind power plants leads to different concerns for power systems, as they burden assurance of constant balance between the power generation and consumption in the system, exchange of power generation and trade with neighbouring countries [1]. Consequently, a power system requires additional power reserve for operating, necessary for ensuring a reliable operation of the entire power system. The amount of

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additional power reserves is limited and depends on the size and load of the power system, structure of power plants, capacity of power lines, interconnections to neighbouring power systems.

To ensure a successful integration of wind power plants into power systems, it is highly important to increase capacity of transmission networks, but more than that to have improved technologies of wind power plants and possibility to regulate variable power generation of wind power plants. In order to ensure reliable and safe operation of a power system and to utilize renewable wind energy as efficiently as possible, it is necessary to have reliable indicators and characteristics of wind power plants operation enabling to integrate these power plants into the power system and preventing additional problems or constraints of the control over power systems regimes.

Characteristics of the investigated object

The following wind power parks (WPP) operating in Lithuania were selected as the object of the investigation: *Benaičiai* (with the installed capacity of 16.5 MW), *Sūdėnai* (14 MW) and *Vėjas I* (30 MW) WPPs built in the Western part of Lithuania, in the seaside area of the Baltic Sea and connected to a 110 kV network (Fig. 1). The distance between WPPs *Benaičiai* and *Vėjas I* (Rūdaičiai village) is 18 km, and between WPPs *Sūdėnai* and *Benaičiai* – 3 km. Operating with an average capacity of 5 MW, the duration of operation at its installed capacity being 2727 h, *Benaičiai* WPP generated 43.6 GWh of electrical energy in the year 2008, resulting in its installed capacity efficiency to be 30%. Within the same period of time, WPP *Vėjas I* generated 71.8 GWh of electrical energy. Annual average capacity of this WPP amounts to 8.2 MW, duration of its operation at installed capacity is 2393 h and efficiency – 27%.

For the purpose of research, measured data of maximum changes in power generation over the following time periods of the year 2009 and measured loads of Lithuanian power system over the same time periods were selected:

I measurement period 28/03/2009–04/04/2009 (7 days);
II measurement period 25/04/2009–07/05/2009 (12 days);
III measurement period 16/05/2009–28/05/2009 (12 days);
IV measurement period 16/07/2009–22/07/2009 (6 days).

Lithuanian power system loads and power generation by WPPs within selected periods of time were calculated for 1-s time steps with the exception of *Sūdėnai* WPP – its power generation was calculated for 1-min. time step. Measurement data on 1-s step changes allow to investigate power generation process of wind power plants by changing time intervals of power generation averaging.

For the purpose of investigation of power generation dependence on wind speed and direction, parameters of wind speed and direction have been measured at the territory of *Benaičiai* WPP at height of wind turbines of wind power plants; data has been averaged for the 10-min time steps.

Fig. 1. Deployment of *Sūdėnai*, *Benaičiai* and *Vėjas I* (Rūdaičiai village) WPP parks.

Assessment of variation of electricity generation by wind power plants

Its is recommended to develop WPPs in as wide area as possible in such a way that electric power transmission networks are uniformly loaded in order to guarantee full utilization of power network capacity. Currently in Lithuania wind power parks are being built as close to the seaside as possible, i.e., in the area of stronger winds, at the distance of several tens of kilometres from each other [2].

Figure 2 shows variation in average power generation by wind power parks under consideration, averaged for 15-minutes time steps for three days of the selected period III.

Analysis of power generation by the wind power plant (see Fig. 2) reveals that the amount of generated power fluctuates in a wide range from minimum to maximum possible values. Such a variance of parameters might be considered to be random, and it might be subject to stochastic analysis

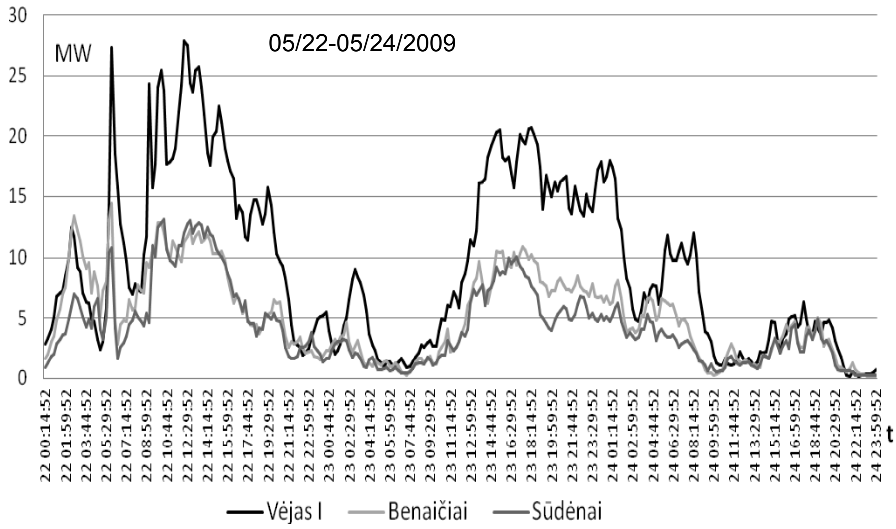

Fig. 2. Variation of electricity generation by wind power parks during selected measurement period III.

with the aim to determine distribution types, average values, standard deviations, correlation coefficients, etc.

The following formula might be used to determine the average value of power generation by the wind power plant:

$$P_{av} = \frac{1}{n}\sum_{i=1}^{n} P_i \, , \tag{1}$$

where P_i – average power generation over selected time step,
n – number of determined power generation values.

Variation in power generation might be determined as follows:

$$\Delta P_i = P_{i+1} - P_i \, , \tag{2}$$

where P_i and P_{i+1} – average power generation over consecutive selected time steps.

The following formula is used to determine standard deviations of variation in power generation:

$$\sigma = \sqrt{\sum_{i=1}^{n} \frac{1}{n-1}\left(\Delta P_i - \overline{\Delta P}\right)^2} \, , \tag{3}$$

where n – number of measurements made under research,
$\overline{\Delta P}$ – average value of variation of power generation, that in this particular case is equal to zero.

The following formula is used to determine correlation coefficient between power generation of two WPPs [3]:

$$r_{12} = \frac{\sum_{i=1}^{n}(\Delta P_{1,i})(\Delta P_{2,i})}{\sqrt{\sum_{i=1}^{n}(\Delta P_{1,i})^2}\sqrt{\sum_{i=1}^{n}(\Delta P_{2,i})^2}}, \quad (4)$$

where ΔP_{1i} and ΔP_{2i} – the i^{th} variation in power generation of the first and second parks, respectively.

The major effect of wind power variation is observed for time steps ranging from 10 min to several hours, whereas it is observed to be sufficiently low in the interval of 10-s time step [4]. For the purpose of investigation of WPP generation process and its influence on the electric power system, 30-s and 15-min step changes in average power generation were selected, as they are necessary for activation of primary and secondary reserves of power generation, as well as for frequency and power generation control. Hourly variations in power generation were investigated too.

Investigation of variation in wind power generation

For the purpose of assessing variations in power generation by WPP, a research was undertaken based on data for individual measurement periods and on the entire data volume. The array of all the data of average power generation for 30-s time steps comprised 107,343 values, and for 15-min time steps – 3573 values. Figures 3 to 5 and Table 1 present calculation results.

Analysis of the results obtained (see Fig. 3) shows distributions of variations in power generation to be normal ones with the average value of zero and standard deviations (σ) of WPP *Vėjas I* being 1.25 MW, and total deviation of all the parks under consideration being 2.05 MW. However, total standard deviation of all the WPPs under consideration (3.39%) is lower than each of individual standard deviations of WPP power generation (see Table 1). The maximum increasing variation for WPP *Vėjas I* is 13.0 MW, while decreasing one – 11.3 MW. The maximum increasing variation of all the WPPs under consideration is 18.8 MW, while decreasing one – 22.4 MW. Such data imply that confidence interval 6.15 MW for 3σ does not exceed one third of the maximum change in power generation, consequently such a confidence interval might be insufficient for analysis of operation regimes of wind power plants.

Determination of maximum change in power generation requires examination of array combinations for the selected time steps of power generation averaging, and finding maximum difference between the consecutive values in formed arrays. The array of combinations with the determined maximum difference of average power generation is to be further used for stochastic research.

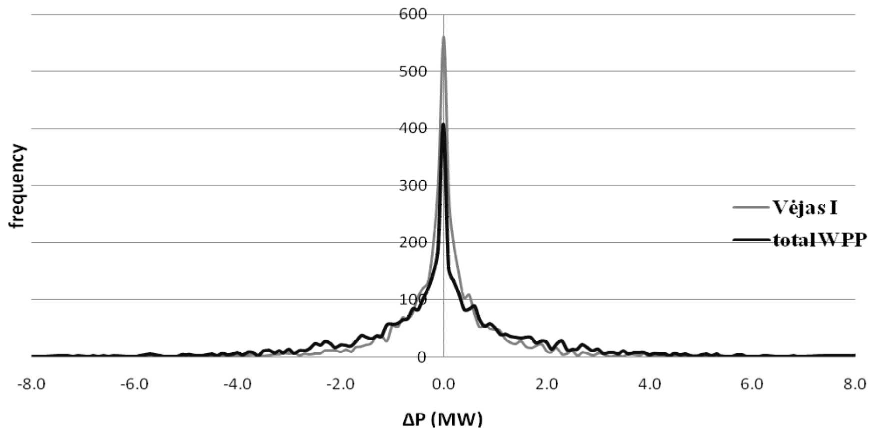

Fig 3. Distribution of variations in average power generation for 15 min of power generation by wind power parks.

Table 1. **Parameters of variations of WPP power generation**

Wind power park	Installed capacity in MW	Interval of power generation averaging											
		30-s time step						15-min time step					
		Standard deviation		Maximum change in power generation				Standard deviation		Maximum change in power generation			
				+ ΔP		– ΔP				+ ΔP		– ΔP	
		MW	%	MW	%	MW	%	MW	%	MW	%	MW	%
Vėjas I	30	0.46	1.53	5.27	17.6	4.11	13.7	1.25	4.20	13.0	43.3	11.3	37.7
Benaičiai	16.5	0.39	2.36	4.26	25.8	4.63	28.1	0.81	4.48	5.11	30.0	9.75	59.1
Sūdėnai	14	–	–	–	–	–	–	0.74	5.29	6.34	45.3	6.67	47.6
Total	60.5	0.61	1.31	5.80	9.59	5.29	8.74	2.05	3.39	18.8	31.1	22.4	37.0

For the purpose of assessing variations in WPP power generation, individually and in total, interrelations and interdependencies of variations in power generation of wind power plants were examined, and their correlations were found for different measurement periods (I–IV).

Analysis of correlation coefficients of variations in power generation of different wind power parks (see Fig. 4) showed that during the selected periods of time, correlation of WPP power generation was positive and varied in the range of 0.14 to 0.68, and correlation among parks and loads were mainly negative and varied in the range of -0.11 to 0.03. Such values of correlation coefficients serve as evidence that development of wind power parks will lead to increased variations in power generation within the entire power system and will require additional operative power reserves. Furthermore, the present research shows correlation of power generation during different periods of time to be the same and only slightly different in numerical value, consequently for further research power generation measurement data of all the time periods under consideration should be used.

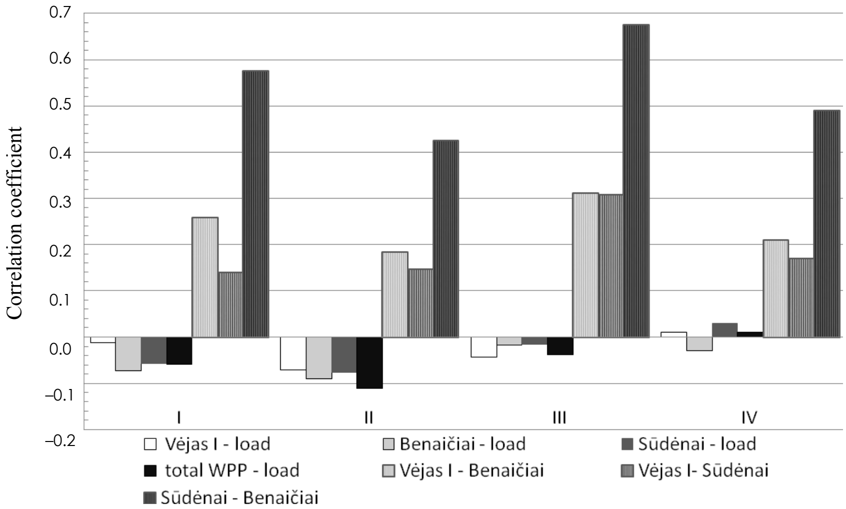

Fig. 4. Correlation of average power variation of 15-min time-steps between wind power parks and between wind power parks and the system load.

Investigation of different step changes in WPP power generation and calculations using all the measurement data (Fig. 5) show that correlation coefficients of changes in 30-s time-step average power generation between the two WPPs under research are positive, very low, and below 0.01, whereas those between WPPs and load – negative and up to 0.04. In this particular case, changes in power generation under research might be con-

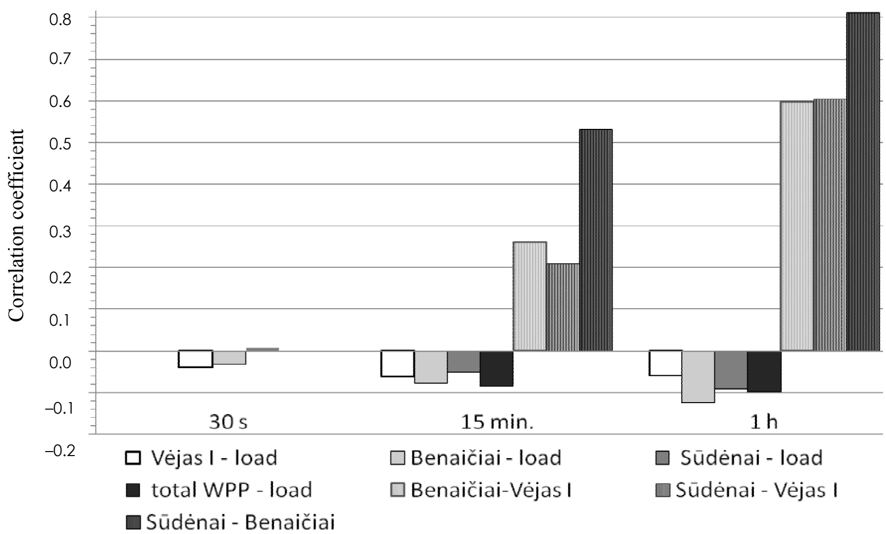

Fig. 5. Correlation of average power variation of different time-steps between wind power parks and between wind power parks and the system load.

sidered uncorrelated. Moreover, standard deviations of power generation variations are low, too (Table 1), therefore system frequency control requires relatively low primary power reserve. However, values of correlation coefficients of 15-min time step average power generation variations among three WPPs are significantly higher, positive, and vary in the range of 0.21 to 0.53. The highest correlation of power generation variations was found between adjacent WPPs *Benaičiai* and *Sūdėnai*, whereas correlation between WPPs and loads was found to be negative and in the range –0.05 to –0.09. Correlation of power generation for this particular time step is considered to be strong enough, and standard deviations of power generation variations are several times those of the 30-s time step, what in turn implies that balancing of wind power generation requires a secondary power reserve to be several times greater. With the increasing time step of averaging, correlation coefficients increase furthermore, and correlation coefficients of 1-hour time step power generation among wind power parks vary in the range of 0.60–0.81, whereas those between parks and loads range from –0.06 to –0.12.

Dependence of wind power generation changes on wind direction and speed

For the purpose of investigation of dependence of wind power generation on wind direction and speed, measurements were taken in the territory of *Benaičiai* WPP at the height of wind turbines (85 m) of wind power generation units. Based on these findings, a Wind Rose was made (Fig. 6) where wind time step and average wind speed were depicted based on wind direction as dimensions (h and m/s). It was found that in Lithuania, at the seaside, winds predominantly occur in Western-Southern sector with the average wind speed of 6.3–8.1 m/s. The most stable wind in this sector was found to be of WSW direction, with the average wind speed of 7.6 m/s. Sufficiently strong winds of E and ESE directions may also occur, with the average wind speed of 8.3 m/s, however they are transient.

Measured wind speed values and calculations allow to determine minimum distances between WPPs for which a research of influence of power generation variation is purposeful using the following formula:

$$\ell_{park} = t_P \cdot v_W , \qquad (5)$$

where t_P – time step of wind power generation averaging;
v_W – wind speed.

In this particular case, under selected 15-min time step of wind power generation averaging, the minimum distance between WPPs has to be at least 3.9–7.3 km. Consequently, it is worth examining interdependencies of changes in wind power generation by the wind power parks that are more distanced from each other, i.e., WPPs *Vėjas I–Benaičiai* and *Vėjas I–Sūdėnai*, as the distance between WPPs *Benaičiai* and *Sūdėnai* is only 3 km.

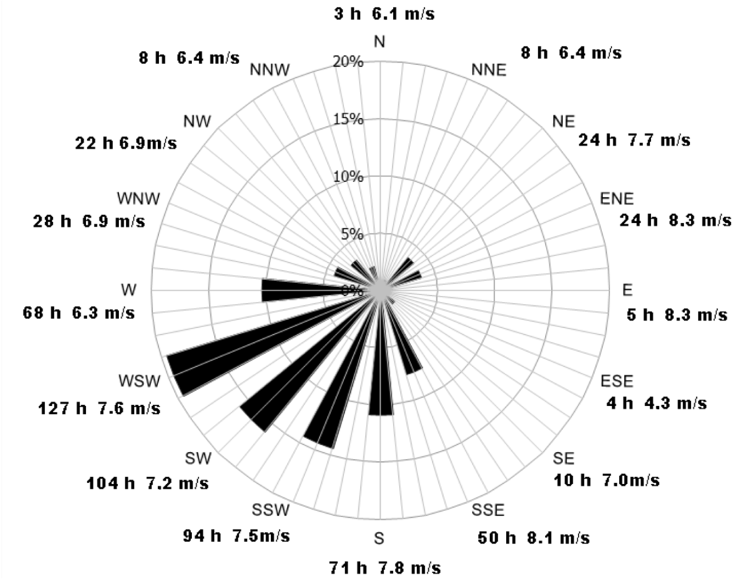

Fig. 6. Wind rose based on time.

Table 2. **Parameters of WPP wind power generation changes based on wind directions**

Wind power parks	Para-meters	Wind directions								
		NE	ENE	SSE	S	SSW	SW	WSW	W	WNW
Vėjas I	r_{12}	0.33	0.27	0.23	0.11	0.24	0.20	0.29	0.51	0.20
Benaičiai	σ. %	4.30	2.80	3.44	3.01	4.52	4.30	4.09	4.95	3.22
Vėjas I	r_{12}	0.32	0.31	0.15	0.07	0.13	0.13	0.36	0.45	0.35
Sūdėnai	σ. %	3.64	2.95	4.09	2.95	4.55	4.32	4.32	4.77	3.18
Vėjas I	σ. %	4.33	3.33	4.33	2.66	5.33	5.33	4.66	5.00	3.33
Benaičiai	σ. %	7.27	5.45	4.24	6.06	6.06	5.45	5.45	6.66	4.84
Sūdėnai	σ. %	5.00	5.71	7.14	5.00	7.14	5.71	5.71	6.42	4.29

To find probabilities of wind direction effect on changes in WPP wind power generation, arrays of 15-min step changes in average power generation were made in respect to wind directions. Power generated by the average hourly wind speeds of up to 4 m/s was not included into data arrays, as wind power plant operation under minimum wind speeds often happens to be very unstable, and due to wind's locality and technical and regime reasons of WPP can misrepresent effect of wind direction in the research.

Research results (Table 2) show that wind direction has a sufficiently significant effect on WPP power generation changes, and both correlation and standard deviations of wind power generation variation achieve highest values at perpendicular wind direction to WPP deployment line (wind direction W), and lowest values – at wind blowing in a direction of WPP deployment line (wind direction S). In the case of WPPs *Vėjas I – Benaičiai*, the lowest correlation coefficient is 0.11, the highest – 0.51, and in the case of WPPs *Vėjas I – Sūdėnai* – 0.07 and 0.45, respectively. The lowest standard deviations of WPP power generation variations examined under the same wind directions were found to be 3.01% and 2.95%, and the highest – 4.95% and 4.77%, respectively. Relative standard deviations of variations of total power generation of two WPPs were found to be lower than those of variations of total power generation of each WPP individually at almost all wind directions (Table 2).

Relative standard deviations of 15-min step changes in average power generation for each WPP individually are also dependent on wind direction, and vary in a quite large range (Table 2) as well as they are rather different from relative standard deviations calculated without taking into consideration wind directions (Table 1).

Calculations of power system regimes and determination of the effect from wind power parks and range of their power generation variations as well as operating power reserves require assessment of the effect determined by wind direction and geographical deployment of wind power parks. Standard deviations of WPP wind power generation and their dependence on wind direction must be determined in advance in every particular case.

Conclusions

1. Correlation between wind power parks power generation was found to be positive, whereas correlation between parks and load – negative, consequently penetration of wind power plants into the power system is expected to increase the amount of operating power reserves.
2. 30-s step changes in average power generation by wind power parks are reported to correlate weakly, and their standard deviations – to be low, therefore the primary power regulation reserve is expected to grow only slightly.
3. Values of correlation coefficients and standard deviations for 15-min step changes in average power generation of wind power parks were found to be sufficiently high, consequently balancing of wind power generation will require a rather big amount of secondary power regulation reserve.
4. Values of correlation coefficients and standard deviations of wind power generation changes were found to be dependent on wind direction, thus calculations of power system regimes and determination of the effect from wind power parks and range of their power generation variations requires assessment of the phenomenon determined by wind direction and geographical deployment of wind power parks.

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