ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2012. No. 2(118)
ELEKTRONIKA IR ELEKTROTECHNIKA

ELECTRICAL ENGINEERING
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ELEKTROS INŽINERIJA

Statistical Analysis of Power Generation of Wind Parks

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crossref http://dx.doi.org/10.5755/j01.eee.118.2.1173

Introduction

Rapid development of wind and solar power plants in Europe as well as other countries all over the world may lead to disturbances of operating conditions of power systems and result in other serious concerns. Accomplished research of wind power plants operating in power systems of EU countries, analysis of studies performed by different companies and international organizations and analysis of public statistical data suggest that variable power generated by wind power plants is also rapidly increasing. As this power is independent on variation of power system load, it is only partially predictable. As the number of power plants and the amount of their generated variable power increase, they burden smooth operation of electric power systems because the need for additional balancing capacities, electric power accumulation and variable load increases.

Successful integration of wind power plants into power systems requires not only increasing of transmission capacity of electrical networks but also improving wind power plants technologies and ability to control and adjust variable power generation of wind power plants. In order to ensure reliable and safe operation of power system and to possibly use renewable wind power more efficiently, it is absolutely necessary to have reliable indicators of wind power plants operation and characteristics that enable maximally precise forecast of power generation by those power plants and making long-term power balance schedules for future.

Characteristic of analysed wind power plants

Benaičiai wind park (WP) with the installed capacity of 16.5 MW, *Sūdėnai* wind park with 14 MW, and *Vėjas I* with 30 MW were selected for the statistical analysis. These wind parks are installed in the Western part of Lithuania, in the seaside area at the following coordinates: *Benaičiai* WP at 56.097, 21.265; *Sūdėnai* WP at 56.087, 21.225; and *Vėjas I* (*Rūdaičiai*) WP at 55.949, 21.172. The distance between WPs *Benaičiai* and *Vėjas I* (Rūdaičiai village) is 18 km, and between WP *Sūdėnai* and *Benaičiai* WP is 3 km. Operating under its average load of 5 MW with the operation time at its installed capacity being 2727 h, *Benaičiai* WP generated 43.6 GWh of electric energy in the year 2008, resulting in its installed capacity efficiency to be 30%. Within the same period of time, WP *Vėjas I* generated 71.8 GWh of electric energy. Annual average power of the latter WP was 8.2 MW, and operation time at its installed capacity was 2393 h with the efficiency of 27%.

For the purpose of statistical research, measured data of maximum power generation variation over the particular time periods of the year 2009 and measured loads of Lithuanian power system over the same time periods were selected.

Power generation by WPs within selected periods of time and Lithuanian power system loads were sampled with 1-second time interval. Measurement data on 1-second step changes allow for investigation of power generation process in wind power plants for different sampling intervals of power averaging [1].

Parameters of variation of wind power plants generated power

Analysis of power generation by the wind power plant reveals that 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 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 generated power of the wind power plant

$$P_{\text{average}} = \frac{1}{n}\sum_{i=1}^{n} P_i \,; \qquad (1)$$

here P_i is the average generated power over selected time interval; n is the number of determined power values.

Changes in power generation might be determined by way of subtracting power generations as follows

$$\Delta P_i = P_{i+1} - P_i; \quad (2)$$

here P_i and P_{i+1} are the average generated power over consecutive selected time intervals.

The following equation is used to determine standard deviations of changes in generated power

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

here n is the number of the measurement made under research; $\overline{\Delta P}$ is the average value of changes of generated power (in this particular case is equal to zero).

The following equation is used to determine correlation coefficient between two changes in generated power of WPs [2]

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

here ΔP_{1i} and ΔP_{2i} are the i-th changes in power generation of the first and the second parks, respectively.

Analysis of variation of wind power plants generated power

For the purpose of evaluating fluctuations in wind power generation, power measurements for 1-second time steps within operating WPPs were used. For the purpose of studying WPP power generation process and its effect on electric power system, time intervals of 30 s., 15 min., and 1 hour of power generation averaging for 1-second time steps were selected. 30 s. and 15 min. step changes in average power generation determine primary and secondary reserves of power generation adjustment that are necessary for frequency and power generation control [3]. 1 hour step changes in average power generation are necessary for sound forecast and planning of power generation by the electric power system as well as for the arrangement of electric power market.

Based on data of measured power generation at WPPs, values of average power generation were calculated and respective arrays made, comprised of 107343 values for 30 s time steps, 3573 values – for 15 min. time steps, and 893 values – for 1 hour time steps. Research was performed in respect of individual power generation by each WPP as well as total power generation by all three WPPs under consideration. Figures 1 and 2 and Table 1 shows main results of the calculations performed.

Analysis of results obtained shows distributions of changes in power generation to be normal ones with the average value of zero (Fig. 1) and calculated standard deviations (σ) with respect to the total installed capacity of all the WPPs under consideration being proportional to the installed capacity of WPP, independent of the time steps of power generation averaging (see Table 1). Standard deviations for 15 min. time steps were found to be more than twice higher than standard deviations for 30 min. time steps, amounting for 2,07 % at *Vėjas I* WP, and 1.22 % at *Sūdėnai* WP. It was also found that sum of relative standard deviations and that of average power generations of all the WPPs under consideration, independent of the time steps of power generation averaging, were higher than total respective parameters of all the WPPs under consideration.

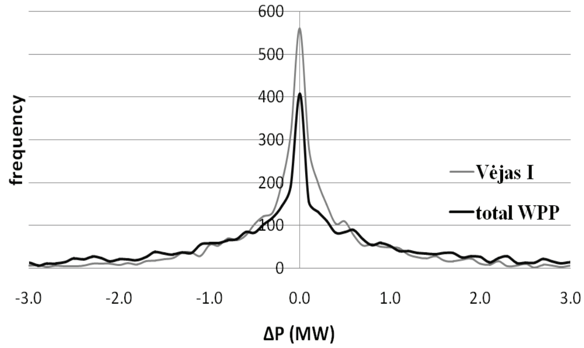

Fig. 1. Distribution of changes in wind parks average power generation for 15 min time interval

Standard deviations and fluctuations of average power generation for 30 s. time steps differed approximately 2 times, and those for 15 min. time steps – approximately 1.3 times. With the increasing time interval of power generation averaging, this difference was found to decrease.

Table 1. Parameters of variations of WPPs power generation

Wind Power Park, installed capacity	Interval of power generation averaging					
	30 s Time Step			15 min. Time Step		
	σ (%)	Maximum change in power generation (%)		σ (%)	Maximum change in power generation (%)	
		+ ΔP	– ΔP		+ ΔP	– ΔP
Vėjas I, 30 MW	0.76	8.71	6.79	2.07	21.5	18.7
Benaičiai, 16,5 MW	0.64	7.04	7.65	1.34	8.45	16.1
Sūdėnai, 14 MW	0.57	6.76	6.32	1.22	10.5	11.0
Total 60,5 MW	1.97	22.5	20.8	4.63	40.4	45.8
Common 60,5 MW	1.02	9.83	8.91	3.39	31.1	37.0

Findings of examination and calculations of correlation coefficients of WPPs power generation for different time steps (see Fig. 2) show that, in all respects, correlation coefficients of power generations among WPPs were positive, whereas those among WPPs and loads were negative. Correlation coefficients of 30 s step changes in average power generation between two WPPs under research were very low and below 0.01, whereas those among WPPs and loads were a little bit higher and up to 0.04. Thus, examined 30 s step changes in average power generation might be considered uncorrelated. Moreover, standard deviations of step changes in power generation were low, too, ranging from 0.57 % to 1.02 % (see Table 1), therefore system frequency control requires for a relatively low primary power reserve.

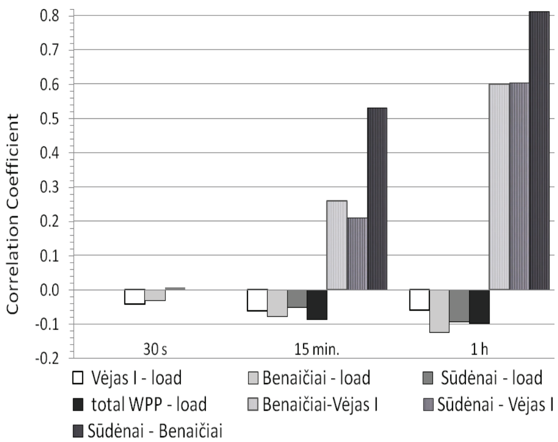

Fig. 2. Correlation of average power variation between wind parks and between wind parks and the system load

Values of correlation coefficients of 15 min. step changes in average power generation between WPPs were significantly higher. The highest correlation of 15 min. step changes in average power generation was found between the adjacent WPs *Sūdėnai* and *Benaičiai*, amounting for 0.53, and correlation between the most distant WPs *Sūdėnai* and *Vėjas I* – 0.21. Correlation coefficients between WPs and loads were found to increase insignificantly, too, ranging from –0.05 to –0.09. Given the increased standard deviations of power generation variance (Table 1), a conclusion can be made that balancing of power generation by wind power plants requires for several times larger secondary power reserve.

With the increasing time steps of power generation averaging, correlation coefficients were found to increase furthermore, and correlation coefficients of variations in power generation for 1 hour time steps between parks were found to be in range of 0.60–0.81, whereas that between WPs and loads – in range of –0.06 to –0.12.

Such values of correlation coefficients prove the fact that development of wind power parks will lead to the increased absolute fluctuations in power generation within the entire energy system and will require for additional operative power reserves [4], although in the relative respective, the need for the latter keeps decreasing.

Influence of wind speed and direction on generated power

For the purpose of determining dependence of wind power generation on wind direction and speed, measurements were taken in the area of *Benaičiai* WP at the height of wind turbines (100 m) of wind power generation units. Based on these findings, a wind rose was made depicting wind time step and wind direction (Fig. 3).

It was found that in Lithuania, at the seaside, winds predominantly occur in Western (W)–Southern (S) 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. Although transient but sufficiently strong winds of E and ESE directions may also occur, with the average wind speed reaching of 8.3 m/s.

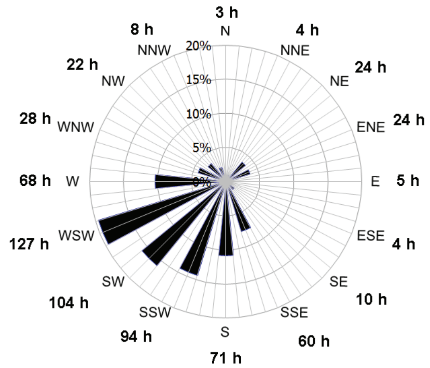

Fig. 3. Wind rose based on time at 100 m height

To find the effect of wind direction on power generation by *Benaičiai* WP arrays of 10 min changes in average power generation were made with respect to wind directions (averages for 10 min time inervals), and diagrams were made enabling to determine maximum power difference between the predominant wind directions.

The obtained curves of power generation by WPs (Fig. 4) were approximated by the 5th degree polynomials that are jointly expressed as follows [5]

$$P = a + b_1 v + b_2 v^2 + b_3 v^3 + b_4 v^4 + b_5 v^5 \, ; \qquad (5)$$

here P is the power of WP; v is the wind speed; a and b are statistical parameters of the function.

The obtained average wind speeds for 10 min time intervals ranged from 3.5 m/s to 12 m/s.

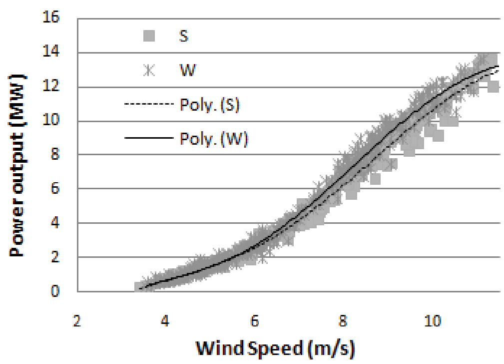

Fig. 4. Curves of power generated at *Benaičiai* WP

Analysis of research findings showed that wind directions had influence on the amount of power generated by WP at all three wind directions under research, and maximum power generation difference was found to exist between Western (W) and Southern (S) wind directions.

Under the same wind speed, the minimum difference of power generation was found to exist at 5 m/s wind speed. Further, with increasing wind speed power generation difference increases too, and at 9 m/s wind speed reaches 4.1% of the installed capacity (see Fig. 4 and Table 2). Afterwards, decrease in power generation difference could have been determined by the volume of statistical data.

In order for the forecasts of variation in WP power generation to be more precise, theoretical curves suggested by producers should be recalculated based on the findings of statistical observations while taking into consideration wind directions.

Table 2. Values of power generation by *Benaičiai* WP at W and S wind directions

Wind direction	Para-meters	Wind speed				
	V, m/s	7.0	8.0	9.0	10.0	11.0
W	*P*, MW	4.6	6.8	9.2	11.3	12.7
S	*P*, MW	4.2	6.3	8.5	10.7	12.4
	Δ P, %	1.9	3.3	4.1	3.5	1.9

Composition of power system regimes and determination of operating power reserves as well as assessment of power generation by wind parks ant its variation range, the effect determined by wind direction and geographical deployment of wind parks must be taken into consideration. Standard deviations of WP wind power generation and their dependence on wind direction must be determined in advance for every particular case individually.

Conclusions

The correlation of wind power generation variations between wind parks was found to be positive, whereas correlation between parks and load – negative, consequently penetration of wind power plants into power system is expected to increase the need for required operating power reserves

Changes in 30 s average power generation of wind parks are reported to correlate weakly, and their standard deviations – to be low, therefore primary power generation control can be expected to be of low relevance for system power control.

Values of correlation coefficients and standard deviations for changes in 15 min average power generation of wind parks were found to be sufficiently high, meaning that balancing of wind power generation will require for rather vast secondary power generation regulation reserve.

Research showed that power generation of the wind park may differ at the same wind speed depending on the wind direction.

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Received 2011 06 15
Accepted after revision 2011 12 17

R. P. Deksnys, A. Stankevicius. Statistical Analysis of Power Generation of Wind Parks // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 2(118). – P. 53–56.

Rapid development of wind power plants and increasing of their generated variable power may cause perturbations of power system operating conditions and power unbalance. Wind power plants' power does not depend on variation of power system load and may be forecasted with insufficient accuracy. That requires additional balancing capacities, energy storage equipment and controllable load. Comprehensive statistical analysis and estimation of operating power plants' power may decrease the problems caused by wind power plants. The changes and their distributions and parameters of wind power plants' generated power were analysed. Factors of power changes correlation and their values depending on power averaging windows are determined. Relationships of power correlations between separate wind parks and wind parks and consumers load are analysed and influence of wind direction and speed on wind parks' generated power is evaluated. Ill. 4, bibl. 5, tabl. 2 (in English; abstracts in English and Lithuanian).

R. P. Deksnys, A. Stankevičius. Vėjo elektrinių parkų generuojamos galios statistinė analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 2(118). – P. 53–56.

Sparti vėjo elektrinių plėtra ir didėjanti jų generuojama kintamoji galia gali sukelti elektros energetikos sistemų darbo režimų sutrikimus ir galių disbalansą. Vėjo elektrinių galia nepriklauso nuo elektros energetikos sistemos apkrovos kitimo ir yra nepakankamai tiksliai prognozuojama. Tai reikalauja papildomų balansavimo galių, elektros energijos kaupimo įrenginių ir valdomos apkrovos. Išsami veikiančių elektrinių galių statistinė analizė ir įvertinimas gali sušvelninti vėjo elektrinių sukeliamas problemas. Tam tikslui buvo ištirti vėjo elektrinių parkų generuojamos galios pokyčiai, jų kitimo skirstiniai ir parametrai. Nustatyti galių pokyčių koreliacijos koeficientai ir kaip jų vertės priklauso nuo galių vidurkinimo laiko intervalų. Ištirtos galios koreliacijų priklausomybės tarp atskirų vėjo elektrinių parkų, tarp vėjo elektrinių parkų ir elektros vartotojų apkrovų ir nustatyta vėjo krypties ir greičio įtaka vėjo elektrinių parkų generuojamai galiai. Il. 4, bibl. 5, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).