Scientific quarterly journal ISNN 1429-7264
Agricultural Engineering
2014: 3(151):119-127
Homepage: http://ir.ptir.org

DOI: http://dx.medra.org/10.14654/ir.2014.151.064

QUALITY CHARACTERISTICS OF ELECTRIC ENERGY GENERATED IN A WIND POWER PLANT

Krzysztof Nęcka*, Jarosław Knaga

Department of the Power Industry and Automation of Agricultural Processes
University of Agriculture in Kraków
*Contact details: ul. Balicka 116B, 30-149 Kraków, e-mail: krzysztof.necka@ur.krakow.pl

ARTICLE INFO

Article history:
Received: March 2014
Received in the revised form: May 2014
Accepted: August 2014

Keywords:
wind generation
electric energy
quality of energy
electricity grid

ABSTRACT

The objective of the analysis was the quality of electric energy in the place of attachment of a single wind power plant to the electricity grid. This objective was performed based on the author's own research carried out in a LV switching station located in the place of attachment of a wind turbine with the power 150 kW to the MV distribution network. The object of the research was located in the northern part of Małopolskie Voivodeship. The assessment of the quality of electric energy was carried out based on the requirements set forth in the Ordinance of the Minister of Economy on detailed conditions of functioning of the power system and the Manual of Movement and Operation of Distributive Network. Based on the analysis, which was carried out, one may assume that the requirements referring to frequency changes, efficient value of the supply voltage, voltage unbalance and its deformation from the sinusoidal waveform have been met. In the period which was covered by the research, during the wind turbine work, insignificant surpasses of the admissible level of the root mean square of voltage were reported, but their number constituted less than 0.07% of observations. During the research, also 20 voltage dips of values exceeding 10% of the rated voltage, average depth of which was 172V were reported. In majority these were disruptions caused by other receivers connected to the network.

Introduction

Wind is one of the renewable sources of energy, energy potential of which is estimated at the level of power equal to 40 TW (Korban, 2010). First mentions on the use of wind energy by man reach 3000 B.C. When sails for boat drive began to be used in Egypt. Few hundreds years later around 640 B.C. first information on the use of wind, inter alia, for mills drive and drying off rice fields in China appeared. Windmill structures construed then had a vertical axis of rotation. In Europe, windmills started to be built in the 12th century and in majority these were windmills with the horizontal axis of rotation. Whereas, the first wind power station was built in Denmark by Poul La Cour in the end of the 19th century. Since that time, many structures of wind power stations had been developed, which differ both on account of the mechanical solutions as well as the structure of the generators of electric energy applied there (Kaldellis and Zafirakis, 2012; Niedźwiecka-Filipiak and Borcz, 1998; Polak and Baranski, 2006).

The total power of wind power stations located on all continents in 2011 was 240 GW and increased in relation to the previous year by approx. 40 GW. The highest increase by 18 GW of the installed power was reported in China. Next positions were taken by the USA (6.8 MW) and India (3MW). In all countries of the European Union a total increase of power by 9.6 GW was reported, out of which the highest number in Germany (2.1 GW), Great Britain (1.3 GW) and Spain (1GW). Assuming an average annual time of operation of the wind turbine as 2200 hours, the obtained electric energy from the wind sources is at the level of 528 TWh. Such amount of the produced energy can satisfy approximately 2.7% of the global demand for electric energy (Global Wind Report, 2011; BTM Consult, 2011).

According to the state as of 31st December 2013 in Poland in the wind power industry there were 3389.5 MW installed (Polskie Stowarzyszenie Energetyki Wiatrowej)**.** On this basis, indexes of the power installed in the wind energy industry per one citizen of the value 0.088 kW and also per a km^2 of the land area at the level of 10.84 kW are the lowest in Europe. Total volume of electric energy generated in Poland by wind turbines along with other renewable energy sources in 2013 was 5822 GWh which constitutes over 2.5% of the total consumption of electric energy (*Polskie Stowarzyszenie Energetyki Wiatrowej*).

The need to meet obligations resulting from, inter alia, the signed protocol in Kioto on reduction of the carbon dioxide emission is a strong impulse for the growth of the wind energy dynamics in Poland, which we have observed in the recent years. However, a systematic increase of the wind power stations participation in the structure of production units brings some negative effects. The most frequent problems are those related to a correct management of generating unit operation, possessed centrally in order to ensure stability of the system and maintain the required quality of electric energy. Main sources which cause deterioration of the electric energy is a change of the rotational moment related to a periodical shadowing of propeller blades by a tower, change of the rotational moment resulting from non-uniform wind speed at various heights and impact of the converter systems installed in some types of wind power stations. The scale of disadvantageous impact on the operation of the electro-energy system to a great extent depends also on the degree of concentration of units which generate wind in this area, distance from conventional wind power stations and the condition of electricity grid (Iwaniak and Chojnowski, 2009; Kowalski, 2007; Nirmal-Kumar, Nair, Jing, 2013; Stavrakakis G.S., 2012; Tascikaraoglu, Uzunoglu, Vural, Erdinc, 2011). Problems of low-investing of distribution networks and transmission grids, and thus unsatisfactory quality of electric energy is especially visible on rural areas (Reiter and Kukiełka, 2011; Trojanowska and Nęcka, 2010), which on account of availability of the area theoretically give the highest possibilities of formation of new wind farms.

Objective of the paper, methodology and object of the research

The objective of the paper was to analyse the electric energy quality in the place of attachment of a single wind power station to the electricity grid and in particular frequency and the root mean square of voltage generated by this power station.

The quality of electric energy is characterized as the quality of supply voltage and reliability of its supplies. The quality of voltage is characterized with inter alia frequency of voltage, its root mean square value and the degree of deformation from the sinusoidal course. Whereas, reliability of the electric energy supply is described mainly with indexes concerning frequency, duration and territorial scope of short and long power cuts in the electric enegry supply.

The objective of the paper was performed based on the author's own research carried out in a LV switching station located in the place of attachment of a wind turbine of Nordtank XLR type with the power 150 kW to the MV distribution network. The object of the research was located on the territory of Słomianki commune in the northern part of Małopolskie Voivodeship. The investigated wind power station was produced in 1997 whereas, in Poland it has been working since 2007. The research which was carried out, consisted in the constant measurement of the amount which characterizes the electric energy quality, which then was averaged and registered in 10-minutes time intervals. For measurements, which were carried out from July to December 2013 a portable analyser of network parameters AS-3 Plus was applied. The result of the investigated research was development of an extensive data base including information on the impact of the wind power station on the quality of electric energy in the distribution network.

The assessment of the quality of electric energy was carried out based on the requirements set forth in the Ordinance of the Minister of Economy as of 4th May 2007 on detailed conditions of functioning of an electro-energy system and the Manual of Movement and Operation of Distributive Network [Polish: IRiESD]. Based on the obtained results it was verified whether particular parameters which characterize the energy quality in the place of attachment of the wind power station to the network of the Distribution System Operator are met. If in the period of research, surpasses of border values of particular parameters were identified, according to IRiESD requirements, it was also checked whether the total time of their duration within one week, when surpasses were reported, is longer than the admissible one.

In the effective acts of law, the frequency of the supply voltage is mentioned as a first parameter which characterizes the quality of voltage. Rated value of frequency for the whole heavy current system in Poland is 50 Hz not related to the root mean square value of voltage. Average value of frequency measured for 10 seconds may deviate from the rated value by ±1% for 99.5% of the one week period. Whereas, for the entire week, it may not change by more than +4% and -6% of the rated value.

For generating units, attached to the distribution network, it is required that for each week at least 95% from the set of 10 - minute average root mean square values of the supply voltage it was within ±5% of the rated value.

Additionally, the operation of the wind power station may not cause sudden changes of root mean square values of the supply voltage which exceed 3% even during the start-up and withdrawal of the wind power station. However, if a regular operation of the wind power station is the source of voltage changes and they have a cyclic nature of frequency from 10 disturbances per one hour, then the change of voltage may not exceed 2.5%. At the increase of disturbances frequency above 100, fluctuations of voltage must be lower than 1.5%. Fast changes of voltage caused by the change of power of the wind power station of frequency 1 Hz should be of amplitude not exceeding 0.7%.

For the supply voltage unbalance it is required that within each week 95% from the set of 10-minute average root mean square values of the constituent symmetrical, the opposite order of the supply voltage was within 0% to 2% of the constituent value of a compatible order.

In the literature, few methods of determination of the unbalance coefficient from the root mean square values of interfacial tensions (EN 61000-4-30; EN 61000-2-2, EN 61000-2-4, EN 61000-4-12, ГОСТ 13109-97, Engineering Recommendation P29) are known. However, from the research results presented by Kosobudzki (2011) one may assume that all methods of determination of the unbalance coefficient give comparable results and existing differences between the obtained results do not exceed few percent.

On account of the paper objective, which consisted in the analysis of the quality of electric energy, results obtained according to the requirements of the standard PN-EN 61000-4-30:2011, pursuant to which the value of the tension unbalance coefficient is determined according to the relation 1, were presented:

$$K_{U2} = 100\% \cdot \sqrt{\frac{1-\sqrt{3-6\cdot\beta}}{1+\sqrt{3-6\beta}}} \tag{1}$$

where:

$$\beta = \frac{U_{AB}^4 + U_{BC}^4 + U_{CA}^4}{\left(U_{AB}^2 + U_{BC}^2 + U_{CA}^2\right)^2}, \tag{2}$$

U_{AB}, U_{BC}, U_{CA} – root mean square values of interfacial tensions.

In the place of attachment of the wind power station to the MV distribution network, the value of particular higher harmonics referred to the basic harmonic may not exceed 0.7%. Whereas, coefficient of tension deformation THD_U which includes all harmonics to the 40th row, in total must be lower than 4%.

Research results

During the research of frequency of the supply voltage, it was between 49.87 Hz and 50.10 Hz independently from the operation of the wind power station. The analyses (fig. 1) which were carried out, show that in over 80% of observations, frequency of supply voltage oscillated in a very narrow scope of variability from 49.96 Hz to 50.04 Hz.

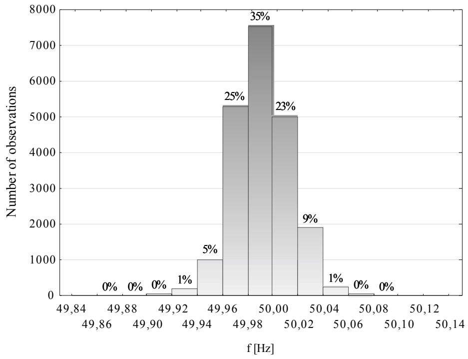

Figure 1. Histogram of the supply voltage frequency

The root mean square value of this voltage was the next parameter of the supply voltage, which was researched.

The average 10-minute root mean square values of supply voltage in the period of all three phases have changed from 224 V to 242 V. In the time when the wind power station worked or worked but with a very low load (fig. 2) a root mean square value of supply voltage oscillated between 226 V and 238 V. During the period of operation of the wind power station with the load exceeding 2.3 kW border values of the tension were 224 and 242 V. Registered average 10-minute maximum values of supply voltage slightly exceeding the admissible value, which was 241.5 V were registered only at a higher production of electric energy. The amount of reported surpasses was however only 15 which constituted almost 0.07% of all observations. One may thus acknowledge that requirements referring to the root mean square value of the supply voltage were met.

On account of the limitations of the used analyser (low volume of memory), during the research, only fast changes of the supply voltage values with values exceeding 10% of the rated voltage were registered. In the period covered by analysis, which was 150 days 20 voltage dips of average depth of 172 V was reported. Its maximum value was 5V. Duration of disruption oscillated between 40 and 1500 ms and its average value was 0.375 s. Due to the fact that in 75% voltage fluctuations took place only in the first stage additional research was carried out which aimed at determination whether disruptions came from the wind power station or from the network. Analysis of time of their appearance showed that in majority of cases, these disruptions took place in the time, when the wind power station did not work. Voltage dips during the work were reported only in the period of electric energy production in extreme conditions when hurricane Ksawery was over Poland. During the research short stoppages in supply were reported 8 times. Their average time of duration was 1.2 s and they occurred in all phases at the same time. These events were registered independently from the electric energy production by the wind power station. However, on account of the equipment limitations based on the research which was carried out, it is impossible to clearly assess whether normative requirements concerning sudden supply voltage changes are met.

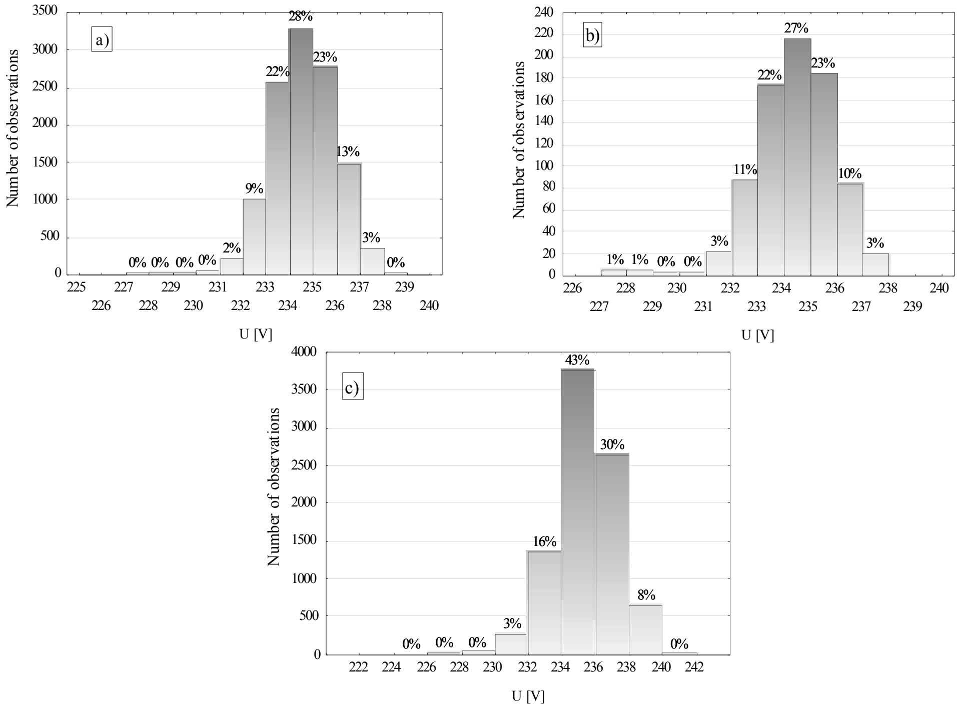

Figure 2. Histogram of the root mean square value of voltage, when: a) a wind power station does not work, b) works with a minimum load of (to 2.3 kW), c) works with a load above 2.3 kW

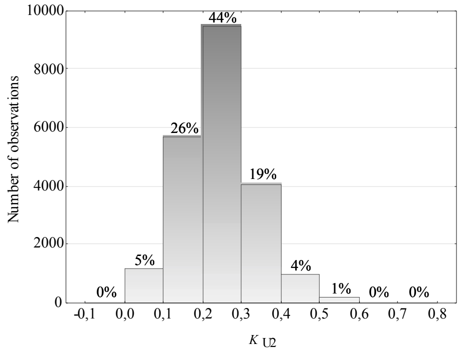

Figure 3. Histogram of changes of the coefficient of voltage unbalance

The analyses which were carried out (fig. 3) show that in the whole period of research, the value of coefficient of voltage unbalance K_{2U} oscillated between 0a 0.6% not exceeding the border level which was 2%.

Figure 4 presents the course of the distribution function of the relative frequency of the determined levels of the voltage deformation coefficient THD_U. During the research, the value of the average coefficient of voltage deformation THD_U was 1.85 and its maximum values reached the level of 3.8%. The participation of observations, the level of which exceeded 3%, was very low and was only 1%. In comparison to the previous research on the quality of electric energy in rural distribution networks [Trojanowska, Nęcka, 2010] one may see that in the researched line of the value of the analysed coefficient it is at the lower level. The analyses which were carried out show that the requirements of the admissible deformation of the voltage curve from the sinusoidal waveform are maintained.

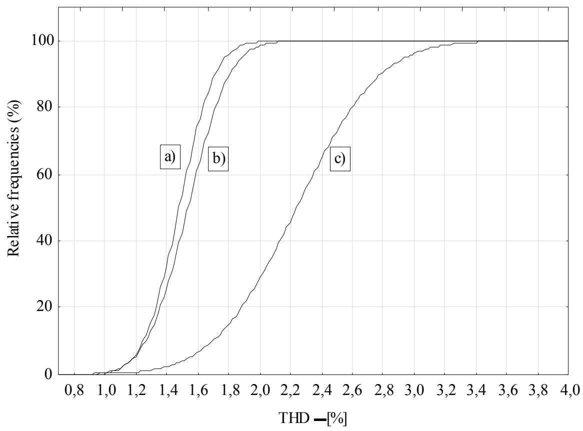

Figure 4. Empirical distribution functions of the voltage deformation coefficient THD_U when: a) a wind power station does not work, b) works with a minimum load of (to 2.3 kW), c) works with a load above 2.3 kW

Conclusion

Based on the analyses which were carried out, one may recognize that requirements concerning the changes of frequency and the root mean square value of the supply voltage have been met. In the period which was covered by the research, during the wind power station work, insignificant exceeding of the upper border value of 241.5 V were recorded, but their number constituted less than 0.07% of observations. Moreover, values of coefficients concerning tension unbalance and its deformation from the sinusoidal course were within the limits considered as admissible.

On account of the limitation of the applied analyser, it is impossible to explicitly assess the impact of the investigated wind power station on the sudden changes of the supply voltage and the index of flickering. Since, during the research only 20 voltage dips were registered but of values exceeding 10% of the rated voltage, average depth of which is 172 V. In majority, however, these were disruptions, the source of which, are other receivers attached to the network. In the further part of the research, the use of the advanced analyser and the detailed analysis in the above-mentioned indexes is planned.

The research, which was carried out, show that cooperation of single wind powers stations of relatively low power with electric energy network with a suitable technical condition, which compose its elements and devices, does not result in deterioration of the electric energy quality. Unquestionable advantage of diffused generation is limitation of transmission losses due to limitaton of the distance between the source of its generation and final recipients.

References

Global Wind Report – Annual market update (2011). *Global Wind Energy Council*. Pozyskano z: http://www.gwec.net.

BTM Consult, World Market Update 2011.

Polskie Stowarzyszenie Energetyki Wiatrowej. *Energia wiatrowa w Polsce*. Pozyskano z: http://www.pwea.pl/pl/energetyka-wiatrowa/ewi-w-polsce

ENION – Spółka Akcyjna. *Instrukcja Ruchu i Eksploatacji Sieci Dystrybucyjnej*. 31 marca 2009 roku.

Iwaniak, A.; Chojnowski, P. (2009). Jakość energii elektrycznej z siłowni wiatrowej. *Wiadomości Elektrotechniczne*, *11*, 14-17.

Kaldellis, J.K.; Zafirakis, D.P. (2012). 2.21 - Trends, Prospects, and R&D Directions in Wind Turbine Technology. *Reference Module in Earth Systems and Environmental Sciences, from Comprehensive Renewable Energy*, *Vol.2*, Current as of 15 January 2014, 671-724.

Korban, Z. (2010). Wybrane aspekty wykorzystania energetyki wiatrowej w Polsce. *Górnictwo i geologia*, *Tom 5, Zeszyt 2*, Politechnika Śląska, Gliwice, 79-90.

Kosobucki, G. (2011). Pomiar niesymetrii napięcia w sieciach trójfazowych. *Prace Naukowe Instytutu Maszyn, Napędów i Pomiarów Elektrycznych Politechniki Wrocławskiej*, *65*, 401-410.

Kowalski, Z. (2007). *Jakość energii elektrycznej*, Wydawnictwo Politechniki Łódzkiej, Łódź 2007.

Niedźwiecka-Filipiak, I.; Borcz, Z. (1998). Zastosowanie niekonwencjonalnych źródeł energii w infrastrukturze wsi. *Inżynieria Rolnicza*, *1*(2), 55-62.

Nirmal-Kumar, C.; Nair, Lei J. (2013). Power quality analysis for building integrated PV and micro wind turbine in New Zealand. *Energy and Buildings*, *Vol. 58*, 302-309.

PN-EN 50160:2010, *Parametry napięcia zasilającego w publicznych sieciach elektroenergetycznych*

PN-EN 61000-2-12:2004, Kompatybilność elektromagnetyczna (EMC), *Poziomy kompatybilności dla zaburzeń przewodzonych niskiej częstotliwości i sygnałów sygnalizacji w publicznych sieciach zasilających średniego napięcia.*

PN-EN 61000-2-2:2003. Kompatybilność elektromagnetyczna (EMC), *Poziomy kompatybilności zaburzeń przewodzonych małej częstotliwości i sygnałów przesyłanych w publicznych sieciach zasilających niskiego napięcia.*

PN-EN 61000-4-30:2011, Kompatybilność elektromagnetyczna (EMC), *Metody badań i pomiarów - Metody pomiaru jakości energii.*

Polak, A.; Baranski, M. (2006). Porównanie turbin wiatrowych. *Zeszyty Problemowe – Maszyny Elektryczne*, *74*, 147-151.

Reiter, E.; Kukiełka, L. (2011). Problematyka wykorzystania energii wiatru w gospodarstwie rolnym. *Inżynieria Rolnicza*, *5*(130), 243-249.

Rozporządzenie Ministra Gospodarki z dnia 4 maja 2007 w sprawie szczegółowych warunków funkcjonowania systemu elektroenergetycznego. Dz. U. 2007 r. Nr 93, poz. 957; 2008 r. Nr 30, poz. 178; 2008 r. Nr 162, poz. 1005.

Stavrakakis, G.S. (2012). Electrical Parts of Wind Turbines *Reference Module in Earth Systems and Environmental Sciences*, *from Comprehensive Renewable Energy*, *Vol. 2,* 269-328.

Tascikaraoglu, A.; Uzunoglu, M.; Vural, B.; Erdinc, O. (2011). Power quality assessment of wind turbines and comparison with conventional legal regulations: A case study in Turkey, *Applied Energy*, *Vol. 88, Issue 5*, 1864-1872.
Trojanowska, M.; Nęcka, K. (2010) Badanie wskaźników charakteryzujących jakość napięcia w wiejskich sieciach elektroenergetycznych. *Inżynieria Rolnicza*, *4*(120), 269-274.

CHARAKTERYSTYKA JAKOŚCI ENERGII ELEKTRYCZNEJ GENEROWANEJ W SIŁOWNI WIATROWEJ

Streszczenie. Celem pracy była analiza jakości energii elektrycznej w miejscu przyłączenia pojedynczej siłowni wiatrowej do sieci elektroenergetycznej. Cel ten zrealizowano na podstawie badań własnych wykonanych w rozdzielni nN, zlokalizowanej w miejscu przyłączenia siłowni wiatrowej o mocy 150 kW do sieci rozdzielczej SN. Obiekt badań był zlokalizowany w północnej części województwa małopolskiego. Oceny jakości energii elektrycznej dokonano w oparciu o wymagania zawarte w Rozporządzeniu Ministra Gospodarki w sprawie szczegółowych warunków funkcjonowania systemu elektroenergetycznego oraz Instrukcji Ruchu i Eksploatacji Sieci Dystrybucyjnej. Na podstawie wykonanych analiz można uznać, że wymagania odnośnie zmian częstotliwości, wartości skutecznej napięcia zasilającego, asymetrii napięcia oraz jego odkształcenia od przebiegu sinusoidalnie zmiennego zostało spełnione. W okresie objętym badaniem podczas pracy siłowni wiatrowej rejestrowano nieznaczne przekroczenia dopuszczalnego poziomu wartości skutecznej napięcia, ale ich liczba stanowiła niespełna 0,07% obserwacji. W czasie badań zarejestrowano również 20 zapadów napięcia o wartościach przekraczających 10% napięcia znamionowego, których średnia głębokość wynosiła 172V. W większości były to zakłócenia, których źródłem są inne odbiorniki przyłączone do sieci.

Słowa kluczowe: generacja wiatrowa, energia elektryczna, jakość energii, sieć elektroenergetyczna