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Power quality experimental research at the Primorsky wind power station

Abstract. *The article presents results of experimental studies of power quality indicators conducted at the wind farm with 52 DFIG wind turbines with a unit capacity of 3.8 MW by General Electric connected to 150 kV network. The way how the research has been prepared and the research algorithm by Metrel MI 2885 power quality analyzer are described. The analysis of changes in Total Harmonic Distortion (THD) voltage and current has been performed. Frequency spectra and maximum values of particular voltage and current harmonics are presented. Short-term abnormal THD of the current curve have been recorded. Wind power plant simulation model and simulated turbulent wind flow for further studies of wind turbines EMC with distribution network are presented.*

Streszczenie. *W artykule przedstawiono wyniki badań eksperymentalnych wskaźników jakości energii przeprowadzonych w farmie wiatrowej, zawierającej 52 turbiny wiatrowe DFIG o mocy jednostkowej 3,8 MW firmy General Electric, przyłączonej do sieci 150 kV. Opisano sposób przygotowania badań i algorytm działania analizatora jakości energii Metrel MI 2885 wykorzystanego w pomiarach. Przeprowadzano analizę zmian współczynnika odkształcenia (THD) napięcia i prądu. Przedstawiono widma częstotliwościowe i wartości maksymalne poszczególnych harmonicznych napięcia i prądu. widma krzywych prądowych Zidentyfikowano występujące w stanach zakłóceniowych krótkotrwałe, ale znaczne wzrosty wartości THD w przebiegach rądu. Przedstawiono model symulacyjny elektrowni wiatrowej i przykładowy symulowany przebieg zmian prędkości wiatru do dalszych badań parametrów EMC turbin wiatrowych współpracujących z siecią dystrybucyjną. (**Badania jakości energii w Przymorskiej elektrowni wiatrowej**).*

Keywords: wind farms, DFIG wind turbine, EMC, power quality, voltage distortion
Słowa kluczowe: farmy wiatrowe, turbiny wiatrowe typu DFIG, EMC, odkształcenie napięcia

Introduction

When coping with various tasks of designing, operating and reconstructing electrical networks, questions have arisen of ensuring electromagnetic compatibility. One of the aspects of electromagnetic compatibility problems is the occurrence of nonlinear voltage distortions or non-sinusoidal modes.

This issue is in Ukraine most relevant nowadays in designing networks with distributed generation of electric energy from wind power plants. This is due to the fact that the share of electric energy generated by wind power plants in the electric network over the past 5 years has grown from 0.3% to 2.15%, and the installed capacity of the Ukraine wind energy sector at the end of 2019 reached 1,170 MW. Only last year 637.1 MW was commissioned in Ukraine, which means almost 10-fold growth compared to 2018 - 67.8 MW [1].

The problem of electromagnetic compatibility of wind turbines with a distribution network today is not fully understood [2-7]. Basically, research is being conducted into questions of the appearance and influence of higher harmonics generated by wind turbines [8-12]. However, the study of harmonic components occurrence does not take into account the wind flow turbulence effect on the currents and voltages amplitude spectra. Among other pressing problems in distributed generation networks, there is the issue of identifying sources of distortion and assessing their contribution to the deterioration of electricity quality at the point of assessment [13].

In addition, the issues of interharmonics components appearance and distribution in electric networks with distributed generation as a result of wind power stations in general and wind turbines separately operation have not been sufficiently studied.

Measurement procedure

For the correct analysis of the complex processes of wind turbines impact on power system from the point of view of electromagnetic compatibility and power quality in a common network, it is necessary to carry out not only theoretical, but also experimental researches of the system. To solve the problem of analyzing the harmonic distortion spreading in systems with wind turbines with adjustable speed with partial frequency conversion, a number of experimental studies were carried out at an existing wind farm, connected to a common network.

For experimental studies, the Primorsky wind power station was chosen, which is located near Borisovka, Zaporizhzhya region in Ukraine. The wind farm includes 52 wind turbines with a total installed power of 200 MW. The site is divided into two groups: Primorskaya-1 (PS-1) and Primorskaya-2 (PS-2). Each of the two groups is equipped with 26 wind turbines and two 150/35/10 kV transformer substations with 50 MVA each for the transfer of energy to the power system.

At the power plant, GE 3.8-130 wind turbines manufactured by General Electric with a unit capacity of 3.8 MW were installed. The principle of their operation is based on the wind turbine type C electrical part construction with adjustable speed with partial frequency conversion. The concept is based on a doubly fed induction generator (DFIG), which allows the adjustment of the wind turbine speed in the range of ± 30% of the generator synchronous speed. The main parameters of GE 3.8-130 DFIG wind turbine are given in table 1.

For the reliability of power quality indicators assessment, Metrel MI 2885 Master Q4 power quality analyzer is used, which refers to class S and fully complies with the IEC 61000-4-30 power quality standard [14].

The analyzer includes a number of measuring functions, namely: analysis of harmonics and interharmonics up to the 50^{th} harmonic, total harmonic distortion, analysis of power quality according to EN 50160 [15]. The device also has two main registration modes: “General registration” and “Signal form registration” [16].

At the Primorsky wind power station, a series of power quality indicators measurements at the 150 kV and 35 kV voltage with 30 to 56 hours total duration with the power quality analyzer Metrel MI2885 were carried out, at the connection point of 13 wind turbines on PS-2 substation.

The following issues were resolved during the measurements of power quality indicators:

– determination of wind turbines impact levels with adjustable speed with partial frequency conversion on the power quality when connected to a common network;
– obtaining information on the actual level of higher harmonics and interharmonics in the AC three-phase network to which the wind farm is connected;
– determination of the influence levels of time-varying wind flow at the distortion level of sinusoidal current and voltage curves of the network.

Table 1. The main parameters of the studied system

Parameter	Value
General power supply network	
Grid rated voltage	150 kV
Grid frequency	50 Hz
Rated power of the transformer 1	55 MVA
Rated voltage of the transformer 1	150/35/10 kV
Rated power of the transformer 2	4,78 MVA
Rated voltage of the transformer 2	35/6/0.69 kV
Generator	
Generator type	DFIG
Model	DF1NXS 120 95/4GH/5
Rated power	3.8 MW
Rated power factor	0.87
Rated stator/rotor voltage	6000/825 V
Rated stator/rotor current	391 B/1486 A
Nominal speed	1741 rpm
Number of poles	4
Converter	
Rated grid/rotor voltage	690/750 V
Rated grid/rotor current	700/1700 A
Grid/rotor frequency	50/25 Hz

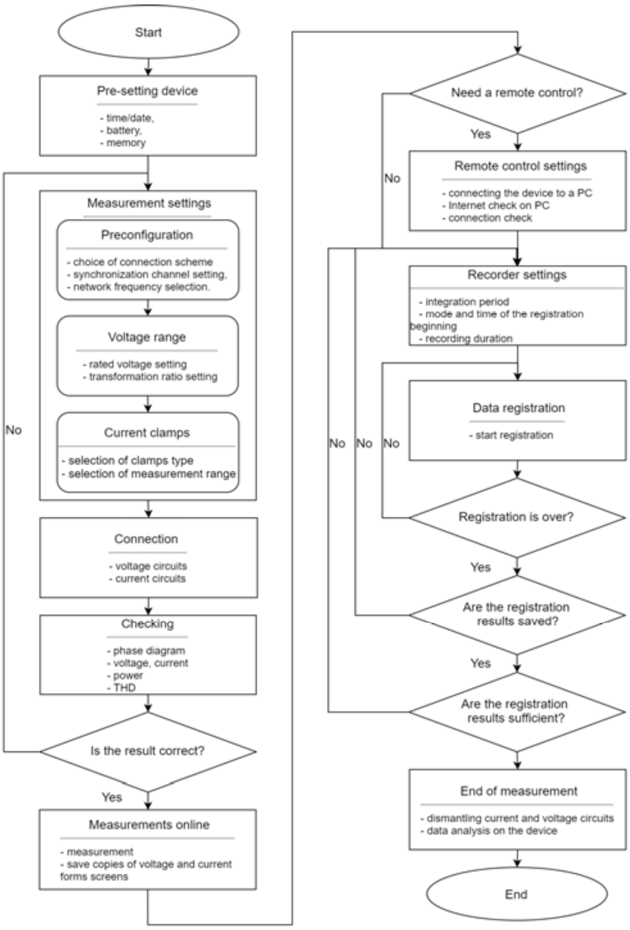


Fig. 1. Algorithm of experimental research

Due to the fact that during the measurements it was not possible to connect the device directly to the primary circuits, it was decided to carry out measurements in the secondary circuits, taking the required values from measuring current and voltage transformers of busbars 150 kV and 35 kV. The algorithm for preparing and conducting experimental research is shown in Figure 1.

To connect the analyzer, some standard accessories of Master Q4 instrument were used such as measuring probes for voltage measurement with a "crocodile" type clamp and flexible current clamps Smart A 1227 for direct measurement of currents with the selected measuring range of 30 A (3 A ÷ 60 A).

Measurements were performed according to the 3-phase 4-wire scheme in the “general recording” mode in autumn and winter under different weather conditions with the minimum possible registration interval Δt = 1 s. It should be noted that the device provides approximately 3 readings per second in the continuous sampling mode, measurements in all channels were performed simultaneously [16].

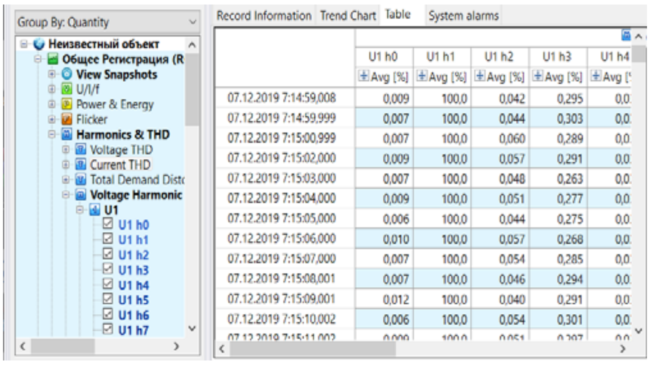


Fig. 2. Table amplitudes of higher harmonics of phase voltage

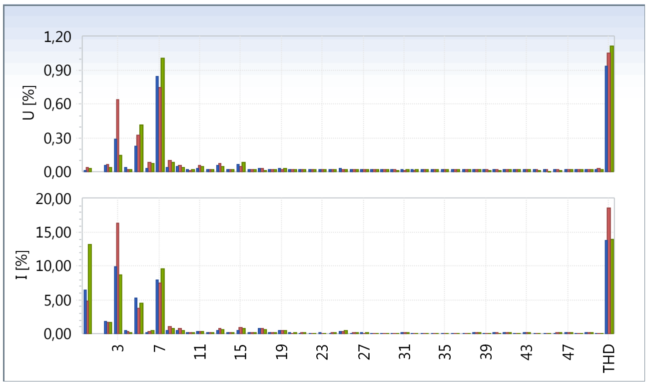


Fig. 3. Harmonic spectrum of output voltages and currents

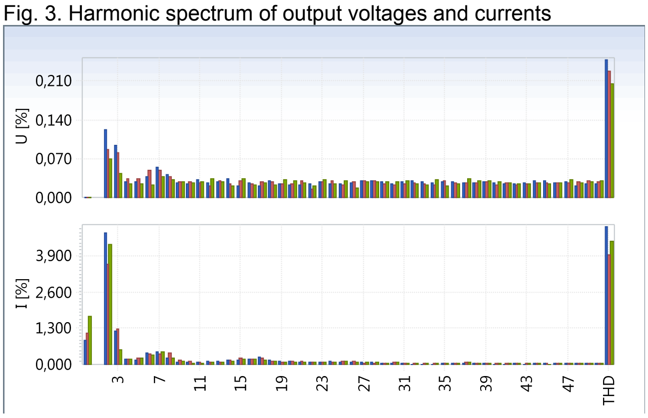


Fig. 4. Interharmonic spectrum of output voltages and currents

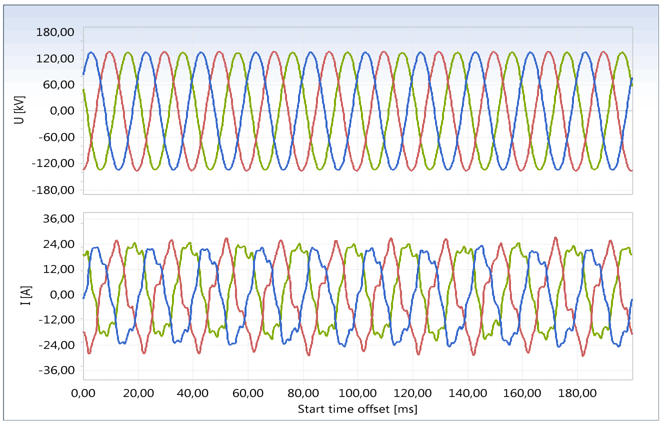


Fig. 5. Output voltage and current curve

The following values were registered in the "general registration" mode: voltage, current, frequency, power, energy, 50 harmonics and 50 interharmonics of current and voltage, asymmetry, voltage deviation. The measurement results were recorded by the device and exported to a PC using the Metrel PowerView software.

Data can be presented in a tabular form (Fig. 2) or in a graphical form (Fig. 3-4). Figure 5 shows the voltage and current curves that correspond to the spectra shown in Figures 3-4.

Collection of measurement data

During a series of experimental research at 150 kV and 35 kV of the Primorsky wind power station, data arrays were obtained with the wind turbine operation parameters values. This allowed analyzing the curve distortion of output currents and voltages generated in the distribution network by wind turbines with adjustable speed with partial frequency conversion. For example, table 2 provides information on the experimental studies recording intervals.

Table 2. Intervals of experimental studies

№	Interval duration, s	Start date	Start time	Stop time	Duration	Number of intervals
150 kV						
1	1	06.12.2019	14:21:12	19:26:33	05:05:21	18 321
2		06.12.2019	19:29:41	07:14:53	11:45:13	42 313
3		07.12.2019	07:14:59	18:48:43	11:33:54	41 625
4		07.12.2019	18:48:50	06:05:55	11:17:05	40 626
5		08.12.2019	06:06:16	16:17:10	10:10:54	36 658
6		08.12.2019	16:17:20	22:17:20	06:00:00	21 600
				∑	55:52:26	201 143
35 kV						
7	1	12.02.2020	11:56:18	23:56:18	12:00:00	43 200
8		13.02.2020	10:26:25	17:27:23	07:00:58	25 258
9		13.02.2020	17:28:24	05:28:24	12:00:00	43 200
				∑	31:00:58	111 658

During the period of experimental research in December, in 150 kV network, overvoltage's in generation mode were recorded, which exceeded 10 % limits allowed by the standards [15-16] and reached maximum values of 96.39 kV at 3rd, 96.96 kV at 5th and 96.72 kV at 6th research interval (Fig. 6-8, a). The currents for the period of experimental research were in a wide range from 3 to 120 A.

During the period of experimental research in February, the 35 kV voltage were within the norm from 19.7 to 20.8 kV. However, 35 kV voltage dip on the 9th interval at 00:42 was recorded, which reached 17.7 kV and associated with voltage regulation of transformer (Fig. 10a). The currents for the period of experimental research were in a wide range from 230 to 740 A.

Analysis of the experimental results

In figures 6-8 (b) and 10b shows graphs of 150 kV and 35 kV voltage and currents total harmonic distortion changes for the previously considered intervals of experimental research respectively. The maximum values of 150 kV and 35 kV voltage total harmonic distortion, recorded during the measurements, reached 1.6% and 2.0% respectively. The maximum values of total harmonic distortion recorded during the measurements are given in table 3.

Table 3. The maximum values of voltage THD

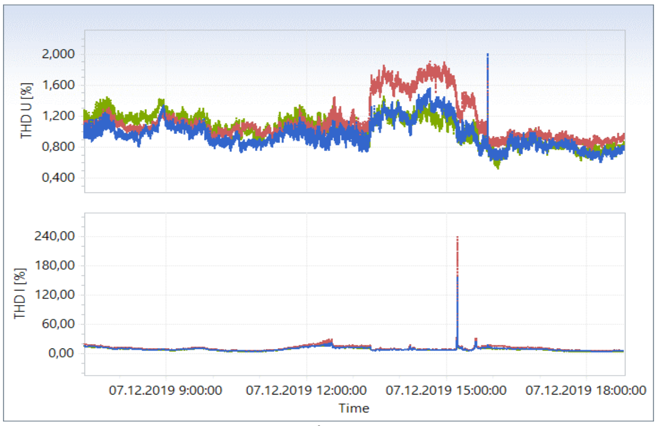
Voltage	THD_A	THD_B	THD_C
150 kV	1,30 %	1,52 %	1,24 %
35 kV	2,00 %	1,90 %	1,50 %.

According to the standards [15-16], the allowable value of total harmonic distortion of the voltage curve in high voltage networks is 3% [17], and in medium and low voltage networks is 8% [15, 17]. Thus, the level of voltage curve distortion at both 150 kV and 35 kV was within acceptable limits.

Despite the fact that during the measurements, sufficiently large values of total harmonic distortion of the current curve were recorded, which reached more than 38% for 150 kV and 5% for 35 kV, the standard maximum permissible values of this indicator of the quality of power are not standardized [15, 17]. The indicated peaks of total harmonic distortion of the current curve correspond to the minimum values of the phase currents. However, with large values of total harmonic distortion of the sinusoidal current curve, significant additional losses of power and voltage can occur in the elements of the power supply system, which can lead to the need to use various filtering instruments of higher harmonics.

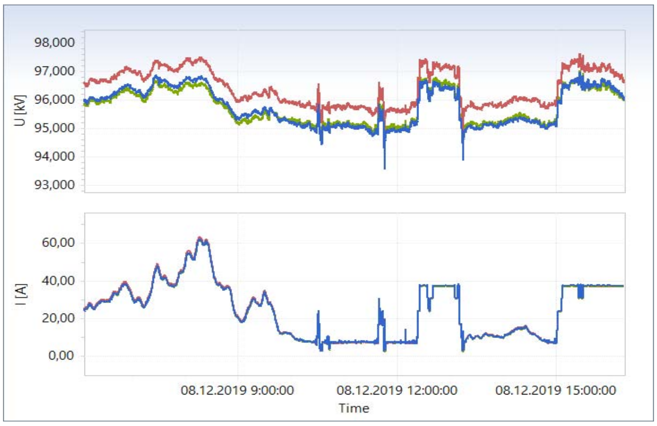
Also, a short-term abnormal total harmonic distortion of the current curve was recorded, the value of which reached 240, 530 and even 1400%. These short-term bursts can be caused by changes in the operating mode of wind turbines that occur relatively frequently, or by sudden changes in load. They can cause a negative effect on the insulation of electrical equipment, they increase a risk of resonance phenomena leading to a failure of electrical equipment, primarily capacitor banks, impair the operation of communication systems, measuring equipment, electronic meters, microprocessor protection modules with programmable logic controllers, etc. [20]. The above factors may be the reason for the application of measures to increase noise immunity in the network with wind turbines.

a



b

Fig. 6. Graphs of 150 kV voltages and currents on 3 interval (a) and the corresponding graphs of voltages and currents THD (b)



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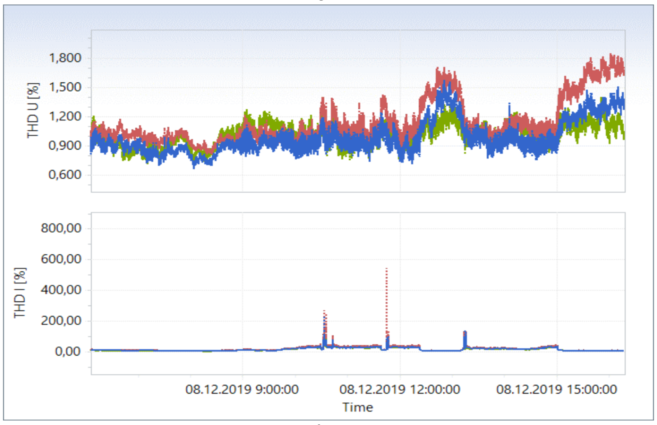

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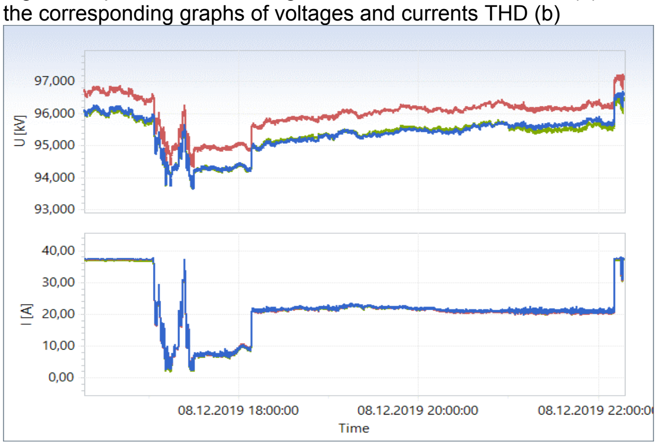
Fig. 7. Graphs of 150 kV voltages and currents on 6 interval (a) and the corresponding graphs of voltages and currents THD (b)



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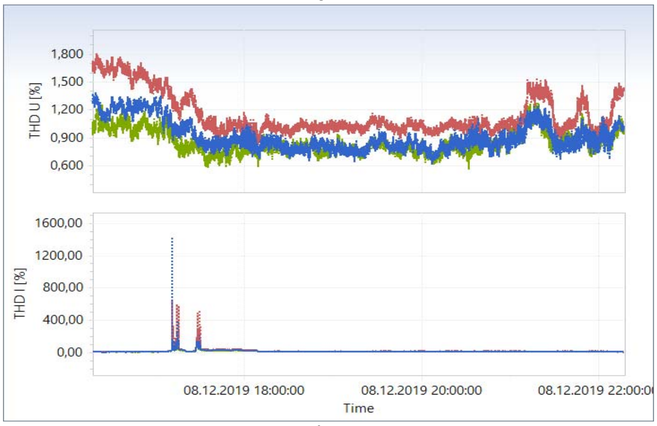

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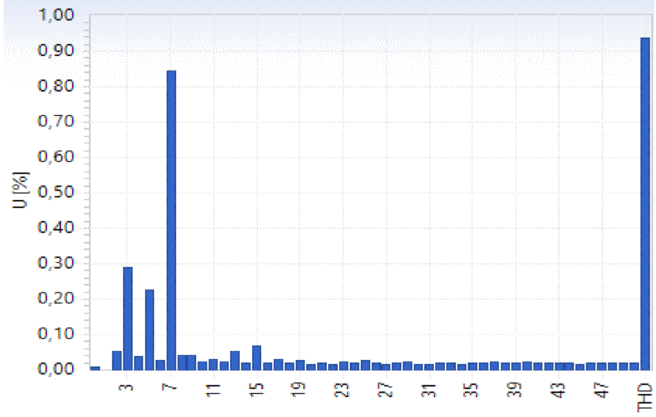
Fig. 8. Graphs of 150 kV voltages and currents on 6 interval and the corresponding graphs of voltages and currents THD



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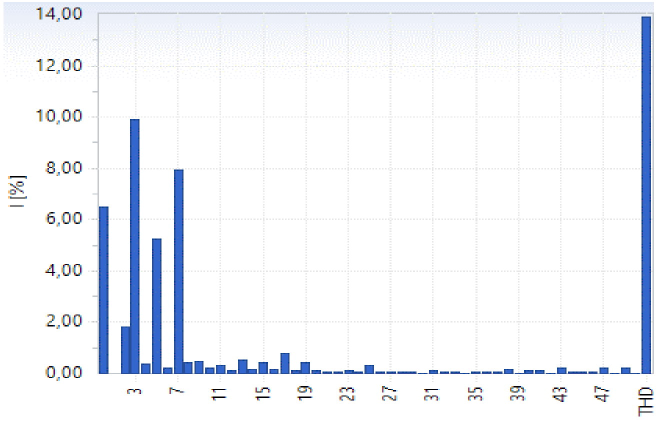

b

Fig. 9. Example of 150 kV individual harmonic voltage (a) and current (b) values

In Fig. 9 and Fig. 11 shows examples of output voltage curves harmonic spectra for the previously considered measurement intervals. The graphs show that the voltage curve contains peak third, fifth and seventh canonical harmonics, which can reach 0.9%, 0.8% and 1.0% at 150 kV and 0.5%, 0.4% and 0.55%, respectively, at 35 kV. The eleventh, thirteenth, fifteenth, and seventeenth harmonics at 35 kV, which are in the range of 0.1-0.3%, are also significant.

In turn, the amplitude-frequency spectrum of the current curve contains one peak value, namely the 3rd harmonic, the value of which can reach more than 1.7%. The 5th, 7th harmonics and the DC component of the current at 150 kV and the 5th, 7th, 11th, 13th, 15th, 17th, 19th harmonics and the DC component are essentials current at 35 kV, which are in the range of 0.1-0.2%.

a

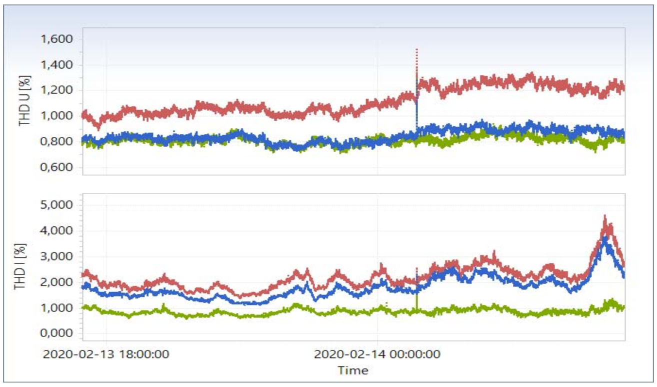

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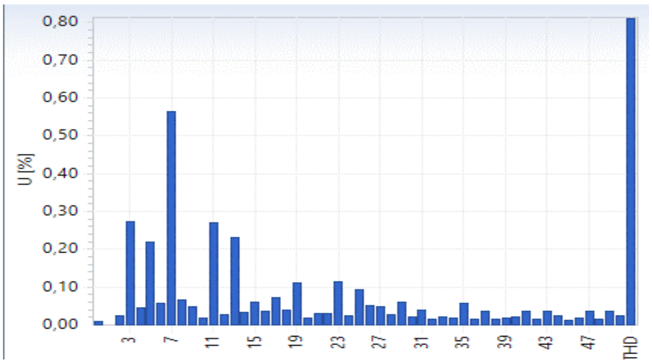
Fig. 10. Graphs of 35 kV voltages and currents on 3 interval (a) and the corresponding graphs of voltages and currents THD (b)



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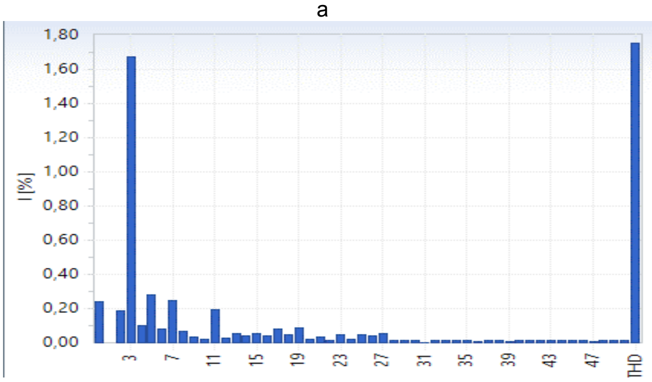

b

Fig. 11. Example of 35 kV individual harmonic voltage (a) and current (b) values

In addition, after conducting and analyzing numerous researches, we can conclude that the amplitudes of higher harmonics and interharmonics significantly depend on the rate of change of wind and its dispersion.

Figure 12 shows active and reactive power graphs corresponding to the previously considered measurement interval for 35 kV voltage. On the considered interval, with an average wind speed of 5.5 m/s, the active power varied in the range from 4.4 to 9.9 MW, which is approximately half of the rated power. As can be seen from the graph, the active power fluctuates significantly over time, which is caused by wind flow fluctuations. At the same time, the reactive power in the considered measurement interval varied from 0.7 to 3.8 MVar, and a sharp drop from 3.51 to 0.65 MVar in reactive power was recorded, which is associated with the transformer voltage regulation.

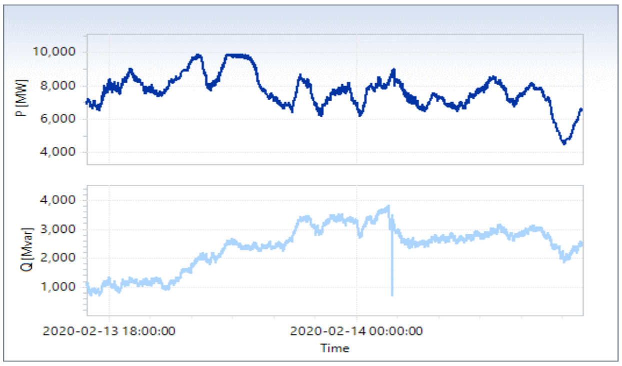

Fig. 12. Active and reactive power changes in 35 kV netrwork on 9th interval

Comparative analysis of modeling characteristics and real experiment

For further research of the electromagnetic compatibility of wind turbines with the distribution network, in particular the impact of turbulent wind flow on harmonic distortions propagation in electrical networks, a wind farm simulation model was developed. For this purpose, a random character of a turbulent wind flow with specified characteristics was simulated and a wind power plant simulation model was developed [19], which is 13 wind turbines of the DFIG type with adjustable speed with partial frequency conversion. An example of a wind farm model and a simulated wind flow change curve are presented in Figure 13 and Figure 14, respectively.

The simulation allows to track the operation of the system taking into account the turbulent wind flow fluctuations. To confirm the correctness of the wind farm simulation, it is necessary to conduct a comparative analysis of the characteristics obtained as a result of modeling and a real experiment.

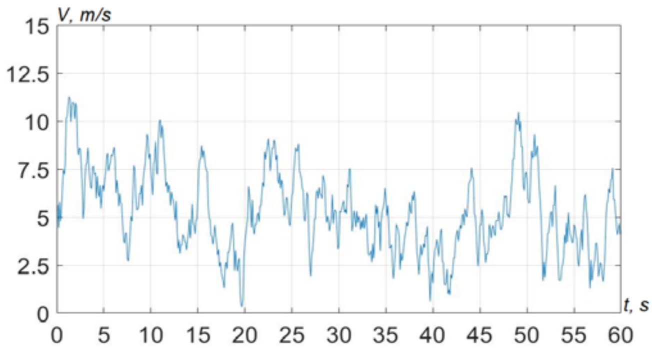

Fig. 13. Wind flow change curve

For example, Figure 15 presents the amplitude-frequency spectrum of the phase A input voltage, obtained by modeling a wind farm with adjustable speed with partial frequency conversion, at an average wind speed v =10 m/s, the damping coefficient of the correlation function of turbulent wind flow α = 0.7, the standard deviation of the turbulent wind flow σ = 2.36 m/s.

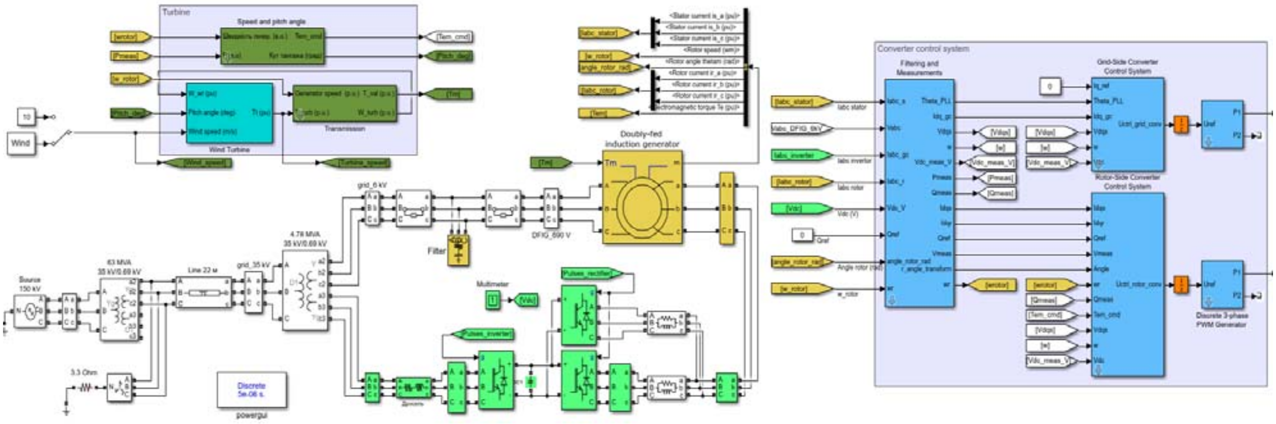

Fig. 14. Wind power plant simulation model

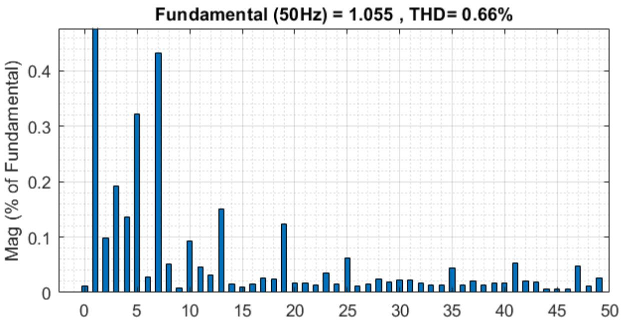

Fig. 15. Amplitude-frequency spectrum of wind turbines output voltage, determined by simulation

Conclusion

1. According to the results of measurements in Primorsky wind power plant electrical network, the level of sinusoidal voltage curve distortion at both 150 kV and 35 kV is within acceptable limits according to the standard.
2. The amplitude-frequency spectrum of the voltage curve contains a significant harmonics total value above the 50th order, which exceeds the individual harmonics peak value.
3. Taking into account the presence of harmonics above the 50th in the spectrum of the voltage curve, it is recommended to use low-pass filters after the 50th harmonic.
4. A study of the DFIG-type wind turbines operation under operating conditions at an existing wind farm confirmed the correctness of adjustable speed wind turbine with partial frequency conversion simulation model for analyzing the harmonic distortions propagation in electric networks. The experimental research shows that the computational error is not more than 15%.
5. A wind farm simulation model allows to conduct a harmonic analysis of the wind turbine operation with adjustable speed with partial frequency conversion taking into account the turbulent wind flow influence on the wind turbines electromagnetic compatibility with distribution network.

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