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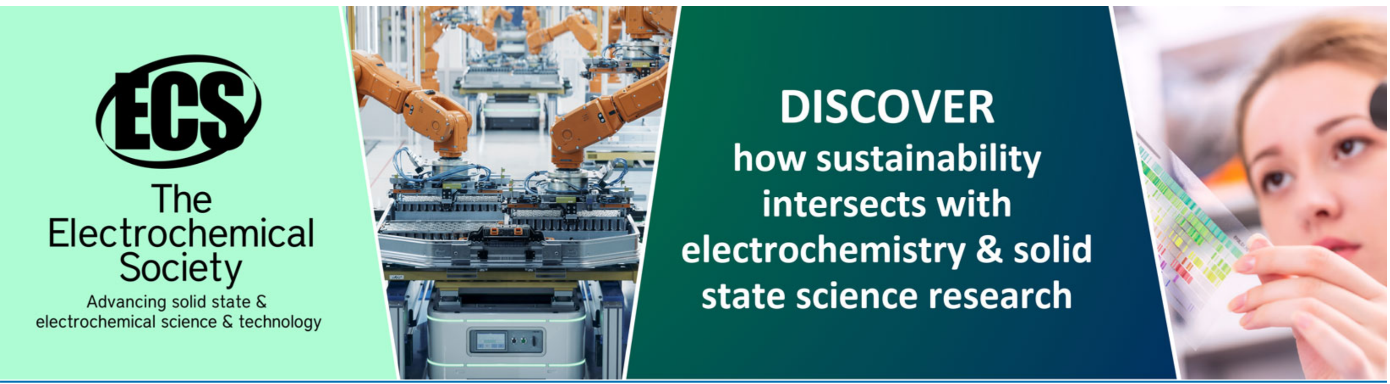

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Connection and operation of wind farms as part of electric power-supply systems through the example of Kaliningrad region

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Abstract. The issues of connecting wind power plants (WPP) to the power-supply system and their joint operation are currently gaining relevance due to the growth of their capacities and an abruptly variable pattern of its delivery to the grid. The paper presents the analysis of standards, recommendations and regulations related to connection and operation of WPPs as part of the power-supply system. The developed mathematical model of the Ushakovskaya WPP is used to analyze its main operating modes. Practical recommendations for changing the scheme of power generation of the plant at increased capacity are given with due regard to the standard requirements.

1. Introduction

For operators of electric power-supply systems, the problem of connecting WPPs to the power grid complex and their joint operation is of current relevance. This is due to the abruptly variable mode of WPP generation, which influences the power balance in the power-supply system and, as a result, affects voltage in the grid nodes, and in systems with a large share of WPP capacity relative to the installed capacity it impacts the system frequency.

2. Prospects for development of wind energy in Russia

Wind energy is the most rapidly developing industry in the world energy (Tables 1 and 2) [1, 2].

Table 1. The share of wind energy in electricity production in the world

Year	2008	2019	2030 (forecast)
The share of wind energy,%	1.5	5.3	12

Table 2. Electricity generation in the world and the share of wind energy in 2020

Country	Electricity generation, TWh	The share of wind energy,%
USA	4 457.4	6.73
Russia	1 109.4	0.031
Germany	515.7	24.6
World	26 653.0	5.3

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The data summarized in Table 2 show that the level of electricity generation using wind power in Russia is very low despite high wind potential of its territory (Table 3).

Table 3. Potential wind area in Russia.

Source	Gross potential, bln kWh/year	Technical potential, bln kWh/year
[3]	2 609 055	52 181
[4]	1 284 000	-
[5]	-	116 000

In Russia, by 2024, it is planned to build fifteen WPPs with a total capacity of 4.5 GW [6]. Until now, the capacity of the wind turbines (WT) in Russia did not typically exceed 225 kW, and no problems with connection and operation of WTs as part of power-supply systems occurred, however, commissioning of high-power WPP made these issues relevant.

3. Analysis of normative and regulatory documents related to connection and operation of wind power plants as part of power-supply systems

WPP operation in the power-supply system affects: 1) power and energy balance; 2) equipment loading; 3) short-circuit currents; 4) power quality. Connection of the WPP to the power-supply system can lead to technical limitations and cause additional capital investments or affect its stability. Thus, it is critical to elaborate the connection of WPPs to the power-supply system and to assess the impact of different WPP operation modes on the power-supply system, which is advisable to perform using mathematical modeling. The mathematical model should be developed and the analysis of the obtained results should be performed with due regard to the requirements of the relevant standards and regulations.

In [7], recommendations are given for connecting small controlled WPPs to the power-supply system. The grid capacity for small independently controlled WPPs is determined based on standard methods related to: 1) the ratio of the short-circuit current level to the rated current; 2) voltage fluctuations when connected to the grid; 3) calculations of power flows; 4) levels of short-circuit currents; 5) assessment of the flicker and the level of higher harmonics. These estimates are currently used as the standard in Germany and are adequate to be used in most practical cases.

The grid bandwidth is determined using the power ratio:

$$S_{WDPP} = 0.02 \cdot S_{SC} \quad (1)$$

$$S_{SC} = U_{RAT}^2 / Z_{SYSTEM} \quad (2)$$

where S_{SC} is short-circuit power; Z_{SYSTEM} is the resistance from the point of connection to the power-supply system to the point where the system capacity is infinitely high relative to the WPP capacity.

The maximum power and the type of WTs connected to grids of different voltage levels recommended in [8] are of interest and are consistent with calculations performed using equation 2 (Table 4). It should be noted that the main requirement for WPP power generation scheme is to provide the maximum power output.

Table 4. Connection of wind turbines to electrical grids of different voltage levels.

Grid type	U_{RAT}, kV	Wind turbine type	Maximum power, MW
Low voltage	<1	WT of low and medium power	Up to 0.3
Medium voltage	1–35	WT of medium and high power, WPP	Up to 2–5
Direct connection to medium voltage buses		WPP	10–40
High voltage	>35	WPP	Up to 100
Extra high voltage	>220	High power WPP	> 500

In the Russian Federation, there are currently 4 state standards in the field of wind energy, (Table 5), and a number of company standards.

Table 5. Russian standards in the field of wind energy.

#	Standard	Standard
1	GOST R 51237-98	Unconventional energy. Wind power. Terms and Definitions
2	GOST R 51990-2002	Unconventional energy. Wind power. Wind power plants. Classification
3	GOST R 51991-2002	Unconventional energy. Wind power. Wind power plants. General technical requirements
4	GOST R 58491-2019	Technical requirements for generating facilities based on wind power plants

GOST R 58491-2019 is the only standard among all listed above to most completely regulate the requirements for connection and operation of WT and WPP both as part of the Unified Energy System of Russia and isolated territorial electric power-supply systems. The provisions of the standard apply to WPP with an electric power exceeding 5 MW based on WT of all types. The standard covers the permissible ranges of voltage and frequency fluctuations at the point of WPP connection to the electric power-supply system (Tables 6, 7).

Table 6. Requirements for wind turbines on the permissible time of operation in various frequency ranges.

Operating mode	Frequency range, Hz	Operating time without shutdown
Long	51.0–49.0	Not regulated
Short-term	49.0–48.0	Up to 5 minutes
	48.0–47.0	Up to 40 s
	47.0–46.0	Up to 1 s

The WT operating mode in the frequency range of 55.0–51.0 Hz and below 46 Hz is regulated by the manufacturer.

Table 7. Allowable grid voltages for WPP operation as part of the power-supply system.

Rated voltage, kV	Safety voltage, kV	Minimum allowable voltage, kV	Maximum operating voltage, kV
110	84.7	88.5	126
220	169.4	177.1	252
330	254.1	265.65	363
500	385	402.5	525
750	577.5	603.75	787

Long-term continuous operation of WT and WPP as part of the power-supply system is possible with voltage fluctuations on the buses of the high voltage switchgear (HVS) (110–750 kV), through which the WPP minimum allowable power to the maximum operating one is transmitted to the grid (Table 7). Under these conditions, the WT regulates the voltage at the point where the WPP is connected to the grid according to a given algorithm by generating or consuming reactive power.

The minimum allowable and safety voltages of WPP operation should be determined with respect to the corresponding safety factor of the power-supply system stability using equation (3). When voltage varies from the minimum allowable one to safety voltage, the operating time of the WPP as part of the power-supply system should not exceed 20 minutes.

$$U_{MIN\ (EMER.)} = 0.7 \cdot U_{RAT}(1 + K_U) \tag{3}$$

where K_U is the safety factor of voltage stability equal to 0.15, when calculating the minimum allowable voltage, and 0.1 when calculating the safety voltage; U_{RAT} is the rated voltage at the WPP connection points.

It should be noted that the worldwide standards almost fully regulate the design, commissioning and operation of WPPs [6]. In our opinion, issues of WPP operation are most fully explicated in [9]. The principle of voltage maintenance in the grid during WT operation is shown in Figure 1.

When voltage goes beyond the range of ± 10% of the effective value of the WT generator voltage, voltage must be controlled in accordance with the algorithm indicated in the diagram (Figure 1).

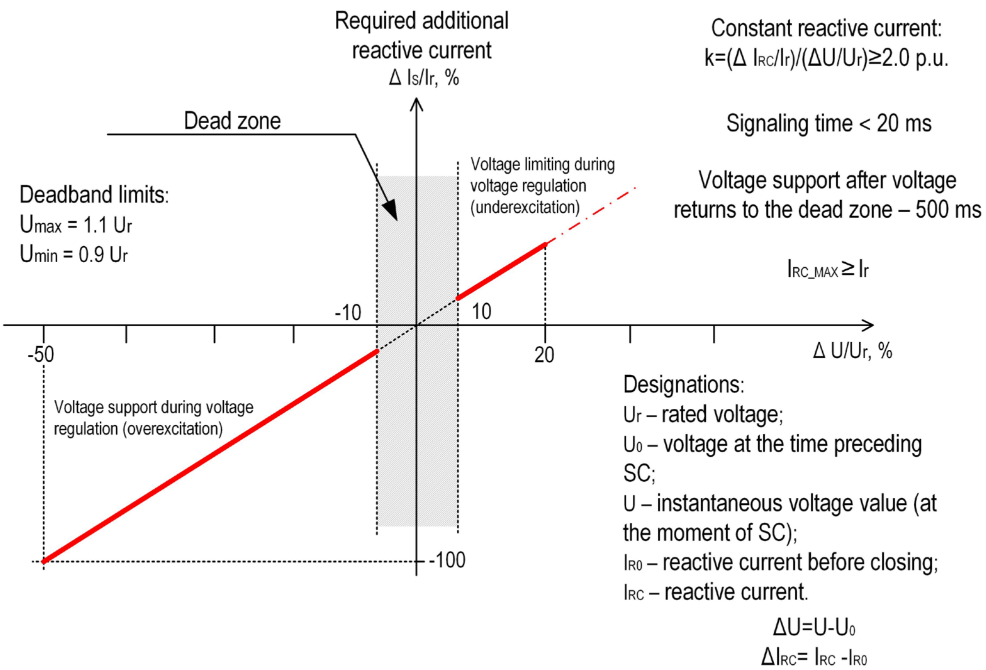

Figure 1. General principle of voltage regulation in the grid [9].

In case of emergency in the grid, the voltage control must be activated within 20 ms. Voltage control in this case implies the supply of reactive power from the low-voltage WT, that is up to the step-up transformer. The reactive power supplied to the grid should not be less than 2 % of the WT nominal power per percentage of voltage drop. Emergencies in the grid are defined as various types of short circuits that occur not far from the WPP connection point and cause voltage drop. When the voltage returns to the deadzone, the voltage is maintained for 500 ms. It should be noted that for successful voltage regulation, WT manufacturers provide for the possibility of supplying increased volumes of reactive power to the grid (up to 100 % of the WT rated power).

In case of sufficiently large rated power of WPPs, they can be actively involved in the general primary frequency regulation by the grid operator. Thus, the WPP operation in high and extra-high voltage grids is aimed at maintaining both voltage and frequency levels.

To regulate the electric current frequency in the grid, WTs as part of the WPP reduce the active power supplied to the grid, whereas the primary regulator droop should not exceed 4–5 %. In frequency control, WTs reduce the level of active power generation by the amount of the required primary power (4) in order to change the frequency level by the required amount.

$$P_{RP} = -(100/S) \cdot (P_{AP}/f_{RAT}) \cdot \Delta f_p \quad (4)$$

where S is primary regulation droop,%; $P_{initial}$ is active power of the WPP at the moment of regulation start, MW; Δf_p is the calculated value of frequency deviation, Hz.

The standard [9] imposes complex requirements on the WT output power when it is connected to the grid. These requirements are stated as a function of the WT power on frequency and voltage of the grid (Figure 2). This function describes a quasi-stationary process. In this case, the frequency gradient is less than 0.5 %/min and the voltage gradient is 5 %/min. The ratios of the parameters of the WPP operation modes presented in Figure 2 show the basic requirements for successful operation of the WPP as part of the power-supply system. However, these requirements are not comprehensive and can be supplemented with regard to a particular grid and operator.

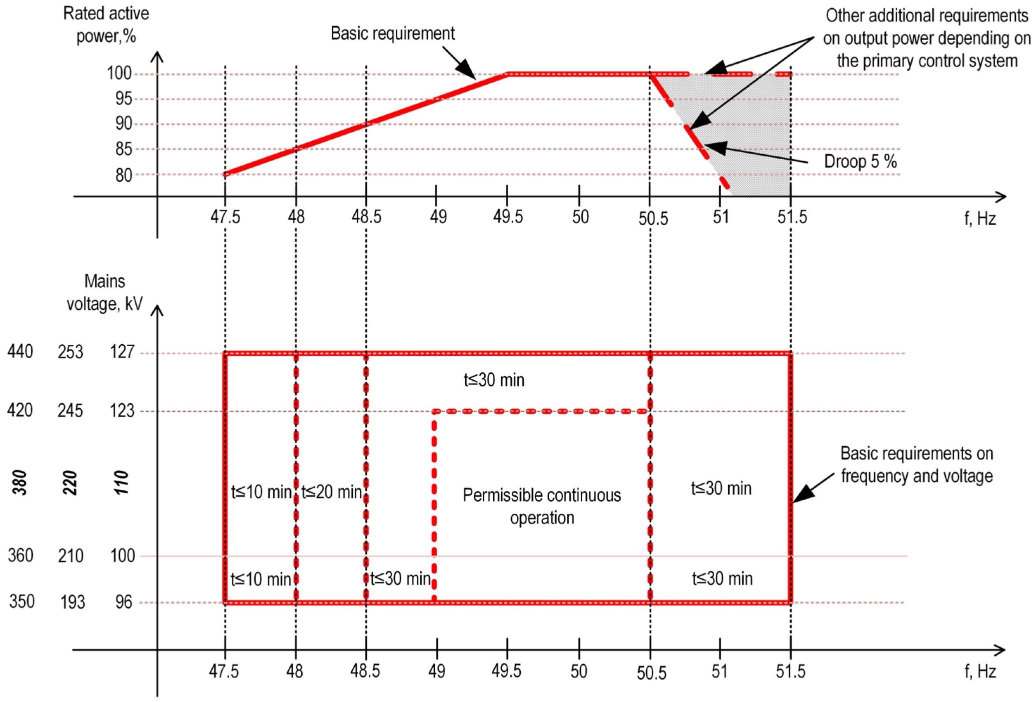

Figure 2. Ranges of frequency and voltage during WPP operation as part of the electric power-supply system [9].

The above requirements are related to the buses of 110 kV switchgears used for the WPP power supply to the grid. Some recommendations for relay protection of such switchgears are provided in foreign standards [10].

4. Connection and operating modes of the Ushakovskaya WPP, part of the power-supply system in Kaliningrad region

The installed capacity of power plants in Kaliningrad region is about 1405 MW with a load of 756 MW in the winter maximum mode [11]. In Kaliningrad region, the Enercon E-70 E4 WT was used in the Ushakovskaya WPP operation. The rated capacity of the WT is 2.3 MW, however, the capacity of each of the three WTs of this type at the Ushakovskaya WPP is limited to 1.7 MW.

Given the small capacity of the WPP in comparison with the installed capacity of the power-supply system, its participation in the general primary frequency regulation is not required. The WPP power supply scheme is implemented through a 15 kV grid using two overhead lines of the same voltage class, which in turn transmit electricity from the WPP to 15 kV switchgears at 330 kV O-1 Tsentralnaya and 110 kV O-39 Ladushkin subplants (Figure 3).

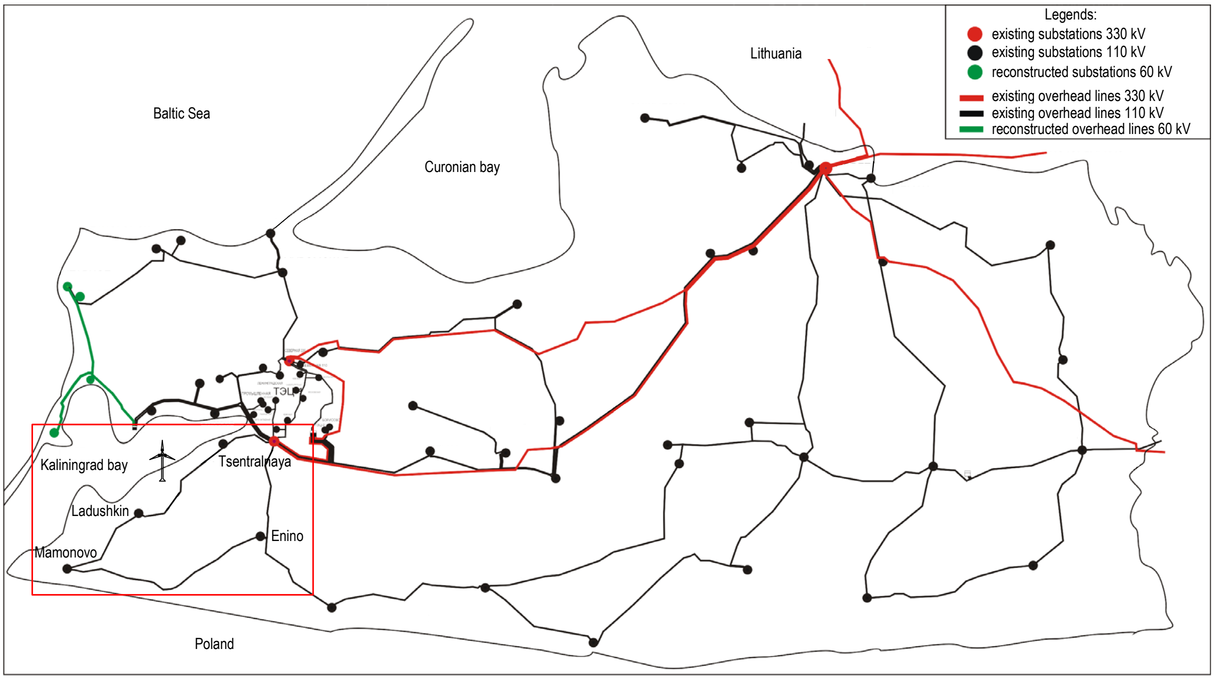

Figure 3. Schematic map of electrical grids in Kaliningrad region.

It should be noted that the WPP is actually divided into two independent parts (Figure 4). Thus, the WPP can affect the voltage in the 15 kV grid using its WTs.

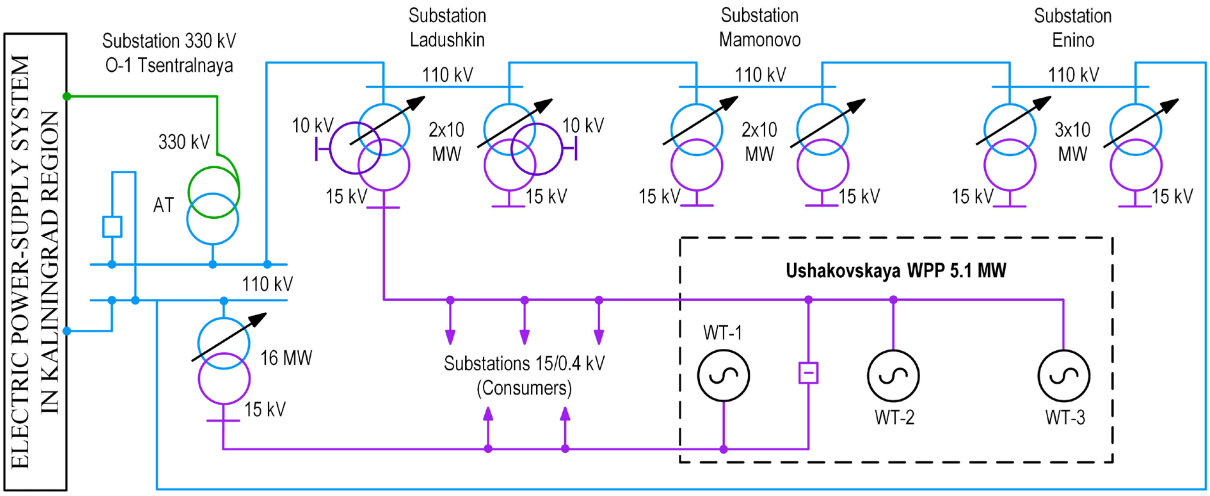

Figure 4. Block diagram of the connection of the Ushakovskaya WPP to the power-supply system in Kaliningrad region.

A small capacity of the WPP enables considering only a part of the power-supply system in Kaliningrad region (Figure 3). This simplification is possible since the 330 kV O-1 Tsentralnaya substation is a node of infinite power for the considered section of the grid and can be represented as a power-supply system (Figure 4). The WPP operating modes as part of the electric power-supply system in Kaliningrad region were calculated via computer modeling using the Neplan software.

Taking into account the requirements of the standards and the features of the power supply scheme at the Ushakovskaya WPP, a number of the most typical operating modes were selected for further analysis (Table 8).

Table 8. Design modes of the WPP operation with respect to the existing power supply scheme.

No.	Design conditions	
	No voltage regulation	With voltage regulation
1.	Winter maximum load when the WPP does not operate	-
2.	Winter maximum load at maximum WPP generation (cos φ = 1)	Winter maximum load at maximum WPP generation and voltage regulation (cos φ = 0.97)
3.	Winter minimum load at maximum WPP generation (cos φ = 1)	Winter minimum load at maximum WPP generation and voltage regulation (cos φ = 0.94)
4.	Summer minimum load at maximum WPP generation (cos φ = 1)	Summer minimum load at maximum WPP generation and voltage regulation (cos φ = 0.93)

Calculation of the electrical operating modes of WPPs at various load values in the 15 kV grid and the nominal parameters of the WT revealed that to generate the rated power and not to exceed the permissible voltage level in the WPP power supply scheme, the reactive power control in the grid is required (Figure 5).

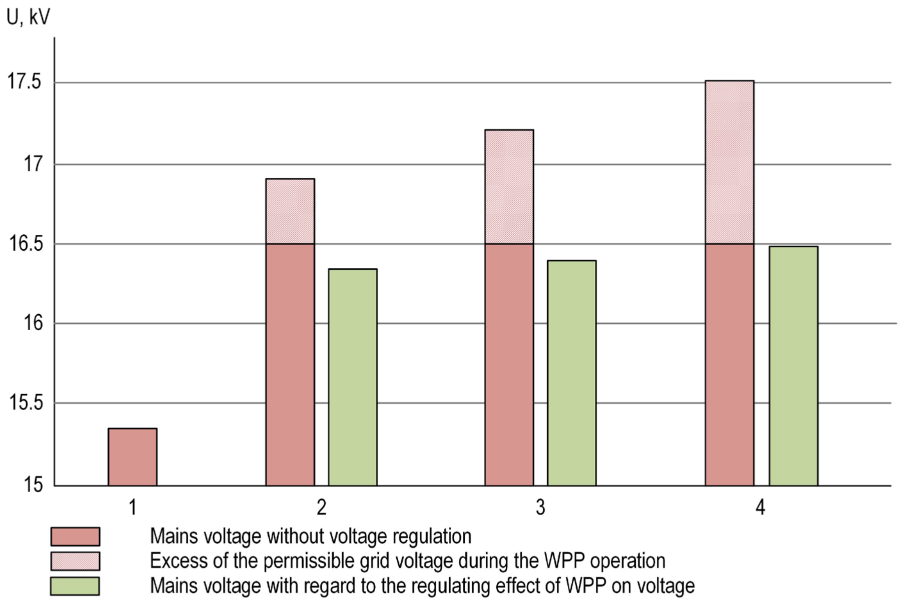

Figure 5. Voltages in the grid during operation of the Ushakovskaya WPP.

The second possible way to control voltage is to reduce the amount of active power generation by the WPP. Thus, the existing scheme of power supply in a number of modes may be limited in active power generation, which is its main drawback and does not allow further increase in the installed capacity of the Ushakovskaya WPP.

To increase the WPP installed capacity, it is proposed to connect it to the 110 kV grid according to the enter–exit scheme using the 110 kV overhead line SS 110 kV Ladushkin – SS 110 kV Mamonovo with due regard to the requirements of the standards (Figure 5).

Table 9. Calculation results for operation modes of the WPP connected to the 110 kV grid.

SS number	Rated voltage, kV	Node voltage U, kV	Node voltage U,%	Deviation from U_{RAT},%
Winter maximum load at maximum WPP generation ($cos\ \varphi = 1$)				
14	110	119.442	108.57	+8.57
39	110	119.428	108.57	+8.57
RU WPP	110	119.603	108.73	+8.73
Winter minimum load at maximum WPP generation ($cos\ \varphi = 1$)				
14	110	119.957	109.05	+9.05
39	110	119.979	109.07	+9.07
switchgear WPP	110	120.104	109.19	+9.19
Summer minimum load at maximum WPP generation ($cos\ \varphi = 1$)				
14	110	120.479	109.53	+9.53
39	110	120.516	109.56	+9.56
open-type switchgear WPP	110	120.592	109.63	+9.63

The analysis of the electrical operating modes of the Ushakovskaya WPP, when it is connected to 110 kV grids, showed that the plant power at the first stage can be increased from 5.1 to 6.9 MW due to elimination of restriction on WT. At the same time, the WPP operation will not have a negative impact on the voltage level in 110 kV grids (Table 9). In this case, the increase in the WPP capacity will be limited by the capacity of the step-up transformer rather than by the operating modes of 110 kV grids.

5. Conclusion

The ratio of the WPP capacity to the short circuit power calculated using equation (1) for the designed scheme was $0.006 \leq 0.02$. For parts 1 and 2 of the WPP, the existing power supply scheme yields the ratio of $0.05 \geq 0.02$ and $0.09 \geq 0.02$, respectively. Therefore, the WPP connection scheme proposed in this study meets the requirements of the standards and other recommendations and can be considered as promising for the Ushakovskaya WPP.

Reference

[1] Statistical Review of World Energy 2020. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf
[2] Beley V, Harzfeld E 2019 *Analysis of technical solutions for the implementation of the wind potential of Russia* 746-754
[3] Bezrukikh P, Degtyarev V *et al* 2007 *Guide to Russian Renewable Energy Resources and Local Fuels / indicators by territories* (Moscow: IAC Energia)
[4] Nikolaev VG, Ganaga SV *et al* 2008 *National cadastre of wind energy resources of Russia and methodological bases for their determination* (Moscow: Atmograph)
[5] Xi L, McElroy M B, Kiviluoma J 2009 *Proceedings of the National Academy of Sciences of the United States of America* **106** (27) 10933–10938
[6] Beley V, Zadorozhny A 2018 *Energy of unified grid* **7** 19-29
[7] Netzanschlußkapazität für Windenergiesysteme. Available at: https://uol.de/physik/we-sys/forschung
[8] Beley V, Nikishin A 2013 *Energy of unified grid* **5** 60-69
[9] E.ON Netz GmbH «Grid Code. High and extra high voltage». Available at: http://www.pvupscale.org/IMG/pdf/D4_2_DE_annex_A-3_EON_HV_grid__connection_requirements_ENENARHS2006de.pdf

[10] Bdew «Technische Richtlinie Erzeugungsanlagen am Mittelspannungsnetz». Available at: https://www.bdew.de/media/documents/20080601_BDEW-Mittelspannungsrichtlinie.pdf
[11] Scheme and program for the prospective development of the electric power industry in the Kaliningrad region for 2020–2024. Available at: https://infrastruktura.gov39.ru/upload/%D0%A1%D0%98%D0%9F%D0%A0%20%D0%9A%D0%9E%202020-2024.pdf.pdf