

Power System Stability Research in the Integration of Wind Power Plant in Almaty Region

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Abstract—Today, the cost of renewable energy has equaled the price of traditional energy sources, and in most countries "green" electric energy has become cheaper than electricity on carbohydrate fuel. Therefore we are less and less beginning to discuss the mechanisms of economic support for renewable energy, but the problem of balancing is still on the agenda. This paper examines the influence of Wind Power Plant during its integration to the electrical grid of 110 kV and higher. The aim of this work is to study the integration of WPPs into traditional power system taking into account the standards and requirements. The object of the study is a WPP in the Almaty region with a capacity of 60 MW. Rotor-angle stability, voltage stability, quasi-dynamic analysis, of the electrical system during the integration of the WPP was carried out. Special attention was paid to the small signal stability, considering the influence of the power system stabilizer and the WPP on the power system.

Keywords—wind power plant, wind power plant integration into traditional grid, power system stability, variable renewable energy, steady-state analysis, transient stability, small signal stability

I. INTRODUCTION

Today, wind generation technologies are making significant progress in economic maturity and competition. Every year the amount of energy obtained from wind is growing, and the cost of technology is significantly reduced. However, it should be noted that the excessive increase in renewable energy facilities creates risks for the reliability of energy system, since renewable energy sources are not permanent energy sources. Due to stochastic nature of wind, grid integration of the Wind Power plants can negatively affect the power system. This intermittent and diffuse quality of the wind power presents a new factor of uncertainty in the grid and may have a negative impact on the grid integrity i.e. the power quality, the system security and the system stability [1].

According to International Energy Agency (IEA), there are four phases of Variable Renewable Energy (VRE)

integration. They differ in the impact on the operation of the electricity system due to the increase of the share of VRE power. The phase division is important to determine certain technical requirements for stations that produce electricity at the expense of renewable energy sources [2].

II. INTEGRATION OF WPP IN TO THE POWER GRID

The main objective of power system operation is to keep the energy supplied in balance with electricity demand [3]. From the classical point of view, the instability of the power system can be considered as a loss of synchronicity when the system is subjected to a certain disturbance. Fig. 1 illustrates the classification of power system stability problems according to IEEE.

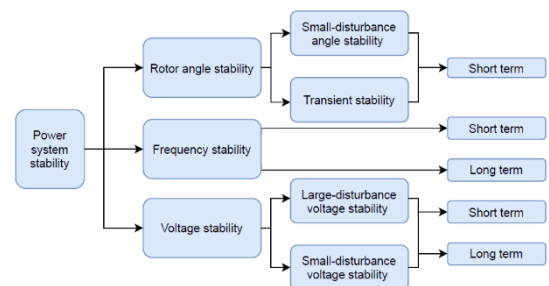


Fig. 1. IEEE Classification of power system stability [3].

Power system stability can be broadly classified into rotor angle, voltage and frequency stability. Each of these three stabilities can be further classified into large disturbance or small disturbance, short term or long term. Due to the fluctuated production of the WPP, in addition, quasi-dynamic analysis observed. Further, the article discusses terms of stability and illustrates its relationship with the range of regulation of the reactive power of renewable energy sources.

A. Rotor Angle Stability. Transient Stability

Transient stability involves responding to large disturbances that can cause quite large changes in the rotor speed, power angles, and power transmission [4]. Transient

stability is a rapid phenomenon that usually manifests itself within a few seconds. The stability of the power system is mainly related to the analysis of the stability of the rotor [5]. This requires various assumptions, such as:

- For stability analysis, balanced three-phase system and balanced disturbances are considered.
- Deviations of machine frequencies from synchronous frequency are small.
- During short circuit in generator and high frequency current are present.
- Network and impedance loads are at steady state. Hence, voltages, currents and powers can be computed from power flow equation.

B. Rotor Angle Stability. Small Signal Stability

Small-signal stability is the ability of the system to be in synchronism when subjected to small disturbances [5]. The disturbances can be switching of small loads, generators or transmission line tripping, etc. The small-signal instability can lead to oscillations in the system [6]. There are three modes of oscillations due to small disturbances:

- Local modes of oscillations are due to a single generator or group of generators oscillating against the rest of the system;
- Intra-plant modes of oscillations are due to oscillations among the generators in the same plant. The typical frequencies of oscillations of local and intra plant modes are in the range of 1 Hz to 2 Hz;
- Inter area modes of oscillations are due to a group of generators in one area oscillating together against another group of generators in a different area. The typical frequency range of inter area mode of oscillations are 0.1 Hz to 0.8 Hz.

This work considers the third mode. The level of damping of oscillations in the power system usually depends on active control by means of system regulators installed at the generators and can vary significantly depending on the current characteristics of the generator and the load [7].

The traditional approach to address low frequency oscillation (LFO) problem is to equip PSS in the machines which has tendency to damp out power oscillations [8].

C. Voltage Stability. Steady-state Stability

Steady-state Stability is associated with the reaction of the synchronous machine to a gradually increasing load. This is mainly due to the determination of the upper limit of the machine load without loss of synchronicity, if the load gradually increases [5]. Concerning this article, steady-state stability was taken into account by incremental load growth as well as the maximum generation of WPP in order to find the maximum point of stability. In this state, the level of voltage and load of the lines and transformers will be analyzed.

D. Frequency Stability

Frequency *stability* refers to the ability of a power system to maintain steady frequency following a severe system upset

resulting in a significant imbalance between generation and load. Generally, frequency stability problems are associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient generation reserve. In large, interconnected power systems, this type of situation is most associated with conditions following splitting of systems into islands. Stability in this case is a question of whether or not each island will reach an acceptable state of operating equilibrium with minimal loss of load [6]. Since considered WPP will be connected to the grid, which does not have any splitting into islands, frequency stability will not be investigated in this article.

E. Quasi-dynamic Analysis

Quasi-dynamic analysis performs multiple load-flow calculations with user-defined time-step sizes. Due to higher loads in winter, the winter mode will be chosen as worst scenario. The winter scenario will be shown with focus on two important segments of analysis: voltage and power factor of the grid elements after WPP integration.

III. GRID CODE FOR WIND POWER INTEGRATION

To connect to high-voltage networks of 110 kV and higher, WPPs must meet certain grid requirements, which may vary depending on the country. These requirements are usually reflected in the grid code in the form of ranges and limits exceeding these limits, deviation of specific parameters can lead to disconnection from the grid and require specific measures to reconnect to the network. For this study, the results of transient simulation modeling will be evaluated in accordance with the Kazakhstan network code issued for the integration of renewable energy facilities into the national energy system [9]. Fig. 2 illustrates possible voltage dips and associated durations in transmission network system that could occur due to the disturbances in the system.

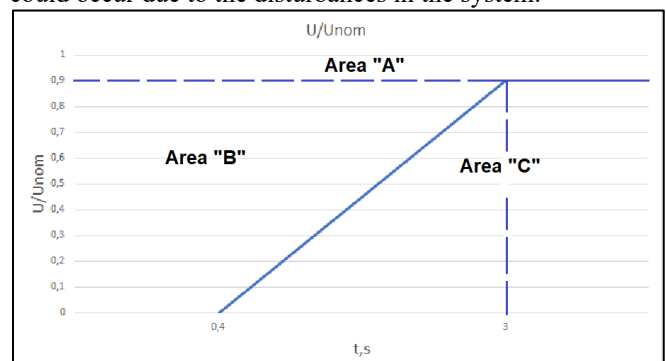


Fig. 2. Grid code requirements on voltage stability for RES facilities in Kazakhstan [9].

There are three main areas that can be described as follows:

- Area "A" – remain RES facility connected to the grid and function steadily, above 0.9 of the nominal voltage;
- Area "B" - remain RES facility connected to the grid and provide maximum voltage. When the voltage is 0, RES should disconnect from the grid in 0.4 second and when the voltage reaches a value below 0.9 of the nominal, RES should disconnect from the grid in 0.4;

- Area "C" - it is required to disconnect the RES facility from the grid

Table I contains the requirements on frequency deviations and acceptable range of duration upon which power plant can operate. WPPs must operate steadily (without automatic disconnection from the network) in the event of a deviation of the frequency in the network from the nominal value within the frequency ranges and time periods.

TABLE I. GRID CODE REQUIREMENTS ON FREQUENCY STABILITY FOR RES FACILITIES [9]

Frequency Response, Hz	Minimum run time
45.0	1 sec
46.0	2 sec
47-49	120 minutes
49-51	Unlimited
51-51.5	90 minutes

WPPs must provide a range of reactive power regulation within the limits indicated in Fig.2 and Fig.3. It can be clearly seen from Fig.3 that the WPP should generate as well as consume reactive power depending on grid request.

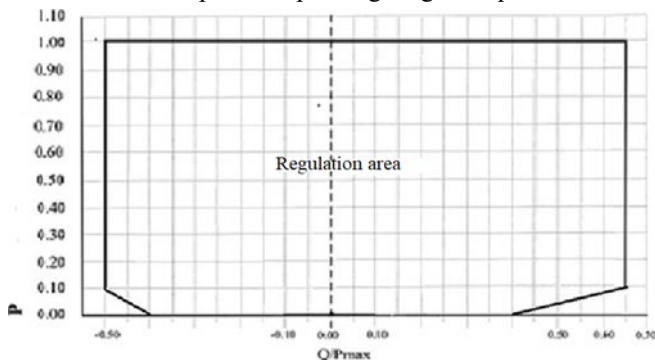


Fig. 3. The dependence of the adjustment range for the reactive power of the WPP on its actual generation

The diapason fluctuates from 50% of reactive power consumption to 65% of generation on its actual active power. When the voltage at the connection point decreases (or increases) beyond the limits indicated in Fig.4, the WPP must operate in the mode of maximum generation (or maximum consumption) of reactive power.

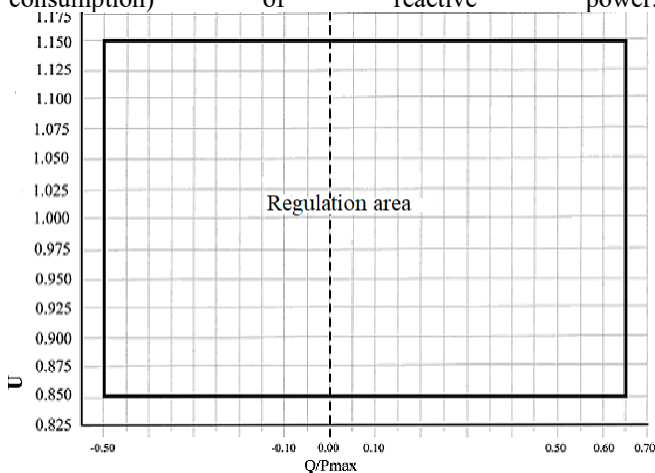


Fig. 4. The dependence of the adjustment range for the reactive power of the wind farm on the actual voltage at the point of connection to the network (110 kV, 220 kV).

IV. RESULTS

A. Study Case

All simulations and calculations are done in DIgSILENT PowerFactory software. In the Fig. 5 the single line diagram of the considered grid is represented. The diagram based on real data of Shelek town, Almaty region, Kazakhstan. Geographical coordinates of the site are 43°53'41", 78°22'09". Currently, the construction and installation work of the object are being carried out at the construction site. The Wind Power Plant contains 25 buses and 29 lines of 110, 220 and 500 kV, 5 traditional power plants, 1 external grid and a new wind power with 60 MW of power. Traditional power plants cover almost 50% of consumption. The area of the new WPP is located at 6 km from the 220-110 kV substation containing 24 wind turbines with a total capacity of 60 MW, 24 transformers with a range of 35-0.69 kV, 4 parallel cable lines with a range of 35 kV and length of 12 km. An additional 6 km of cable is taken as a reserve for the length of the cable to the wind turbines.

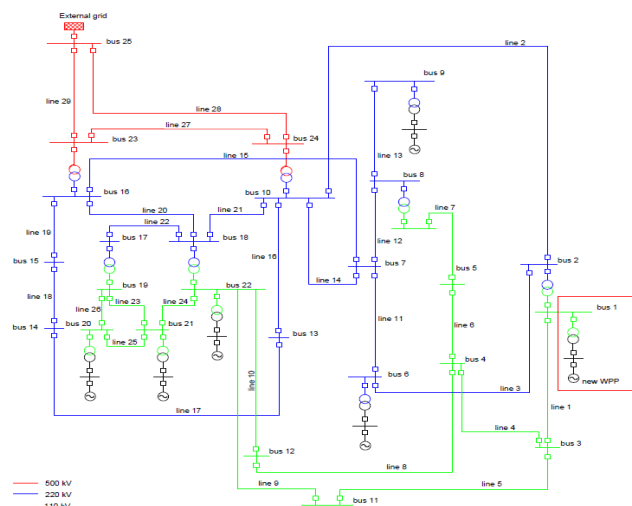


Fig. 5. Single line diagram of the considered grid.

The wind turbine type was selected according to the power production efficiency of 5 different wind turbines. As in Shelek town the average wind speed is 6,27 m/s in 100 m of height (calculated in WindPRO), the most effective wind turbine for 6 m/s is Envision EN131-2.5. The wind turbine generator type is doubly fed induction generator (DFEG). Fig.6 shows block diagram of the WPP with DFEG and its connection to the grid.

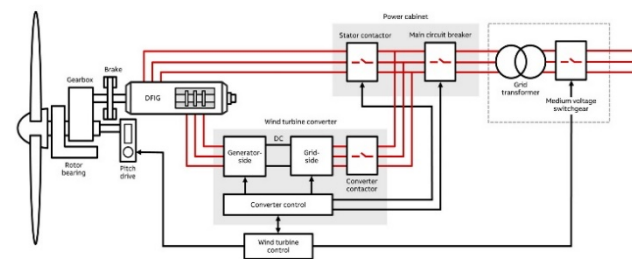


Fig. 6. A block diagram of the WPP with DFEG type connection to the grid.

In this work several issues will be considered:

- Steady-state analysis to find the maximum point of load or the maximum power generation of WPP;
- Transient stability to define system stability in an enormous disturbance such as short-circuit and disabling the generator;
- Small signal stability to define condition of each generator in the scheme and their relation to each other;
- Quasi-dynamic analysis to design the power system in Almaty region with selecting hourly changes of load and WPP generation;

B. Rotor Angle Stability. Transient Stability

In this article, the worst case of transient stability in the considered grid with the inclusion of the new WPP 60 MW is carried out. Transient stability calculations done for the heaviest transient process scenario: normal grid diagram, three-phase short circuit at the line 1.

A Table II with the results of calculations of transients is shown below:

TABLE II. TRANSIENT STABILITY RESULTS

№	Emergency impact	Duration of short-circuit	Result
1	3-phased s.c. at the line 1	0.2 sec	Stability is maintained

Fig. 6 represents behavior of mode parameters on substations and lines near to the new WPP 60 MW. Transient stability according to DigSilent PF simulations is stable due to damping of oscillations within 10 seconds. Fig. 7 illustrates frequency and voltage deviation in buses 1, 2 and 3. The frequency and voltage in bus 1 shows the maximum level of deviation from the nominal value, with the difference of 1.6 Hz in frequency and 0.85 per units in voltage.

However, according to grid operation requirements, the WPP should disconnect from the grid in 120 minutes and in more than 0.4 second in voltage requirements. As it is seen, these parameters come back to their initial value faster, showing stable performance.

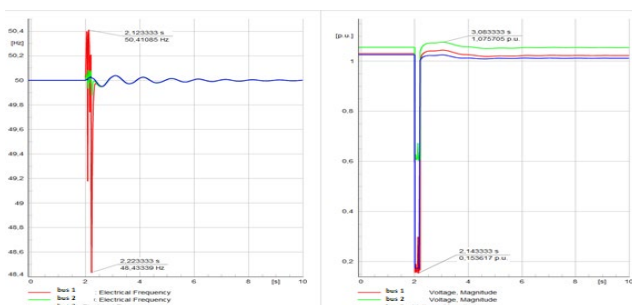


Fig. 7. Frequency and voltage response to short circuit at the line 1.

One of the main parameters that define transient stability is rotor speed and angle [10]. It is presented in Fig.8, these parameters remain damping pattern throughout 10 seconds.

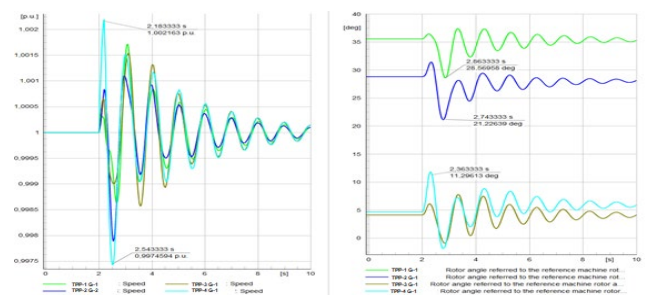


Fig. 8. Rotor speed and angle response to short circuit at the line 1.

In addition, there is no excessive deviation of the rotor angle, which is the main evidence of stability. In transient stability, large disturbances as short circuit and switching event were simulated in the heaviest scenario. Mode parameters such as voltage, frequency, rotor angle and rotor speed were simulated. It is concluded that the short circuit in lines 110 kV has more significant impact to the grid.

C. Impact of PSS and WPP on the Small Signal Stability

A modal analysis of the small signal stability under disturbances was performed. It is based on the results of calculations of dynamic stability. The type of PSS is PSS5B. From Fig.9 it is clearly seen that PSS and WPP have a positive effect on small signal stability. PSS accelerates the damping process and within 10 seconds the fluctuations in the speed and angle of the rotor reach the nominal value using PSS [11-15].

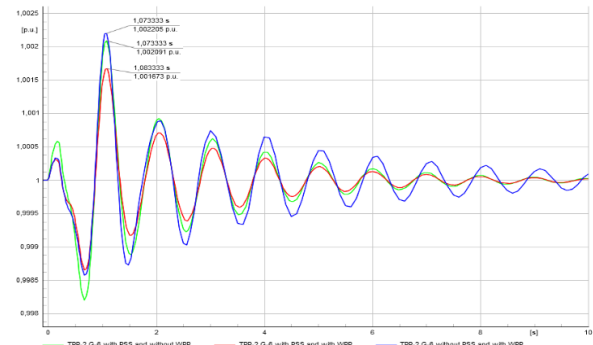


Fig. 9. Rotor speed of TPP-2 G-6 in 3 scenarios.

In turn, the WPP also has a good effect, reducing the amplitude of the oscillations. Rotor speed deviation amplitude decreased from 1.002091 to 1.001673 per unit, providing more reliable operation of the generator.

D. Quasi-dynamic Analysis

The maximum voltage decreased slightly after integration of WPP with the capacity of 60 MW, while power factory remains constant. It means the WPP affect positively to the grid although it had a little effect. Fig. 10 displays the voltage at the neighboring substations and the power factor values

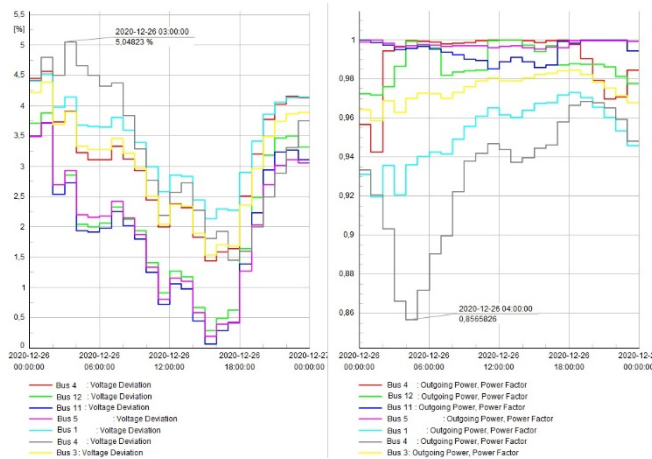


Fig. 10. Voltage variation and power factor in the grid in scenario with WPP.

E. Voltage Stability. Steady-state Stability

To compare the different stages of development and changes in the electrical system, an analysis was carried out for 4 stages according to the voltages in substations and the loads of lines and transformers:

- Existing grid without WPP integration.
- Existing grid with WPP integration.
- Steady-state analysis with the maximum load growth.
- Steady-state analysis with the maximum generation of WPP.

With a gradual increase in the load in the Almaty region, it was noticed that the maximum point of stability occurs when the load increases by 50%, with a load above 50%, the system is unstable. In the 4th stage, the maximum generation of WPP was 150 MW of capacity, when the capacity is higher, overloading is noticed in 110 kV lines near the WPP. The Table I shows voltage deviations in substations of 110 kV and higher, as well as the lines and transformers load located near the WPP in 4 stages.

In the 1st, 2nd and 4th stages, voltages in substation fit the limits, whereas in the 3rd stage voltage decreased by 7%, which may lead to bad consequences in grid system.

TABLE III. VOLTAGE VARIATION IN SUBSTATIONS IN 4 STAGES

Stages	Bus 1 - 110kV	Bus 2 - 220kV	Bus 3 - 110kV
Without WPP	112.7 kV	230.9 kV	112.3 kV
With WPP 60 MW	113.3 kV	232 kV	112.8 kV
Max. load growth by 50%	104.1 kV	209.6 kV	102.3 kV
Max. WPP generation 150 MW	112.7 kV	232 kV	112.2 kV

As it is shown in Table IV, the lines and transformers load do not exceed 70% of loading in the 1st and 2nd stages, whereas in the 3rd stage the line 6 reached 90.5% of loading and there is an overloading by 104.3% in the line 7. It is due to fact that the load increased by 50%, reached 30 MW at the bus 4 and the power flow reached 55 MW in these lines. In the 4th stage, loading of the line 1 increased from 50.7% to

96.5% due to the fact that capacity of WPP passes through this line only.

TABLE IV. VOLTAGE VARIATION IN SUBSTATIONS IN 4 STAGES

Stages	AT between bus1 and bus2	Line 1	Line 6	Line 7
Without WPP	35.2%	26.7%	50.7%	59.1%
With WPP 60 MW	11.8%	50.7%	43.8%	52.1%
Max. load growth by 50%	46.8%	76.5%	90.5%	104.3%
Max. WPP generation 150 MW	32.7%	96.5%	34.2%	41.9%

F. Grid Code For Wind Power Integration

Since WPP Shelek will be located in Almaty region, it is necessary to comply with the rules and requirements of the grid operator and take into account the local standard. The following tables show the limits for indicators in accordance with the local standard [16].

TABLE V. VOLTAGE DEVIATION LIMITS

Conditions		ST RK GOST 51317.4	Results from simulation
Normal operating conditions	max	+5%	5.07%
	min	-5%	-0.2%
Emergency operating conditions	max	+10%	7.57%
	min	-10%	

Frequency deviation limits according to local standards shown in Table VI.

TABLE VI. FREQUENCY DEVIATION LIMITS

		ST RK GOST 51317.4	Results from simulation
Frequency	max	+0.2 Hz	+0.05 Hz
	min	-0.2 Hz	-0.05 Hz

From the results, it is clear that WPP integration to the grid fit required limits according to the voltage and frequency.

V. CONCLUSION

Within the framework of these work, an assessment of the impact of renewable energy on the operation of the power system at various degrees of penetration, an assessment of throughput, dynamic stability, and the existing theoretical and actual ranges of rump up power were investigated. As an object, the WPP Shelek in Almaty region was chosen due to the potential wind resource, the annual average wind speed is 6.27 m/s in 100 m of height. The capacity of the WPP Shelek is 60 MW, considering 24 wind turbines with 2.5 MW of nominal output. Wind turbines were selected by analyzing power curves of several turbines. Cable lines that connect the WPP with power grid were selected by calculation the permissible current load for heating.

From the technical point of view, simulations and analysis such as quasi-dynamic analysis, steady-state stability, transient stability and small signal stability were carried out.

- In quasi-dynamic analysis, WPP Shelek integration impact was considered by taking the winter mode, 26th of December, and mode parameters such as voltage deviation, power factor and loading were

analyzed. All these parameters fit the limits of the international and local standards and requirements when WPP Shelek was connected to the grid;

- In steady-state analysis, the maximum point of load and WPP generation was simulated in DIgSILENT PowerFactory. The maximum point of stability occurs when the load increased by 50% and the maximum generation of WPP was 150 MW of generation. Furthermore, mode parameters as voltage deviation and loading were considered;
- In transient stability, large disturbances as short circuit and switching event were simulated in three scenarios. Mode parameters such as voltage, frequency, active and reactive power flow, voltage angle rotor angle and speed were simulated in DIgSILENT PowerFactory. It is concluded that the short circuit in lines 110 kV has more significant impact to the grid. Nevertheless, in all scenarios, transient stability keeps a stable mode;
- In small signal stability, the impact of power system stabilizer and WPP on the low frequency oscillations was carried out. It is concluded that the use of power system stabilizer at TPP-2 and WPP have a positive effect on small signal stability when short circuit at the line 126I and switch event at the autotransformer occurred. Power system stabilizer increases damping ratio, decreasing low frequency oscillations, while the connection of WPP decreases amplitudes in first seconds. In addition, the modal analysis was simulated in DIgSILENT PowerFactory to perform visually the impact of WPP and power system stabilizer. The result shows the stable eigenvalues in the system and the damping ratio became more than 5% when PSS and WPP were implemented, which shows a positive impact on the electrical scheme.
- Large-disturbance voltage stability relates to a system's ability to control voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. In this article this type of stability is not considered, since the WPP is located at a distance of about 120 km from large power plants, as well as Almaty TPP-2 and Kapchagai HPP. Loss of generators at large power plants does not have such a dramatic impact as a short-circuit in high-voltage lines near WPP.
- WPP integration to the grid fit required limits according to the voltage and frequency

REFERENCES

- [1] T.R. Ayodele, A.A. Jimoh, J.L. Munda, J.T. Agee, "Challenges of Grid Integration of Wind Power on Power System Grid Integrity: A Review" International journal of renewable energy research.. Vol.2, No.4, 2012
- [2] International Energy Agency. "Getting wind and sun". A Manual for policy makers, 2017
- [3] P. Kundur et al., "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," in IEEE Transactions on Power Systems, vol. 19, no. 3, pp. 1387-1401, Aug. 2004
- [4] Abdelhay A. Sallam and Om P. Malik. Power System Stability. Modeling, analysis and control, 2015
- [5] Ali Reza Sobbouhi, Abolfazl Vahedi. Transient stability prediction of power system; a review on methods, classification and considerations. Electric Power Systems Research. Volume 190, January 2021.
- [6] Jan Shair a, Haozhi Li a, Jiabing Hu b, Xiaorong Xie. "Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics" Renewable and Sustainable Energy Reviews. 2021
- [7] P. Kundur, "Power System Stability and Control," McGraw- Hill, New York, 1994.
- [8] Doradla Prathap, Hari Krishna, Porika Venkatesh. Design Of Power System Stabilizer to Improve Small Signal Stability By Using Modified Heffron-Phillip's Model. International Journal of Engineering Science and Technology 3(6). June 2011.
- [9] Kazakhstan Electricity Grid Operating Company. Requirements for WPP and SPP, 2020
- [10] Dong Xie, Dajin Zang and Peng Gao. Research on Stability of the Power System. Published under licence by IOP Publishing Ltd, 2017.
- [11] H. Li and Z. Chen, "Transient Stability Analysis of Wind Turbines with Induction Generators Considering Blades and Shaft Flexibility," IEEE Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the 2007, pp. 1604-1609
- [12] Doradla Prathap, Hari Krishna, Porika Venkatesh. Design Of Power System Stabilizer to Improve Small Signal Stability By Using Modified Heffron-Phillip's Model. International Journal of Engineering Science and Technology 3(6). June 2011.
- [13] A. S. Chuang and C. Schwaegerl, "Ancillary services for renewable integration," Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium, 2009, pp. 1-1.
- [14] J. A. P. Lopes, N. Hatziaargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating Distributed Generation into Electric Power Systems: A review of Drivers, Challenges and Opportunities," Electric Power System Research, vol. 77, pp. 1187-1203, 2007.
- [15] T. Miki, D. Okitsu, E. Takashima, Y. Abe, and M. Tano, "Power system transient stability assessment using critical fault clearing time functions," IEEE/PES Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. , 2002, pp. 1514-1517 vol.3.
- [16] Grid code of Kazakhstan. Standart R 51317.4-2002.