UDC 123.45
MRNTI 12.34.56
DOI 10.56525/MAAI4983

ADVERSE IMPACT OF REDUCED INERTIA CONSTANT ON TRANSIENT STABILITY IN MANGYSTAU POWER SYSTEM

Y. Aisayev[1*], K. Tergemes[2], S. Sheryazov[3]
[1]Branch of JSC "Kazakhstan Electricity Grid Operating Company" "National Dispatching Centre of System Operator"; Astana, Kazakhstan
[2]Almaty University of Power Engineering and Telecommunications Named after G. Daukeyev; Almaty, Kazakhstan
[3]South Ural State Agrarian University, Chelyabinsk, Russian Federation
e-mail: e.aisayev@gmail.com, k.tergemes@aues.kz, sakenu@yandex.ru

Abstract. Climate change and growing environmental risks are accelerating the global shift toward renewable energy sources (RES), but this transition brings new challenges for power systems. Replacing conventional generation with RES reduces system inertia, which can negatively affect dynamic stability.This article analyzes how reduced inertia impacts the stable parallel operation of the Mangystau power plant and the Unified Energy System of Western Kazakhstan. The study focuses on electromechanical transients in scenarios with high-RES penetration and generator outages. Five inertia scenarios were modeled under two initial operating conditions using PowerWorld Simulator 23, evaluating the effects of a three-phase fault with unsuccessful reclosing on 220 kV lines.The results show that lower inertia significantly weakens dynamic stability, creating potential risks for secure power system operation. The findings highlight the need to account for inertia when planning RES integration and underscore the importance of developing new principles of emergency automation. These results demonstrate the critical importance of maintaining sufficient system inertia to ensure reliable and stable power system operation under increasing RES penetration.

Key words: renewable energy sources, inertial constant, transient stability, emergency automation, automatic re-activation.

Introduction

Climate change is becoming a growing global concern, largely driven by rising greenhouse gas emissions since the Industrial Revolution. According to the IPCC [1], CO_2 from fossil fuel combustion and methane are the primary contributors to warming. The power and heat sectors remain the largest emitters, producing about 16 $GtCO_2$ in 2019 [2].

The global energy transition is accelerating the retirement of coal-fired plants and the integration of renewable energy sources (RES). Kazakhstan has been actively implementing the Paris Agreement since 2016 and has recently expanded its climate initiatives [3]. By the end of 2022, the country operated 130 RES facilities with a total capacity of 2,400 MW, generating 5.11 billion kWh (4.53% of total production) [4]. In 2023, another 16 plants with 495.6 MW of capacity were commissioned [5]. Despite clear environmental benefits, large-scale RES integration introduces technical challenges. A key issue is the lack of rotational inertia, which can threaten frequency stability and dynamic stability of interconnected power systems [6–7]. A real example occurred in South Australia [8–9], where low inertia caused the system frequency to fall below 47 Hz after a major generation outage, leading to system collapse.This article examines how reduced inertia from a high share of wind power affects the dynamic stability of the parallel operation of the Mangystau power plant with the Unified Energy System of Western Kazakhstan. Lower inertia alters the parameters of the rotor motion equation [10], decreasing the system's ability to maintain synchronism. Loss of synchronism and the onset of asynchronous mode represent the most dangerous operating condition, producing severe voltage fluctuations [11–12] that can trip auxiliary systems of thermal or nuclear plants [13]. Extensive research has addressed dynamic stability issues in inverter-based renewable systems. Studies have examined inertia's impact on fault clearing times [14], transient behavior and power contributions of DFIG-based generators [15], stability criteria using delta–power–frequency relationships [16], and time-varying equivalent inertia under high-RES penetration [17].

This work continues the analysis presented in [18] by studying the impact of reduced inertia on the dynamic stability of the 220 kV L-2075+L-2085 (Beineu–MAEK) corridor. Two additional initial operating modes are included, and five scenarios involving generator-unit outages at Mangystau are evaluated.

The objectives of the study are:

1. Develop a 110–220 kV network diagram of the Mangystau power system.
2. Link inertia constants to rated parameters of MAEK synchronous generators.
3. Define generator-outage scenarios representing different inertia levels.
4. Establish two initial modes (maximum and minimum).
5. Simulate electromechanical transients caused by a three-phase fault with unsuccessful reclosing on 220 kV line L-2075 (Beineu–MAEK).
6. Analyze and compare results for five reduced-inertia scenarios under both initial modes.

All simulations are carried out using PowerWorld Simulator 23.

Theoretical basics of transient stability

Case study considers the simplest system with a single generator operating in parallel with a large power grid and connected to an infinite bus via two parallel power lines. Figure 1 shows the system in pre-emergency (I), emergency (II) and post-emergency (III) mode, when the line damaged by a short circuit is disconnected from both sides.

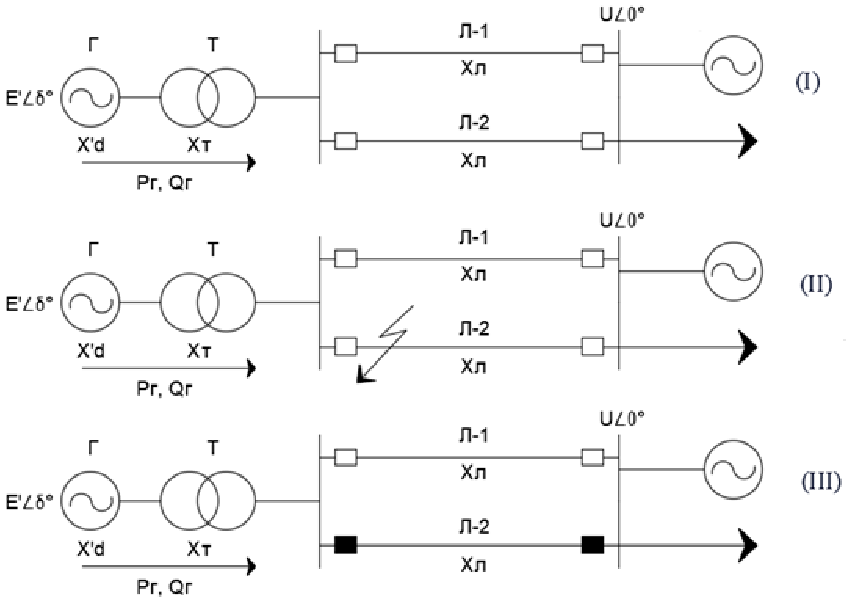

Figure 1. The scheme of the simplest power system in 3 modes

It is assumed that the generator generates a certain amount of active power P. The equivalent reactance of the network through which the generator outputs active power is determined as follows:

$$X_{экв} = X_d' + X_m + \frac{X_{л-1}(= X_{л-2})}{2}, \quad (1)$$

Where,

$X_d^{'}$ – transient reactance of the generator;
X_m – transformer reactance;
$X_{л-1} (= X_{л-2})$ – reactance of two power lines.

The relationship between the power P, the absolute values of E' and U, and the angle δ can be determined using the vector diagram shown in Figure 2. The diagram illustrates the active and reactive components of the current (I_a and I_r). The current itself is derived from the power output of the generator. Accordingly, the longitudinal ($I_r \cdot Xq$) and transverse ($I_a \cdot Xq$) components of the voltage drop ($I \cdot X$) are shown. The electromotive force E' and the voltage V are represented as phasors. The corresponding equation follows from the diagram.

$$I_a \cdot X = E^{'} \cdot \sin(\delta) \tag{2}$$

Multiplying both parts by $3 \cdot U/X_{eqv}$, one gets the following equation:

$$3U \cdot I_a = \frac{3E^{'} \cdot U}{X_{eq}} \cdot \sin(\delta) = \frac{E_L^{'} \cdot U_L}{X_{eq}} \cdot \sin(\delta) \tag{3}$$

Knowing the three phase active power $P = 3 \cdot U_{ph} \cdot I_a$, one gets the following equation:

$$P = \frac{E_L^{'} \cdot V_L}{X_{eq}} \sin(\delta) \tag{4}$$

$$P_{max} = \frac{E_L^{'} \cdot V_L}{X_{eq}} \tag{5}$$

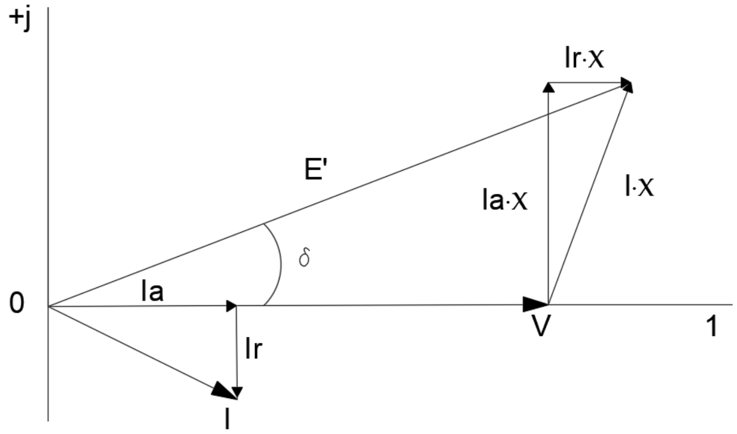

Figure 2. Vector diagram of voltages and currents for a single generator operating on a large power grid

Equation (4) is called the angular characteristic of the generator, and expression (5) defines the limit of static stability of the generator, which supplies its power to the network through a transformer and two power lines. Expression (5) defines the amplitude of the angular characteristic of the generator:

1. When the network is weakened (for example, when one of the lines is disconnected), the limit of static stability decreases due to the fact that the equivalent resistance increases. Accordingly, the amplitude of the angular characteristic decreases.

2. In case of a short circuit on any part of the network in Figure 1, the voltage on the infinite power bus and the EMF of the generator are reduced to unacceptable values. Accordingly, the

amplitude of the angular characteristic of the generator in the short-circuit mode is significantly reduced.

In the future, expressions (4) and (5) will be used in the equation of motion of the generator rotor.:

$$T_j \frac{d^2\delta}{dt^2} = P_m - P_э \quad (6)$$

where, - T_j – inertial rotation constant of the generator;

δ – the angle of the generator rotor relative to the angle of the voltage vector IB;

P_m – the power of turbine;

$P_э$ – the electromagnetic power of the generator, defined by the expression (4).

The second time derivative of the angle (acceleration) depends on the balance of the mechanical and electromagnetic power of the generator. When the generator is operating at a frequency of 50 Hz, the angle takes on a certain value, which is determined by the operating mode of the network. At the slightest fluctuations in the load or generation in the external network, the angle of the generator rotor changes according to the conditions of the mode change. By shifting the inertial constant of equation (6) to the right-hand side, it becomes clear that how much the angle of the generator rotor changes in any transient process depends inversely on the inertial constant.

Figure 3 shows the angular characteristics of the generator in pre-emergency, emergency and post-emergency modes. The initial mode corresponds to point 1, the intersection of the power developed by the turbine with the angular characteristic of the generator in pre-emergency mode. In this case, the electric transmission angle has the value δ0.

When an emergency occurs in the form of a short circuit, the angular transmission characteristic of the generator weakens and takes the form illustrated in Figure (II). Due to a short circuit and a deep voltage drop in the network nodes, there is a significant reset of the active electrical power of the generator, determined by point 2. The reset of electrical power depends on the nature of the damage (the location of the short circuit and its type). Since electromagnetic transients and relay protection operation occur in fractions of a second, it is assumed that the turbine regulators do not have time to work to increase or decrease the steam supply. Accordingly, the turbine power is assumed to be equal to a constant. When moving from point 1 to point 2, there is an imbalance between the electromagnetic and mechanical power of the generator. According to formula (6), the mechanical rotation of the turbine begins to accelerate the rotor of the generator, which leads to an increase in its angle. This process proceeds according to characteristic II up to point 3, and the angle of the generator rotor takes the value δ2. Point 3 corresponds to the moment of disconnection of the connection, where a short circuit occurred, i.e. disconnection of the transmission line from both sides. During the time when δ0 grew to δ2, the generator rotor acquired kinetic energy, which is proportional to the area S1, limited by turbine power, angular characteristics I and II, and points 1 and 3. S1 is called the acceleration area of the generator.

After the damaged line is excluded from the circuit, the angular characteristic of the generator switches to the III state, and point 3 switches to point 4. At this point, based on the figure, it can be seen that the electromagnetic power of the generator is higher than the turbine power. Accordingly, at point 4, the braking process of the generator will begin, accompanied by an increase in the angle. Point 5 corresponds to the angle δ3, which is the moment when all the stored kinetic energy is not exhausted and converted into potential energy. The depletion of stored energy is directly proportional to the braking area (S2), which is limited by the angular characteristic, the turbine power in the initial mode, and the angles δ2 and δ3. The S3 area from Figure 3 determines the reserve braking area of the generator. In other words, the braking area margin is the area determined by the critical angle of dynamic stability. The smaller the margin of braking area, the higher the probability of a violation of dynamic stability and the occurrence of asynchronous operation.

The condition for maintaining dynamic stability is determined by the fact that the braking area of the generator must be greater than the acceleration area:

$$\int_{\delta_0}^{\delta_2} (P_m - P_{мax}^{II} \sin\delta) d\delta \leq \int_{\delta_2}^{\delta_{crit}} (P_{мax}^{III} \sin\delta - P_m) d\delta \tag{7}$$

where - $P_{мax}^{II} \sin\delta$ – a function that determines the angular characteristic of the generator in emergency mode;

$P_{мax}^{III} \sin\delta$ – a function that determines the angular response of the generator in emergency mode;

$\delta_{crit} = 180 - \delta_1$ – the critical angle of dynamic stability, which is determined by the angle of the established emergency mode (δ_1).

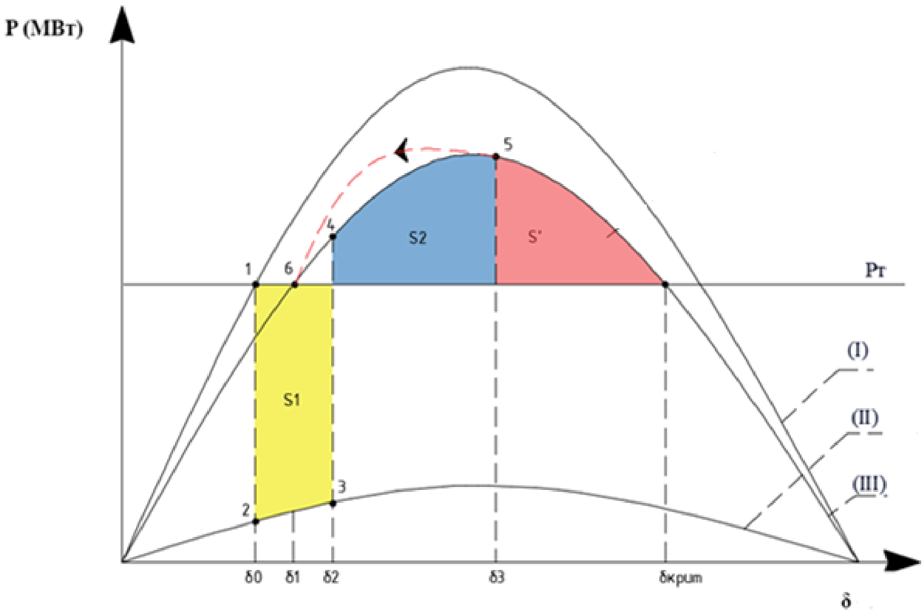

Figure 3. Angular characteristic of the generator in 3 modes

In equation (7), 3 constants are noted, which are determined by the initial regime – turbine power, initial angle and critical angle of dynamic stability. Accordingly, the angle δ2 at which the damaged line is disconnected determines the result of the transient process and the preservation of dynamic stability. Increasing the angle δ2 expands the acceleration area and reduces the braking area. In turn, δ2 is determined by the equation of motion of the rotor during a short circuit.

$$T_j \frac{d^2\delta_2}{dt^2} = P_m - P_{мax}^{II} \sin\delta \tag{8}$$

Integrating both parts of expression (8) over time, an expression of the rate of change of the rotor angle over time is obtained:

$$\frac{d\delta_2}{dt} = \frac{1}{T_j}(P_m - P_{мax}^{II} \sin\delta) \int_0^{t_1} dt = \frac{1}{T_j}(P_m - P_{мax}^{II} \sin\delta)t \tag{9}$$

where, - t_1 – duration of the short circuit.

Further, integrating both parts of expression (8), the value of the angle at the moment of termination of the short circuit is obtained:

$$\delta_2 = \delta_0 + \frac{1}{T_j}(P_m - P_{max}^{\text{II}} sin\delta) \int_0^{t_1} tdt = \delta_0 + \frac{1}{2 \cdot T_j}(P_m - P_{max}^{\text{II}} sin\delta) t_1^2 \quad (10)$$

Taking into account that the duration of the main protection and the connection switch does not change, the angle after the short circuit is eliminated depends on the value of the inertial constant for a certain initial mode.

The angle δ3 is also determined by the equation of motion of the rotor. However, it is determined by the angular response in the post-emergency mode.

$$T_j \frac{d^2\delta_3}{dt^2} = P_m - P_{max}^{\text{III}} sin\delta \quad (11)$$

Having performed the integration similar to (9) and (10), we obtain:

$$\delta_3 = \delta_2 + \frac{1}{T_j}(P_m - P_{max}^{\text{III}} sin\delta) \int_0^{t_2} tdt = \delta_2 + \frac{1}{2 \cdot T_j}(P_m - P_{max}^{\text{III}} sin\delta) t_2^2 \quad (12)$$

where, - t_2 is the time taken to exhaust the stored kinetic energy of the generator.

Thus, from equations (10) and (12), it can be concluded that a decrease in the inertial constant of the Mangystau receiving power system affects not only the increase in angle during acceleration of generators (in short-circuit mode), but also the increase in angle during braking (in emergency mode). In addition, the angle δ2 also affects the growth of the angle δ3, which results in the effect of superimposing the acceleration area in short-circuit mode on the braking area in emergency mode.

In the case of an unsuccessful AR of one of the overhead lines-220kV Beineu – MAEK, the dynamic processes on the angular characteristic are reflected in Fig. 4 [18].

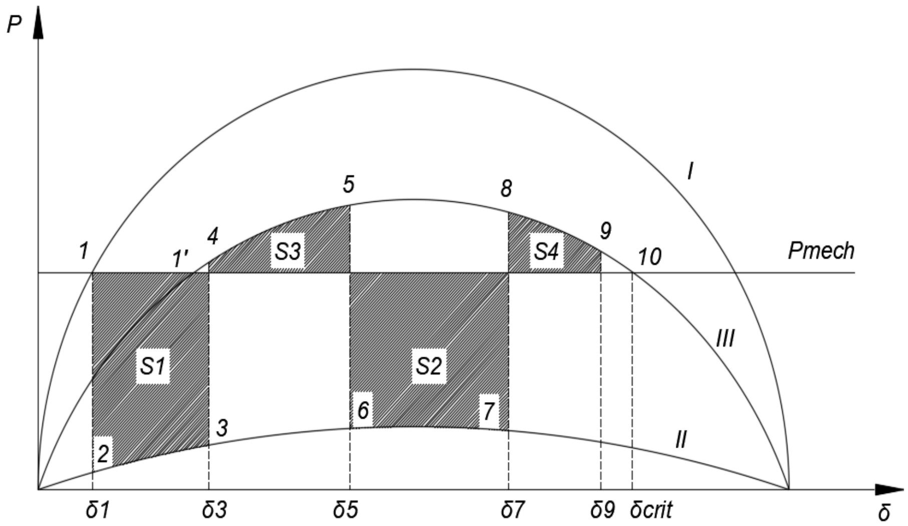

Figure 4. Angular characteristic of power transmission in the scenario of a three-phase short circuit and unsuccessful AR

In this case, the condition for maintaining dynamic stability will look like:

$$\int_{\delta_1}^{\delta_3} (P_m - P_{мax}^{\text{II}} \sin\delta) d\delta + \int_{\delta_5}^{\delta_7} (P_m - P_{мax}^{\text{II}} \sin\delta) d\delta \le \int_{\delta_3}^{\delta_5} (P_{мax}^{\text{III}} \sin\delta - P_m) d\delta + \int_{\delta_7}^{\delta_{крит}} (P_{мax}^{\text{III}} \sin\delta - P_m) d\delta \quad (13)$$

The values of the angles in certain integrals of equation (13) are determined by the following formulas

$$\delta_3 = \delta_1 + \frac{1}{T_j}(P_m - P_{мax}^{\text{II}} \sin\delta) \int_0^{t_1} t dt = \delta_1 + \frac{1}{2 \cdot T_j}(P_m - P_{мax}^{\text{II}} \sin\delta) t_1^2 \quad (14)$$

$$\delta_5 = \delta_3 + \frac{1}{T_j}(P_m - P_{мax}^{\text{III}} \sin\delta) \int_0^{t_2} t dt = \delta_3 + \frac{1}{2 \cdot T_j}(P_m - P_{мax}^{\text{III}} \sin\delta) t_2^2 \quad (15)$$

$$\delta_7 = \delta_5 + \frac{1}{T_j}(P_m - P_{мax}^{\text{II}} \sin\delta) \int_0^{t_1} t dt = \delta_5 + \frac{1}{2 \cdot T_j}(P_m - P_{мax}^{\text{II}} \sin\delta) t_1^2 \quad (16)$$

$$\delta_9 = \delta_7 + \frac{1}{T_j}(P_m - P_{мax}^{\text{III}} \sin\delta) \int_0^{t_2} t dt = \delta_7 + \frac{1}{2 \cdot T_j}(P_m - P_{мax}^{\text{III}} \sin\delta) t_2^2 \quad (17)$$

Where, δ_3– angle at the moment of termination of the first short circuit cycle;

δ_5 – the angle, at the moment of exhaustion of the stored kinetic energy, obtained from the acceleration of the generator in the first short circuit cycle;

δ_7 – angle, at the moment of termination of the second short circuit cycle after an unsuccessful AR;

δ_9 – the angle, at the moment of exhaustion of the stored kinetic energy, obtained from the acceleration of the generator in the second short circuit cycle after an unsuccessful start-up.

In equations (14-17), there is an effect of superimposing an angle increment from the process of accelerating the generator in short-circuit mode due to a decrease in the inertial constant.

Methodology

The main components of the Mangystau power system are:

• 3 generating sources of MAEK – TPP-1, TPP-2 and TPP

• TPP-1 and TPP-2 generators are presented as equivalents, rolled into 1 generator

• Generators at the MAEK thermal power plant are modeled separately due to the significant value of the inertial constant of each unit

• The collapsed UES system of Western Kazakhstan is connected to the 220 kV Beineu substation and acts as a balancing node

• One of the overhead lines 220kV L-2075/L-2085 between Beineu and TPP MAEK is damaged.

This figure shows the inertia constant of each generator block and the equivalent station (for example, the inertia of CHP-2 is 11.5 seconds). The essence of the methodology of this article is the gradual reduction of the inertial constant intake system of Mangystau.

Table 1 shows the composition of each turbogenerator unit at all 3 MAEK stations and the inertial constant of each unit, adjusted to a base power of 100 MVA.

Based on the data in this table, it is possible to create 5 scenarios, each of which outputs alternately blocks of turbo generators and their replacement by generation from wind farms.

Table 1. The composition of generators and their inertial constant

Power plant	Generator	H(s) S_{base} = 100 MVA	Total inertia
CHP-1 75 MW	G-1, 32 MW	0,666	1,998
	G-2, 32 MW	0,666	
	G-3, 32 MW	0,666	
CHP-2 630 MW	G-1, 60 MW	1,184	11,494
	G-2, 60 MW	1,184	
	G-3, 60 MW	1,184	
	G-4, 100 MW	1,603	
	G-5, 60 MW	1,184	
	G-6, 60 MW	1,184	
	G-8, 63 MW	1,184	
	G-9, 63 MW	1,184	
	G-10, 100 MW	1,603	
TPP 625 MW	G-1, 200 MW	3,083	8,768
	G-2, 210 MW	3,081	
	G-3, 220 MW	2,604	
Total	Mangystau power system	22,26	22,26

Descriptionofscenarios:
1) Scenario No. 1 – full complement of synchronous generators at MAEK stations
2) Scenario No. 2 – replacement of units No. 1-3 at CHP-1 and unit No. 1 at CHP-2
3) Scenario No. 3 – replacement of units No. 1-3 at CHP-1 and units No. 1-3 at CHP-2
4) Scenario No. 4 – replacement of units No. 1-3 at CHP-1 and units No. 1-5 at CHP-2
5) Scenario No. 5 – replacement of all units at TPP-1 and TPP-2 and unit No. 1 at TPP

In addition, this paper considers 2 modes:

1) Mode № 1 is minimal. The balance between generation and consumption (Mangystau deficit) is 25 MW. The transfer of power in the section L-2075 + L-2085 is 33 MW towards MAEK. The angle difference between the voltage vectors Beineu and MAEK is 2.62 degrees.

2) Mode № 2 is the maximum. The balance between generation and consumption is 95 MW. The power flow in the L-2075 + L-2085 section is 103 MW towards the MAEK, while the angle difference between the Beineu substation and the MAEK TPP is 9.17 degrees.

Then, electromechanical transients (hereinafter referred to as EMF) are calculated and modeled using the PowerWorld Simulator 23 software. In EMF modeling, it is set:

• The occurrence of a three-phase metal short circuit on the L–2075 Beineu- MAEK (close to the 220kV MAEK buses), followed by the operation of the main protections and disconnection of the 220kV L-2075 overhead line from both sides.

• With a shock-free pause time of 3 seconds, the AR works to turn on the line. The short circuit is stable, and the AR operates on an unresolved short circuit.

• Re-operation of accelerated protections for line disconnection on both sides and AR bans.

In addition, several assumptions are accepted:

• Intermittent generation from wind farms is ignored.

• The location of wind farms that replace individual MAEK units is not taken into account.

Results

Figure 5 shows graphs of fluctuations in the angle between the voltage vectors Beineu and MAEK at the minimum initial mode.

It is worth noting that in the minimal initial mode, dynamic stability is not impaired in all five scenarios. However, based on Figure 6, there is a tendency to increase the value of the difference in the angles of the voltage vectors between Beineu and MAEK.

Thus, the maximum deviation of the relative angle *δ* in different scenarios increased from 10.2° (Scenario No. 1) to 12.3° (Scenario No. 5) during the first short-circuit cycle. Also, a similar behavior of the mutual angle is observed in the second short-circuit cycle after the unsuccessful action of the AR.

In addition, based on the figure, it can be seen that the mutual angle increases and reaches its maximum value at different times under different scenarios. For example, inscenarioNo.1, when all the generator units are switched on and inertia is high, the angleδreaches a maximum value of 10.2degreesat2.1seconds of the transition process (in the first short-circuit cycle), whileinscenarioNo.5(a significant decrease in inertia of the power system), the angleδreaches12.3degreesat1.8seconds. In other words, reducing the inertial constant of the power system contributes not only to an increase in the parameter of the mutual angle itself, but also to a reduction in the time at which this angle increases.

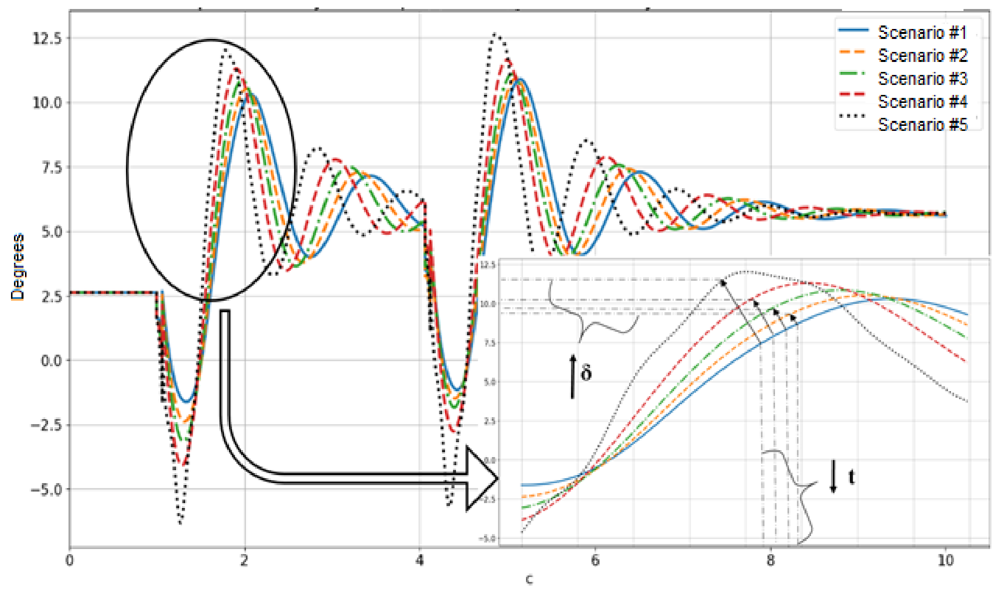

Figure 5. EMF simulation results for 5 scenarios in mode №1

Figure 6 shows graphs of fluctuations in the angle *δ* under five scenarios and the maximum initial mode. It is noteworthy that in this mode there is a violation of dynamic stability and the occurrence of asynchronous running. The initial mode for EMF simulation turned out to be very difficult for Scenario No. 5, since it is obvious that the asynchronous mode occurs even before the operation of the AR.

It should also be noted that, although the initial electric angle δ in mode No. 2 is higher than in mode No. 1 by a small value (+6.55 degrees), the discrepancies of this angle in the transient process are significant (50-65 degrees). This indicates that the angular characteristic of the L-2075+L-2085 section is significantly reduced, due to the low voltage level in the initial mode.

In general, based on the simulation results in mode 2, dynamic stability is maintained under the first 4 scenarios. However, the additional output of unit No. 1 to the thermal power plant, which is the station closest to the section L-2075+L-2085, leads to the fact that dynamic stability is not maintained even without the action of an unsuccessful AR.

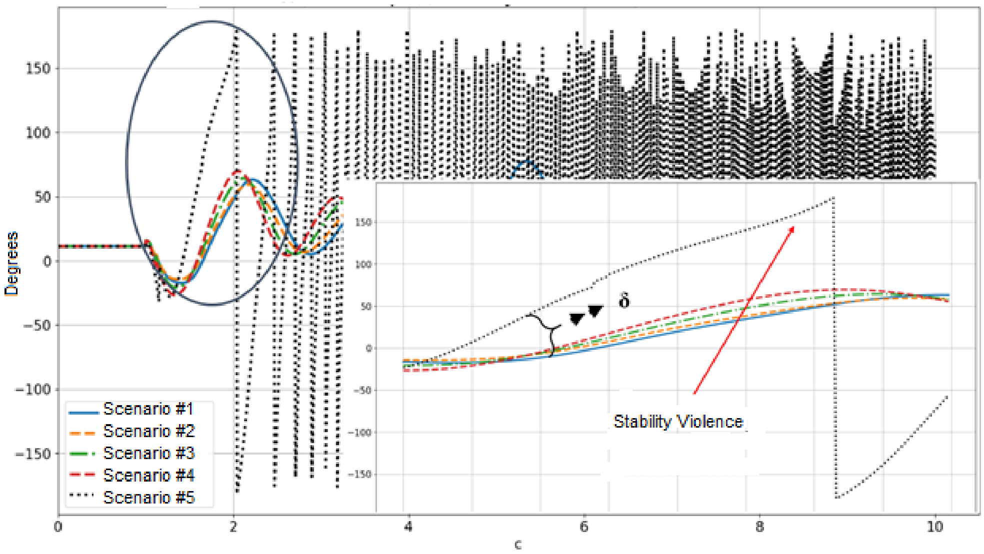

Figure 6. EMF simulation results for 5 scenarios in mode №2

Thus, under different initial conditions, i.e., at different values of the deficit or excess of active power in the Mangystau power plant, the conditions of dynamic stability differ significantly. For example, in [18], there is also a violation of dynamic stability after the second short-circuit cycle, while in this work, stability was disrupted before reaching the action of the AR. This indicates that under different modes, the location of the short circuit, its type, stability may or may not be maintained.

Conclusion

The study of reduced inertia in the Mangystau power system under high wind energy penetration shows that lowering the system's inertia constant has a substantial impact on dynamic stability. Simulation of electromechanical transients indicates that replacing synchronous generators with inverter-based sources increases the angular divergence of voltage vectors between nodes, especially in low-load modes where stability is lost more quickly and with larger deviations.

The results demonstrate that under minimal load, the system remains dynamically stable in all scenarios, though the growing angle differences and shorter time to reach peak angles signal a reduced stability margin. Under maximum load, however, significant inertia reduction leads to loss of dynamic stability—particularly when generator units near the fault location are taken offline. This underscores the need to consider system inertia carefully when integrating renewable energy sources.

To ensure reliable operation of a grid with a high share of renewables, additional measures are required. These include modernizing emergency control algorithms, incorporating AR modes into automation actions, developing new principles for automatic stability prevention, and implementing smart grid technologies such as stability-margin monitoring and centralized emergency automation. Together, these measures can enhance both dynamic and steady-state stability in an evolving energy landscape.

REFERENCES

1. Intergovernmental Panel on Climate Change (IPCC) Climate Change 2022. Mitigation of Climate Change; IPCC: Geneva, Switzerland, 2022.

2. Ritchie, H.; Roser, M.; Rosado, P.CO2 and Greenhouse Gas Emissions. *2020*. Available online: https://ourworldindata.org/co2-and-greenhouse-gas-emissions(accessedon 12 December 2023).

3. The Government of the Republic of Kazakhstan(gov.kz). Prime Minister of the Republic of Kazakhstan Askar Maminto okpartinthe 26th Conference of the Parties to the United Nations

Framework Convention on Climate Change (COP26), emphasizing Kazakhstan's strongcommitment to the implementation of theglobalclimate change agenda. https://www.gov.kz/memleket/entities/mfa-zagreb/press/news/details/278599?lang=ru

4. Ministry of Energy of the Republic of Kazakhstan. (2023). Development of renewable energy sources. https://www.gov.kz/memleket/entities/energo/activities/4910?lang=ru;

5. The official information resource of the Prime Minister of the Republic of Kazakhstan. (2023). Results of the year:strengthening of the Western Energy Zone, the launch of Newfield sand the Beineu-Zhanaozen gas pipeline. https://primeminister.kz/ru/news/itogi-goda-usilenie-zapadnoy-energozony-zapusk-novykh-mestorozhdeniy-i-gazoprovoda-beyneu-zhanaozen-26816

6. Glover, D.; Overbye, T.; Sarma,M. Power System Analysis and Design,6thed.; Cengage Learning, Boston, MA, USA, 2015.

7. Makolo, P.; Zamora, R.; Lie, T. The role of inertia for grid flexibility under high penetration of variable renewables — A review of challenges and solutions. Renew. Sustain. Energy Rev. 2021, *147*, 111223.https://doi.org/10.1016/j.rser.2021.111223.

8.AustralianEnergyMarketOperator (AEMO). Black System South Australia. 28 September 2016; AEMO: Melbourne, Australia,2017.

9.Australi an Energy Market Operator (AEMO). Final Report–Queensland and South Australia System Separation on 25 August 2018; AEMO: Melbourne, Australia,2019.

10. Zhdanov P.S. (1979). Issues of stability of electricalsystems/Edited by L.A.Zhukov.–M.,Energy.

11. Gurevich Yu.E., Libova L.E., Okin A. A. (1990). Calculations of stability and emergency automation in power systems. Moscow: Energoatomizdat.

12.Berkovich M.A., GladyshevV.A., SemenovV.A.(1991). Automation of power systems. Moscow: Energoatomizdat.

13. Ovcharenko N.I. (2000). Automation of electric power plants and electric power systems: Textbook for universities / Edited by A.F. Dyakov. Moscow: NC ENAS.

14. Naik, P.; Nair, N.; Swain, A. Impact of reduced inertia on transient stability of networks with asynchronous generation. Int. Trans. Electr. Energy Syst. 2015, 26, 175–191. https://doi.org/10.1002/etep.2079.

15. Liu, S.; Li, G.; Zhou, M. Power System Transient Stability Analysis with Integration of DFIGs Based on Center of Inertia. CSEE J. Power Energy Syst. 2016, 2, 20–29. https://doi.org/10.17775/CSEEJPES.2016.00018.

16. He, C.; He, X.; Geng, H.; Sun, H.; Xu, S. Transient Stability of Low-Inertia Power Systems With Inverter-Based Generation. IEEE Trans. Energy Convers. 2022, 37, 2903–2912. https://doi.org/10.1109/TEC.2022.3185623.

17. Ulbig, A.; Theodor, S.; Andersson, G. Impact of Low Rotational Inertia on Power System Stability and Operation. IFAC Proc. Vol. 2014, 47, 7290–7297. https://doi.org/10.3182/20140824-6-ZA-1003.02615.

18. Aisayev, Y., Tergemes, K., Zhauyt, A., Sheryazov, S., Bakenov, K. (2024). The Impact of Replacing Synchronous Generators with Renewable-Energy Technologies on the Transient Stability of the Mangystau Power System: An Introduction to Flexible Automatic Dosage of Exposures. *Energies, 17,* 2314. https://doi.org/10.3390/en17102314.

НЕГАТИВНОЕ ВЛИЯНИЕ УМЕНЬШЕНИЯ МОМЕНТА ИНЕРЦИИ НА ПЕРЕХОДНУЮ УСТОЙЧИВОСТЬ В МАНГИСТАУСКОЙ ЭНЕРГОСИСТЕМЕ

Е.С. Айсаев[1*], К.Т. Тергемес[2], С.К. Шерьязов[3]

[1]АО «KEGOC», «Национальный диспетчерский центр Системного оператора», Астана, Казахстан

[2]Алматинский Университет Энергетики и Связи имени Гумарбека Даукеева, Алматы, Казахстан

[3]Южно-Уральский государственный аграрный университет, Челябинск, Российская Федерация
e-mail: e.aisayev@gmail.com, k.tergemes@aues.kz, sakenu@yandex.ru

Аннотация. Изменение климата и растущие экологические риски ускоряют глобальный переход на возобновляемые источники энергии (ВИЭ), но этот переход создаёт новые проблемы для энергосистем. Замена традиционной генерации на ВИЭ снижает инерционность системы, что может негативно сказаться на её динамической устойчивости.

В данной статье анализируется влияние снижения инерционности на устойчивую параллельную работу Мангистауской электростанции и Единой энергосистемы Западного Казахстана. Исследование сосредоточено на электромеханических переходных процессах в сценариях с высоким уровнем проникновения ВИЭ и отключениями генераторов. С помощью Power World Simulator 23 было смоделировано пять сценариев инерционности при двух начальных условиях эксплуатации для оценки последствий трёхфазного короткого замыкания с неудавшимся повторным включением на линиях 220 кВ.

Результаты показывают, что снижение инерционности существенно снижает динамическую устойчивость, создавая потенциальные риски для безопасной работы энергосистемы. Результаты подчеркивают необходимость учета инерционности при планировании интеграции ВИЭ и важность разработки новых принципов противоаварийной автоматики. Эти результаты демонстрируют критическую важность поддержания достаточной инерционности системы для обеспечения надежной и стабильной работы энергосистемы в условиях растущего проникновения ВИЭ.

Ключевые слова: возобновляемые источники энергии, инерционная постоянная, переходная устойчивость, противоаварийная автоматика, автоматическое повторное включение.

МАҢҒЫСТАУ ЭНЕРГЕТИКА ЖҮЙЕСІНДЕГІ ӨТКІШТІК ТҰРАҚТЫЛЫҚҚА АЗАЙТЫЛҒАН ИНЕРЦИЯЛЫҚ ТҰРАҚТЫЛЫҚТЫҢ ЖАҒЫМСЫЗ ӘСЕРІ

Е.С.Айсаев[1*], К.Т. Тергемес[2], С.К. Шерьязов[3]
[1]АҚ «KEGOC», «Жүйелік оператордың Ұлттық диспетчерлік орталығы»;
Астана, Казахстан
[2]Ғұмарбек Дәукеев атындағы Алматы энергетика және байланыс университеті;
Алматы, Казахстан
[3]Оңтүстік-Орал мемлекеттік аграрлық университеті, Челябинск, Ресей Федерациясы
e-mail: e.aisayev@gmail.com, k.tergemes@aues.kz, sakenu@yandex.ru

Андатпа: Климаттың өзгеруі және өсіп келе жатқан экологиялық тәуекелдер жаңартылатын энергия көздеріне (ЖЭК) жаһандық көшуді жеделдетуде, бірақ бұл ауысу энергетикалық жүйелер үшін жаңа қиындықтар туғызуда. Дәстүрлі генерацияны ЖЭК-мен ауыстыру жүйенің инерциясын төмендетеді, бұл оның динамикалық тұрақтылығына теріс әсер етуі мүмкін. Бұл мақалада Маңғыстау электр стансасы мен Батыс Қазақстанның Бірыңғай энергетикалық жүйесінің тұрақты параллель жұмысына төмендеген инерцияның әсері талданады. Зерттеу жаңартылатын энергияның жоғары енуі және генератордың үзілістері бар сценарийлердегі электромеханикалық өтпелі процестерге бағытталған.

Power World Simulator 23 көмегімен 220 кВ желілердегі сәтсіз қайта жабылумен үш фазалы қысқа тұйықталудың салдарын бағалау үшін екі бастапқы жұмыс жағдайында бес кідіріс-жауап сценарийі модельденді. Нәтижелер қысқартылған жауап беру уақытының динамикалық тұрақтылықты айтарлықтай төмендететінін, энергия жүйесінің қауіпсіз жұмысына әлеуетті тәуекелдерді тудыратынын көрсетеді. Бұл нәтижелер жаңартылатын энергия көздерін біріктіруді жоспарлау кезінде әрекет ету уақытын ескеру қажеттілігін және апатты басқаруды автоматтандырудың жаңа принциптерін әзірлеудің маңыздылығын көрсетеді. Бұл нәтижелер ЖЭК енуінің жоғарылауы жағдайында қуат жүйесінің сенімді және тұрақты жұмысын қамтамасыз ету үшін жүйенің жеткілікті инерциясын сақтаудың маңыздылығын көрсетеді.

Түйін сөздер: жаңартылатын энергия көздері, инерциялық константа, өтпелі тұрақтылық, авариялық автоматика, автоматты қайта қосу.