METHODS FOR STABILIZING KAZAKHSTAN'S POWER SYSTEM WITH THE INTEGRATION OF RENEWABLE ENERGY SOURCES

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Abstract
This article examines modern methods for stabilizing the power system with an increasing share of renewable energy sources. Particular attention is paid to the current state of renewable energy in Kazakhstan in 2024–2025, as well as the technical challenges arising from the integration of solar, wind, and energy storage systems. It is shown that an increasing share of inverter energy resources leads to a decrease in the natural inertia of the power system, increased complexity of frequency and voltage regulation, and the need for new control methods. The article analyzes the capabilities of grid-following and grid-forming inverters, revealing their advantages and limitations. It is concluded that the most promising approach is a hybrid model, in which grid-following inverters provide efficient power output, while grid-forming inverters perform the system-forming functions of stabilizing voltage, frequency, and inertia-like response.

Keywords: renewable energy sources; RES; Kazakhstan's power system; power system stabilization; grid-following inverters; grid-forming inverters; virtual inertia; energy storage systems; Smart Grid; frequency stability; voltage stability.

The relevance of this topic is determined by the fact that the integration of variable renewable energy sources-primarily wind and solar generation—requires not only the construction of new facilities but also changes in power system management methods. The IEA emphasizes that as the share of solar and wind generation increases, the power system goes through several phases of renewable energy integration, and each phase creates new technical challenges that require special measures to maintain the reliability and efficiency of the grid. NREL defines renewable energy integration as the practice of developing efficient methods for transmitting variable renewable energy to the grid while maintaining or improving the stability and reliability of the power system.

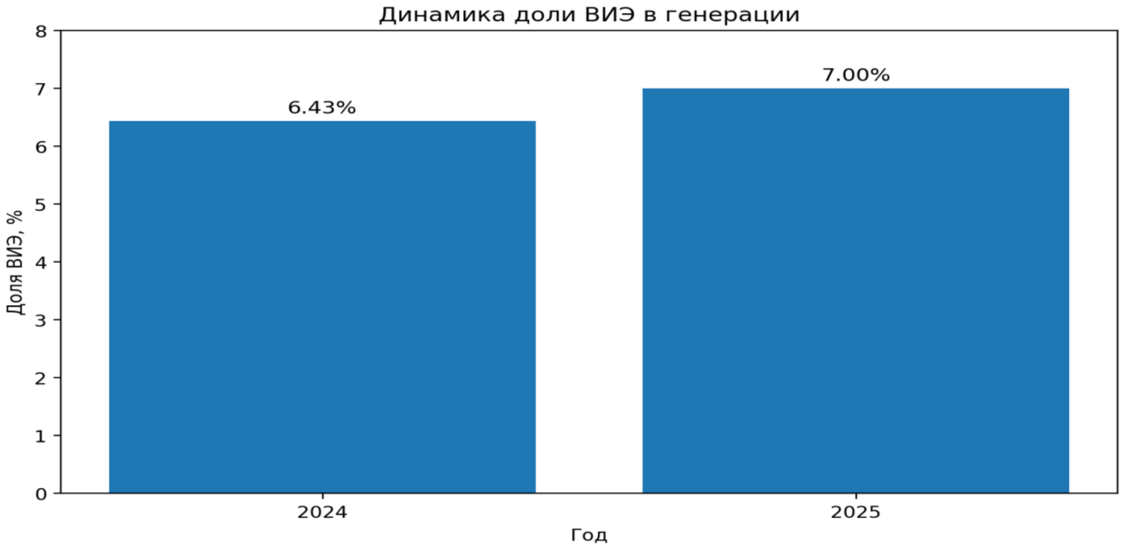
The objective of the study is to analyze methods for stabilizing the power system during the integration of renewable energy sources and compare the capabilities of grid-following and grid-forming inverters. Research methods: literature review, comparative analysis, systems analysis, and analysis of statistical data on renewable energy in Kazakhstan for 2024–2025. The scientific novelty lies in the generalization of modern approaches to stabilizing a power system with a high share of renewable energy sources and the comparison of the capabilities of GFL and GFM inverters as applied to the conditions of the Kazakhstan power system.

This topic is particularly significant for Kazakhstan, as KEGOC's strategy explicitly states the objective of ensuring the reliable operation of the Unified Electricity System of Kazakhstan amid the energy transition and the integration of renewable energy sources into the system. The Ministry of Energy of the Republic of Kazakhstan also sets a goal of achieving a 15% share of renewable energy sources by 2030, including the development of renewable energy projects with energy storage systems.

As of 2024-2025, the use of renewable energy sources in Kazakhstan has transitioned from the stage of point projects to a more sustainable electricity sector, however, RES still retain a supporting rather than a core role in the country's energy balance. In 2024, RES facilities generated 7.58 billion kWh, which accounted for 6.43% of all electricity generation; the installed capacity reached approximately 3.03 GW, and about 153 facilities were in operation. Wind power plants made the largest contribution - 4.51 billion kWh, followed by solar power plants - 1.89 billion kWh, small hydroelectric power plants - 1.18 billion kWh, while bioelectric power plants had a minimal share - about 1.58 million kWh. In 2025, the growth continued: according to data published with reference to the Ministry of Energy of the Republic of Kazakhstan, the generation of renewable energy sources reached 8.62 billion kWh, that is, an increase of 13.7% compared to 2024, and the share of renewable energy sources in total generation was about 7%. The installed capacity of renewable energy sources by the end of 2025 reached 3.537 GW, of which 1.909 GW were wind power plants, 1.313 GW were solar power plants, about 314 MW were small hydroelectric power plants, and 1.77 MW were bioenergy [1]. Thus, in Kazakhstan in 2024–2025, it was wind energy that developed most dynamically, which is associated with the natural and climatic potential of the steppe regions and the state's focus on large wind power plant projects. At the same time, the growth of renewable energy requires the parallel development of flexible generation, energy storage, digital control, and grid infrastructure, as the increasing share of solar and wind generation increases the demands on power system stability, power balancing, and generation forecasting. The government's goal of increasing the share of renewable energy to 15% by 2030 and commissioning at least 8.4 GW of new renewable energy capacity by 2035 demonstrates that the sector will expand, but its continued effectiveness depends not only on the construction of new plants but also on the technological stabilization of the power system [1].

Indicator	2024	2025
Renewable Energy Generation	7.58 billion kWh	8.62 billion kWh
Share of Renewable Energy in Total Generation	6.43%	about 7%
Installed Renewable Energy Capacity	3.03 GW	3.537 GW
Wind Energy	4.51 billion kWh	5.38 billion kWh
Solar Energy	1.89 billion kWh	2.04 billion kWh
Small Hydropower	1.18 billion kWh	about 1.2 billion kWh
Bioenergy	1.58 million kWh	about 2.8 million kWh

Dynamics of the share of renewable energy sources in generation



Consequently, Kazakhstan is demonstrating steady growth in renewable energy sources, but the transition to a higher share of renewable generation requires not only capacity expansion but also a comprehensive modernization of the power system—developing storage, flexible capacity, grid-forming inverters, forecasting, and digital dispatch control.

Today, the main problem with renewable energy sources is their variable and inverter-based nature. Traditional power systems relied on synchronous generators, which have mechanical inertia. Replacing some of these generators with solar and wind turbines connected via power electronics reduces the natural inertial frequency support. As a result, the power system becomes more sensitive to sudden changes in load, generation, emergency outages, and power fluctuations.

The concept of inverter-based energy resources deserves special attention. NREL emphasizes that solar, wind, and battery systems are connected to the grid through inverters, making grid-forming inverters - inverters that can not only follow grid parameters but also shape voltage and frequency - increasingly important for the future energy system.

It should be noted that the main methods for stabilizing a power system using renewable energy sources are: 1. Grid-forming inverter control. This is one of the most promising approaches. Grid-forming inverters can operate as voltage sources, maintain frequency and voltage, provide synchronization, and contribute to grid stabilization. NREL research considers grid-forming inverters a key approach for power systems with a high proportion of inverter sources.

2. Virtual synchronous generator/virtual inertia. The VSG/VSM method simulates the behavior of a synchronous generator: the inverter is given an algorithm that allows it to respond to frequency changes like a traditional rotating machine. Reviews of grid-forming control indicate that droop control, virtual synchronous machine, and synchronverter are the most common control strategies.

3. Droop control. Droop control allows active and reactive power to be distributed among multiple sources without constant centralized communication. This method is especially important for microgrids, stand-alone power systems, and hybrid renewable energy + storage systems.

4. Energy storage systems. Battery storage systems can smooth out fluctuations in renewable energy generation, participate in primary frequency regulation, support voltage, provide power reserves, and increase grid flexibility. IRENA considers grid flexibility a key requirement for the energy transition and renewable energy integration.

5. Smart Grid, digital control, and forecasting. Accurate forecasting of solar and wind generation, digital monitoring, automated load management, the use of PMUs/WAMS, SCADA, EMS, and intelligent algorithms are essential for grid stabilization. KEGOC's strategy also includes the implementation of modern, innovative, and digital technologies, including the Smart Grid.

6. Increasing grid flexibility. Flexible resources include storage systems, hydroelectric power plants, fast-start gas-fired power plants, demand response, in-

terconnections, grid redundancy, and grid modernization. The IEA emphasizes that as the share of renewable energy increases, targeted measures are needed for each phase of integration, including flexibility, network infrastructure, and operational solutions.

Therefore, the purpose of this article is to substantiate and describe a set of methods for stabilizing a power system with a high share of renewable energy sources based on the use of grid-forming inverters, virtual inertia, energy storage systems, and intelligent control algorithms. To achieve this goal, it is necessary to analyze the impact of solar and wind generation on the frequency and voltage stability of the power system; examine modern methods for stabilizing power systems with a high share of renewable energy sources; compare the capabilities of grid-following and grid-forming inverters; and determine the prospects for applying these methods in the power system of Kazakhstan.

As we know, in power systems with a high share of renewable energy sources, the difference between grid-following and grid-forming inverters becomes fundamental, since it is no longer just a matter of connecting solar, wind, and battery installations to the grid, but rather the ability of inverter resources to contribute to maintaining power system stability. Grid-following inverters (GFLs) have historically been a more common and technologically mature solution for renewable energy sources: they operate as controlled current sources, synchronized with the existing grid voltage, typically via a PLL mechanism, and perform well in the areas of active power generation, MPPT, current regulation, reactive power compensation, and operation in strong grids.

However, their key limitation lies in their dependence on an external grid reference signal: with reduced inertia, a drop in short-circuit power, voltage distortions, or operation in weak grids, GFL inverter stability deteriorates, and large numbers of such devices can exacerbate frequency and small-signal stability issues..

In 2024-2025 studies, the transition from grid-following to grid-forming control logic is considered a natural response to the growing share of inverter energy resources in the power system. In a 2024 NREL presentation, B. Kroposki directly links the need for GFM inverters to the rapidly increasing number of inverter-based resources "from Solar PV, Wind, and Batteries" in the grid—that is, solar, wind generation, and battery energy storage systems [2]. Unlike grid-following inverters, which are primarily synchronized with the existing grid voltage and "follow" grid parameters, grid-forming inverters are capable of more actively participating in the formation of the power system's reference parameters—voltage, frequency, inertial-like response, and oscillation damping.

B. Bahrani, M. H. Ravanji, B. Kroposky, et al., in a 2024 article, emphasize that GFM control allows the inverter resource to respond to changes in the system "nearly instantaneously," that is, almost instantly, helping to stabilize the grid during disturbances [3]. Therefore, GFM inverters have broader stabilization capabilities: they can maintain local frequency and voltage, operate in weak grids and microgrids, provide island operation, participate in black start, and improve system performance with reduced inertia and a high share of renewable energy sources.

In a 2025 review by M. V. Kaisar and C. Fan, grid-forming converters are characterized as a technology necessary for "reliable, stable, and resilient operation" of power systems transitioning to low-inertia and inverter-dominated configurations [4]. At the same time, the researchers emphasize that the transition to GFM does not mean a complete abandonment of GFL: the future power system will likely be hybrid, where grid-following inverters will retain their role as efficient power sources, while grid-forming inverters will take on system-forming functions.

However, hybridity creates new challenges: S. Chen, Y. Wang, M. Yang, et al. (2025) show that in hybrid systems, a GFL inverter can act as an "excitation source" of forced oscillations for GFM inverters [5]. Consequently, the advantage of GFM inverters lies not simply in a more complex control scheme, but in the qualitatively different role of renewable energy sources in the power system: renewable generation ceases to be only an alternating power source and becomes an active tool for maintaining stability.

At the same time, as B. Bhowmick, M. A. Akwa, and S.-Y. Kim show, even modern hybrid-compatible GFM inverters require solutions to problems of coordination, current limitations, and fault ride-through, since the replacement of synchronous generators with renewable energy sources creates "low-inertia power systems" with increased vulnerability to frequency instability [6].

Summarizing the scientists' opinions, it can be noted that the widespread deployment of inverter resources—primarily solar, wind, and storage—requires a shift from a simple "grid-following" logic to a more active role for inverters in shaping its parameters. Grid-forming inverters (GFMs) offer broader stabilization capabilities in this regard: they operate closer to the voltage source, can maintain local frequency and voltage, provide an inertia-like response, dampen oscillations, operate in weak grids, microgrids, and island modes, and, if equipped with energy storage, participate in black start and system restoration after failures.

NREL notes that GFM inverters are becoming necessary due to the growing share of inverter-based resources in the power system, and also notes that, in practice, it is beneficial to deploy GFMs primarily in the weakest sections of the grid and that the combination of GFMs and storage maximizes their potential. In a 2024 IEEE Power & Energy Magazine review, GFMs are considered a key resource for renewable-rich power systems because they are able to respond almost instantly to system changes and help stabilize the grid, while conventional IBRs without grid-forming functions lack a number of capabilities, including autonomous operation and participation in blackout recovery.

At the same time, GFM inverters cannot be considered a simple, one-size-fits-all solution. They still face challenges in terms of current limitations during faults, configuring droop control, virtual synchronous machine, and virtual oscillator control algorithms, coordination with GFL inverters, interaction with existing relay protection, and preventing new types of oscillations. GFM technologies are essential for the stable and reliable operation of low-inertia systems, but require further development of topologies, control strategies, small-signal stability modeling, and inverter-grid interactions. It is particularly important that the power system in the near future will be neither fully GFL nor fully GFM, but a hybrid. In systems where GFL and GFM operate simultaneously, a GFL inverter with MPPT can act as a source of forced oscillations, inducing GFM inverter modes, requiring specialized compatibility analysis and parametric tuning. Therefore, the most rational strategy for renewable energy sources is not to completely abandon GFL inverters, but to combine them with GFM resources and energy storage. GFLs remain effective for mass generation and cost-effective power delivery to a stable grid, while GFMs must perform system-forming functions—maintaining voltage, frequency, inertia-like response, resilience of weak nodes, and recovery from disturbances.

This is confirmed by studies of the coordination of GFL and GFM storage systems for virtual inertia, where differences in synchronization and frequency response mechanisms require coordinated control, but with proper configuration, can achieve the desired overall inertia effect. Practical results from the PNNL/IEEE PESGM also show that replacing GFL batteries with GFM batteries in power systems with a high concentration of inverter-based resources improves the voltage profile, active power during and after a fault, and increases the permissible renewable energy output from a local area. Therefore, when comparing the capabilities, we can conclude: GFL inverters remain technologically mature, economical, and efficient in a strong grid, but rely on pre-established voltage and frequency; GFM inverters are more complex and expensive in terms of control and system coordination, but they ensure the transition of renewable energy from a passive power source to an active element of power system stabilization.

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