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INTEGRATION OF RENEWABLE ENERGY SOURCES INTO THE POWER GRID UNDER CONDITIONS OF PRODUCTION VARIABILITY

Аннотация. The article analyzes the relevance, key challenges, and technical and economic aspects of integrating renewable energy sources into electric power systems. It examines issues such as system stability, reactive power management, and frequency regulation that arise when connecting variable sources like wind and solar energy to existing grids. The paper also highlights modern technological solutions currently being applied to optimize the integration process.

Ключевые слова: Renewable energy sources, electric power system, solar energy, wind energy, integration technologies.

In order to ensure sustainable development in the energy sector, the share of renewable energy sources (RES) is increasing year by year. This trend plays a crucial role in reducing global carbon emissions and strengthening energy independence. However, integrating variable sources such as wind and solar energy into existing electric power systems has introduced a number of challenges.

Renewable energy sources based on solar, wind, small hydropower, biogas, and other natural resources stand out for their environmental friendliness and lower dependency on fuel-based resources compared to conventional thermal power plants. Nevertheless, the inherent variability in their production output leads to significant technical and operational issues during integration into the power grid [1-2].

There are several key natural factors that cause this variability in the output of RES. In solar energy generation, fluctuations are primarily caused by cloud cover, day–night cycles, and seasonal changes. For instance, while power production is high on sunny days, it drops sharply during cloudy conditions or ceases entirely after sunset. Wind energy production is highly dependent on wind speed and direction, which vary continuously, leading to an unsteady supply from wind farms. In hydropower systems, electricity production depends directly on seasonal variations in river flow and reservoir water levels. For example, during spring snowmelt, generation capacity increases, while during dry summer periods it decreases [2-5].

As a result, these natural influences cause both temporal and geographical disparities in the production of RES, which introduces a set of technical difficulties in their effective integration into electric power systems.

The variability of production from renewable energy sources has a direct impact on the stability of electric power systems. One of the fundamental principles of grid operation is maintaining real-time balance between power generation and consumption. Since the output from RES constantly fluctuates, any imbalance disrupts system stability and introduces technical complications.

One of the key consequences is voltage and frequency instability. For example, a sudden loss of solar irradiance due to cloud cover or a drop in wind speed leads to an immediate decrease in output power. This, in turn, causes voltage sag and frequency deviations within the grid, potentially resulting in operational disruptions at other power stations.

$$\frac{2H}{\omega_0} \cdot \frac{d^2\delta}{dt^2} = P_m - P_c \qquad (1)$$

Renewable energy sources (RES), particularly photovoltaic (PV) and wind systems, have low rotational inertia, which results in a small system inertia constant (H). Consequently, the rotor angle δ changes more rapidly, leading to frequency instability within the system.

In electric power systems- especially those with a high penetration of renewable energy production variability must be compensated by fast-responding reserve generation. To ensure real-time power balance, gas turbines, diesel generators, or battery energy storage systems (BESS) are activated when needed. However, reliance on these reserve sources leads to increased operational costs.

To estimate the required reserve capacity, the following fundamental formula is used:

$$P_{rez} \geq \Delta P_{QEm}^{max} \quad (2)$$

where P_{res}- denotes the required reserve capacity (MW); ΔP_{QEm}^{max}- represents the maximum anticipated reduction in RES output (MW).

This equation implies that the power grid must have the capability to rapidly compensate for a sudden 50 MW reduction in RES generation through available reserve sources.

In power networks with a high share of renewable energy sources (RES), the requirement for reserve power is not merely a technical necessity, but rather a strategic imperative to ensure system stability, limit frequency deviations, and preserve global power reliability. Renewable sources such as solar and wind energy, which are directly dependent on natural conditions, can experience significant drops or even complete interruptions in generation within minutes. In such cases, if the system lacks rapidly deployable reserve power, it may result in energy shortages, voltage sags, or even widespread blackouts.

When reserve capacity is insufficient, the power system may resort to automatic load shedding algorithms to protect itself, temporarily disconnecting certain industrial and residential consumers from the grid. This not only disrupts production processes, but also reduces the quality of life for the population and can cause failures in critical sectors such as healthcare and transportation. Ultimately, such disruptions may lead to economic losses and public dissatisfaction.

Therefore, in the context of widespread RES deployment, it is essential to scientifically plan reserve capacity, strategically allocate it based on geographic and grid-connection conditions, and widely implement energy storage technologies. These are all key factors for ensuring the stability, reliability, and resilience of modern electric power systems [3].

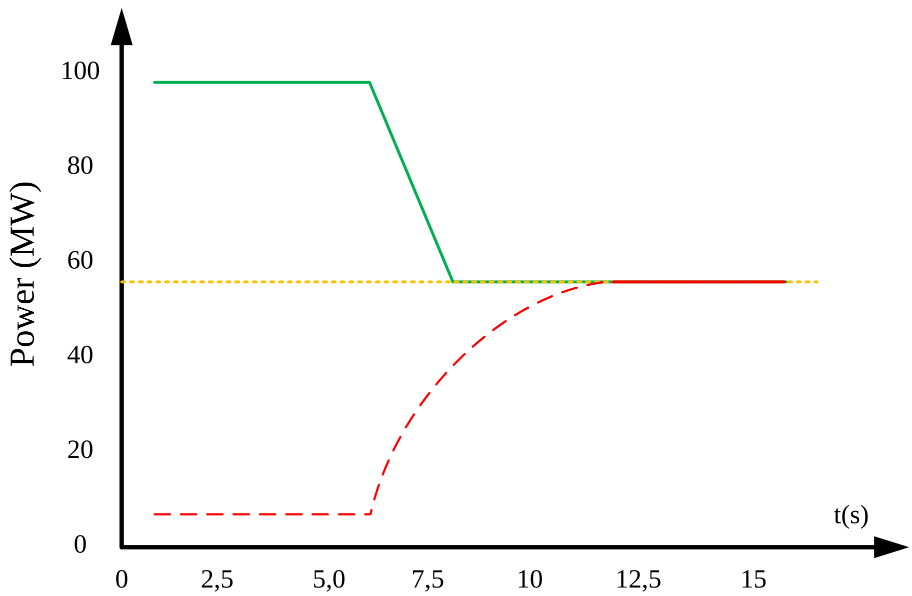

Figure 1. Variability in Generation and Reserve Power Response

Figure 1. The graph illustrates a sudden drop in power generation from renewable energy sources (RES) and the corresponding response of reserve power (P_{pes}). The reserve system activates with a time delay to compensate for the adverse effects of production variability and helps maintain the balance of the power grid.

$$P_{res} = \max\left[\mu_{QEM}(t) - \min\left(P_{QEM}(t)\right)\right] \quad (3)$$

here $\mu_{QEM}(t)$- denotes the average power output of the renewable energy source over time; $\min\left(P_{QEM}(t)\right)$- represents the minimum observed generation power.

$$P_{res} = -2HS \cdot \frac{df}{dt} \quad (4)$$

here H- total system inertia (s); S – nominal system power (MVA); $\frac{df}{dt}$- rate of change of frequency (Hz/s).

In certain situations particularly on sunny and windy days the amount of energy generated by renewable energy sources (RES) may exceed the actual load demand. If there is no energy storage capability in place, this excess energy may either be wasted or require curtailment of generation.

Moreover, as RES are increasingly integrated into the grid, bidirectional power flows emerge. That is, power no longer flows solely from power plants to consumers, but also from distributed generators back into the grid. This introduces new challenges for relay protection, automation, and dispatching systems, which may not be originally designed to manage such complex dynamic behavior. Consequently, these systems must be upgraded or reconfigured to ensure reliable grid operation under high RES penetration conditions [5-6].

Conclusions.

The successful integration of renewable energy sources (RES) into the electric power system is a complex yet essential process. To ensure stable operation, it is necessary to deploy inverter technologies, energy storage systems, smart grid components, and forecasting tools. In the context of Uzbekistan, expanding the use of solar energy in particular can significantly contribute to energy security and environmental sustainability.

The large-scale integration of RES into electric power systems has become a key component of modern energy policy. However, due to the dependence of RES on natural factors, their output is highly variable, which creates serious challenges for maintaining real-time power balance in the grid.

Sudden drops in generation especially from solar or wind sources lead to frequency and voltage deviations. To address these fluctuations and ensure uninterrupted power supply, it is essential for the power system to have sufficient and fast-responding reserve capacity. In practice, this reserve is typically provided by gas turbines, battery storage systems, or pumped-storage hydro plants, which are capable of quick response. Furthermore, the dynamic behavior of these reserves follows an exponential response pattern, allowing for gradual restoration of system stability.

Overall, taking into account the inherent variability of RES output, accurate planning and strategic placement of reserve power is a fundamental requirement for maintaining a stable, secure, and efficient electricity supply.

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