Impact of Integrated Renewable Energy Sources with Variable Power Output in Terms of Constrained Voltage Stability Limit

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***Abstract* — The paper is concerned with the development of a methodology for estimating the amount of balancing power in a system with a high penetration of renewable energy sources. To this end, it is crucial to analyze the influence of growing installed capacity of wind farms on the value of the balancing power of the energy system and random characteristics of its variability for various numbers of wind farms operating in the system. The possibilities of balancing power distribution are considered for characteristic critical load conditions of the system. The operating conditions of a real-world power system are simulated using wind speed measurement data obtained for the geographical locations of wind farms. The simulation is performed on a PC using developed programs for various combinations of these farms. The research involves constructing the relationships for the balancing power, determining the conditions for its reduction and the conditions for its limitation in terms of voltage stability in the balancing part of the system.**

***Index Terms* — power system, variable renewable energy sources, balancing power, load flow in the electrical network, voltage stability.**

I. INTRODUCTION

The increasing share of renewable generation has significantly changed the approaches to the technological implementation of balancing power in the modern energy system. As a result, along with traditional sources that have a preset specific character of power generation, modern energy systems have renewable sources operating in parallel. A substantial proportion of the renewable sources are wind turbines and solar PV electrical systems with variable (randomly indefinite) output. A balancing source (BS) to be chosen under these conditions should with a high probability provide the absolute range of variability of power generation (MW), as well as the average value of the rate of power generation increase (MW/min).

In addition, it is also crucial that a balancing source is chosen so as to ensure the system stability for each range of variability of balancing source generating capacity. The production of electrical energy by renewable sources depends on weather conditions and load [1–3].

Continuous spatio-temporal balancing of the magnitude of deviations between supply and demand in the power system enables a stable and reliable power supply. However, it is not possible based only on measurements of random processes of power generation from wind and solar

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sources to accurately build a model of the magnitude of their variability [4].

The rise in the number of renewable energy sources connected directly to the buses of the load node of the electrical network in the power system makes the consumption prediction highly uncertain [5]. Electrical energy storage devices (battery systems) are used when there is insufficient power generation to cover the load of the node to which they are connected [6].

The random and intermittent nature of power generation from wind farms and solar power plants (SPPs) requires selecting a source to balance (compensate for) the random share of power generation from them. In most cases, one or two of the existing traditional power plants are selected as balancing sources, which allocate part of their total generated power to compensate for the surplus or shortage of power output from the wind farm and solar power plants integrated in the system.

The choice of the value of the preset power for the balancing plant enables optimal load distribution between the plants in various periods of the daily load curve, control of the power flow in the electrical network of the power system, and effective utilization of the power output from wind farms and solar power plants.

Preliminary results of the research demonstrate that for the energy system of Azerbaijan, the gas turbine stations Shirvan and Sumgait, which are connected to 110 kV distribution networks, can be considered as balancing ones. These stations are also connected to the system's supply network through 220 kV lines. It was established that the probability of line overload in distribution networks due to fluctuations in the power generation from wind and solar power plants is small, which leads to a slight reduction in their generation.

Power systems with a high share of integrated renewable energy sources [7–11] present a challenge for dispatchers due to the intermittency of their power output and limited predictability. At some point, the operator may be forced to reduce wind and solar generation relative to current generation. This amount of reduction in the output from wind and solar energy conversion can be considered as an opportunity to cut down the total generation in the system. Thus, limitations arise when transmitting power through the supply network or when balancing power in the distribution network between incoming and consumed power [7, 8, 12]. Therefore, it is necessary to boost the flexibility of the power system in order to increase variable renewable generation while compensating for the intermittent power generation from renewable sources [8, 13, 14]. Some conventional power plants are unable to quickly adapt the control of their output in the system due to technical or economic limitations [4].

Operating restrictions are related to the load increase rate, start-up duration, and the magnitude of the minimum load [8, 13, 14].

According to the above restrictions and purposes of operational control, power plants can be classified into those not participating in the control process, those used in certain situations, and those completely involved in control to provide power flow in the system [15, 16].

The power generation from wind and solar power plants is intermittent and probabilistic, which does not allow system dispatchers to involve these plants in operational control of the power system. Power plants that do not participate in the operational control of the energy system usually include nuclear power plants and thermal power plants, i.e., those meeting the basic part of the total demand of the power system. Power plants with traditional technology (gas turbine, hydroelectric power plants) and all other renewable sources (except for wind and solar) are involved in the power flow control in the system.

The steady-state voltage stability of the power system, which can be compromised primarily due to overloading of backbone power lines or insufficient means of the active and reactive power flow control in the electrical networks of existing traditional power systems, faces new problems caused by the large-scale integration of variable renewable generation. This paper proposes a method for assessing the steady-state voltage stability in a system with a large portion of power generation from wind and solar plants. This study examines the influence of the number of operating wind farms and solar power plants on the operation of the balancing source in order to determine the amount of power to be generated by it to maintain voltage stability. An analytical criterion is derived to ensure voltage stability on the buses connecting wind farms and solar power plants to the system for their various power outputs and their shares of participation in the total demand at current time points. A methodology for optimal system planning is proposed to minimize power generation from a balancing station by optimally distributing active and reactive power generation between renewable sources.

II. MODELING THE ESTIMATION OF THE BALANCING POWER RESERVE IN A POWER SYSTEM WITH RENEWABLE ENERGY SOURCES

Integration of RES into the energy system enhances the uncertainty of the generated power and, together with the effect of load uncertainty, makes it impossible to strictly deterministically describe the amount of balancing power. In general, the amount of balancing power can be determined from the following equality:

$$0 = P_{conv.s.}^{t_i} + P_{RES}^{t_i} - P_{load}^{t_i} - \Delta P^{t_i} + P_{b.p.}^{t_i}, \qquad (1)$$

where $P_{conv.s.}^{t_i}$, $P_{RES}^{t_i}$ are power of conventional and renewable sources in the interval of the daily load curve; $P_{load}^{t_i}$ is load power in the balancing part of the power system in interval t_i; ΔP^{t_i} is electrical network losses; $P_{b.p.}^{t_i}$ is the value of balancing power.

In equation (1), $P_{conv.s.}$, P_{RES}, P_{load} are specified based on the measurements obtained during a long period of system operation. Balancing power and network losses ΔP, $P_{b.p.}$ are desired parameters.

To solve equation (1) with stochastic set input parameters $P_{conv.s.}$, P_{RES}, P_{load}, the latter are specified by limits of their range of variation in the form of inequality equations, for example

$$P_{\min,RES} \le P_{RES} \le P_{\max,RES}, \qquad (2)$$

$P_{\min,RES}$, $P_{\max,RES}$ are set at the stage of preliminary analysis of stochastic variables P_{RES}.

Thus, the estimation of balancing power $P_{b.p.}^{i}$ in each interval $[0, t_i]$ is reduced to solving a stochastic system of equations (1) subject to

$$P_{\min,RES}^{t_i} \le P_{RES}^{t_i} \le P_{\max,RES}^{t_i}.$$

III. STUDIES ON THE INFLUENCE OF RENEWABLE ENERGY SOURCES ON THE POWER BALANCE IN THE AZERENERGY SYSTEM

Due to the unpredictable nature of renewable energy sources (RES) generation, the probabilistic approach is used to determine the power reserve needed to balance supply and demand. The use of stochastic approach to choose balancing power is associated with a probabilistic analysis of observational data on wind speeds and solar radiation over a long observation period. This approach is also important to obtain a robust estimate of the characteristics of their distribution and to design a predictive model of power generation from wind plants in the geographical area under study, and other parameters. At the same time, it is also crucial to have data on the nature of the stochastic variability of the system load.

Determining the balancing power for steady-state post-emergency conditions (after failures of generators and power lines) will require an analysis of stability limits for the system under these operating conditions. The value of the balance during periods of critical conditions, in contrast to the existing deterministic approach, must be probabilistically estimated considering the uncertainty of the expected emergency conditions. This paper proposes a method for statistically assessing the limit of steady-state voltage stability for N-1 and N-2 states of the system.

The paper presents the results of the power balance calculation in the national energy system of Azerbaijan with various combinations of RES-based power plants for normal and post-emergency steady-state conditions and various states during emergency shutdowns of system components. Given that the basic part (80% of the installed capacity) of the power plants consists of thermal power plants, which are expected to be used to place the capacity reserve to cover the imbalance caused by renewable energy sources, the placement of the capacity reserve and the determination of strategies to manage power flow in the network are significant factors.

In 2025, Azerenergy plans to put into operation three wind farms in the system: 240 MW Khyzi wind farm (conventionally named Baku wind farm), 220 MW Janub wind farm (Lankoran), and 240 MW Shimal wind farm (Maraza).

Assessment of balancing power and analysis of power flow in the Azerenergy system for the case of commissioning the above variable renewable energy sources involved modeling and computer tests for the following options:

- the Baku wind farm is connected to the system;
- the Maraza wind farm is connected to the system;
- the Lankoran wind farm is connected to the system;
- the Baku wind farm + Lankoran wind farm are connected to the system;
- the Baku wind farm + the Maraza wind farm are connected to the system;
- the Baku wind farm + Lankoran wind farm + Maraza wind farm are connected to the system.

Figure 1 shows the balancing and synchronous parts of the Azerenergy system. In the synchronous part, the

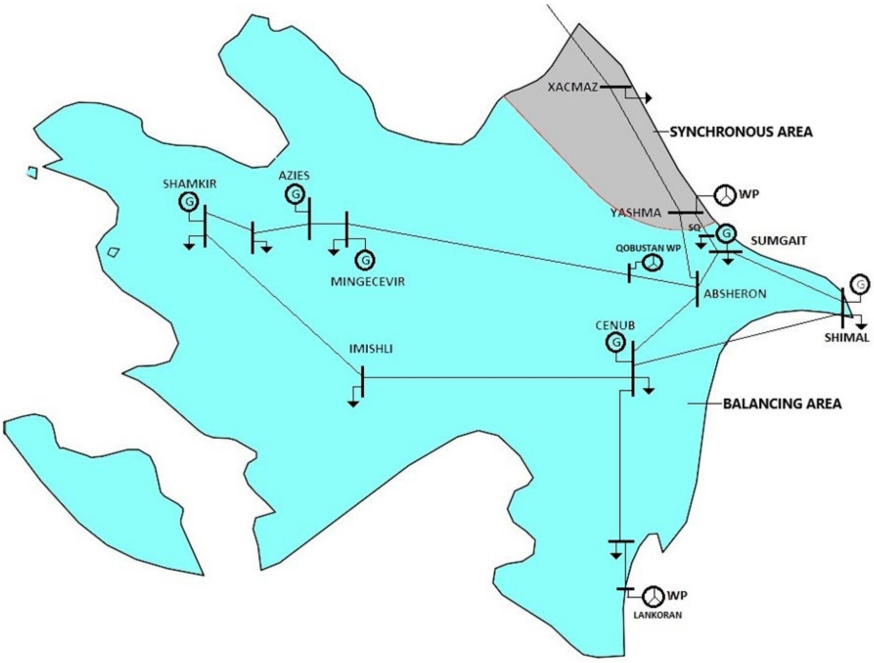


Fig. 1. Balancing and synchronous areas.

Azerenergy system is connected to the Russian unified power system by a 330 kV power transmission line Khachmaz–Darbend. This line is used to eliminate active power imbalance and to control frequency.

Figures 2a, 2b show the probability distribution function of the wind farm power prediction error for various values of the power output. When solving the problem of integrating renewable energy sources and estimating the capacity reserve at the nodes to which they are connected, it is crucial to correctly determine errors in their power output prediction as the errors affect the determination of the balancing power. As seen from Fig. 2, there is a gradual decrease in the magnitude of the error in different options for connecting wind farms, which reduces the error in determining the balancing power.

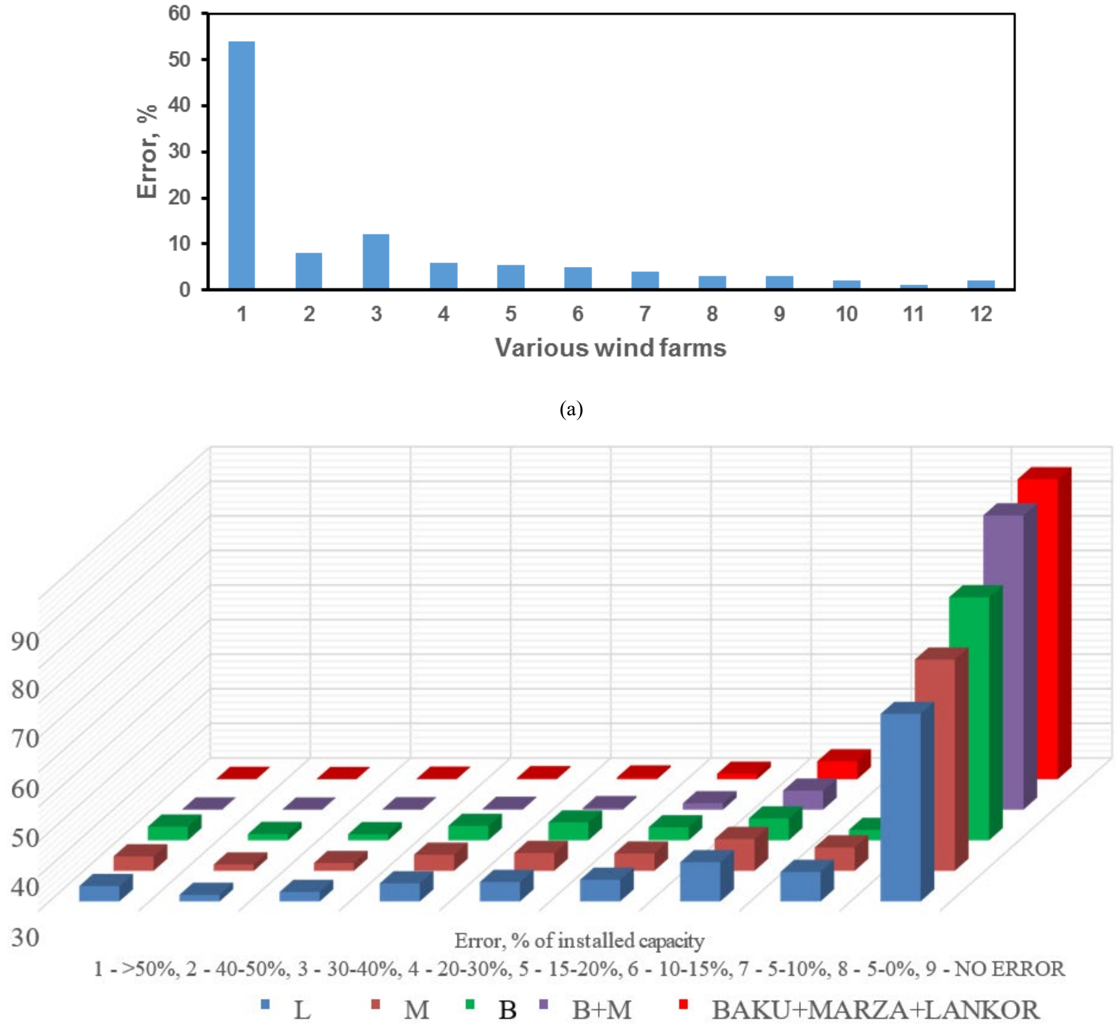
Figure 3a indicates a reserve for balancing power in the energy system of Azerbaijan for each case of the wind farm location, including the Baku wind farm, Lankoran wind farm, and Maraza wind farm. Figures 4–6 show the change in wind speed in the areas of Baku, Maraza, and Lankoran.

Figure 7 shows the average seasonal wind speeds for individual areas in which wind farms are installed. As seen from the figure, placement of wind farms in these areas is feasible and their integration into the system needs appropriate power flow studies in terms of power system stability.

IV. IMPACT OF RENEWABLE ENERGY SOURCES ON STEADY-STATE STABILITY WHEN BALANCING POWER

The need to analyze the impact of RES on steady-state stability of Azerbaijan's energy system when providing the operational control of the selected value of the balancing power reserve is caused by the large proportion of power generated from wind farms (up to 20% of the installed capacity of conventional power plants). Long-term observations of climatic conditions show that in some areas of Azerbaijan, the electrical energy produced by wind turbines in some periods of time can have a large amplitude due to the characteristic features of the dynamics of the energy potential of wind speeds. This study employs the method of sequential increase in the load at each stage of the balancing power reserve implementation to assess the limit of voltage stability in the balancing part of the power system (Fig. 1) [6].

Figure 8 shows the *U–P* relationship curves for power transmission along a 220 kV power transmission line during the hours of evening peak load. The total output from all wind farms is about 340 MW, which is about 10% of the total demand of the system. As was established earlier [3], when three wind farms (Baku, Maraza, and Lankoran) operated together, the total reserve was about 25% of the installed capacity of the wind farms (≈ 80–85 MW).



(a)

(b)

Fig. 2. Distribution of wind farm power prediction error probability for various levels of power output.

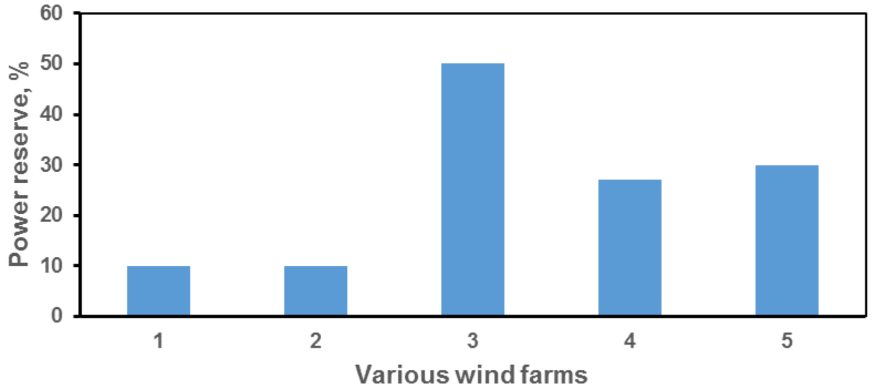


Fig. 3. Reserve for balancing power in the energy system of Azerbaijan for each location of wind farms (Baku, Maraza, Lankoran) and their combinations; 1 – Lankoran; 2 – Maraza; 3 – Baku; 4 – Baku+Maraza; 5 – Baku+Maraza+Lankoran.

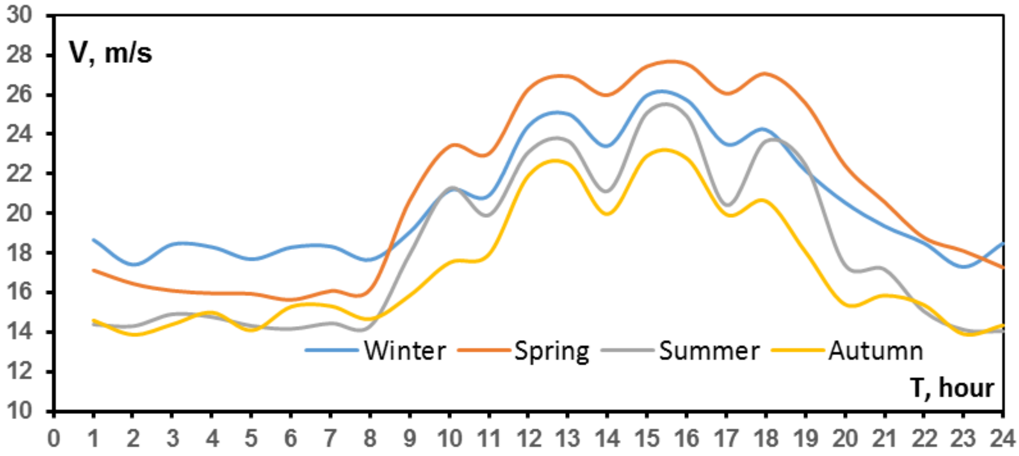


Fig. 4. Hourly changes in wind speed in the area of the Baku wind farm.

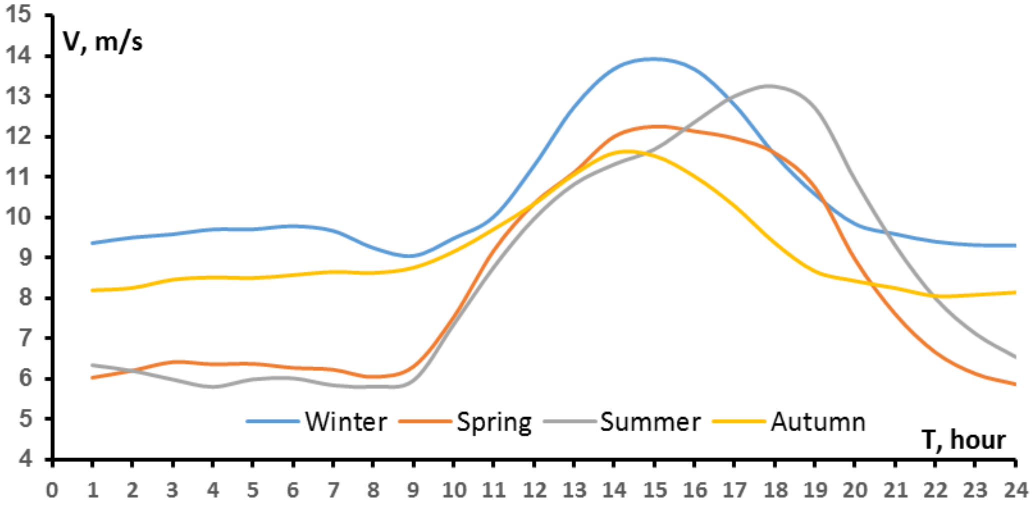


Fig. 5. Hourly changes in wind speed in the area of the Maraza wind farm.

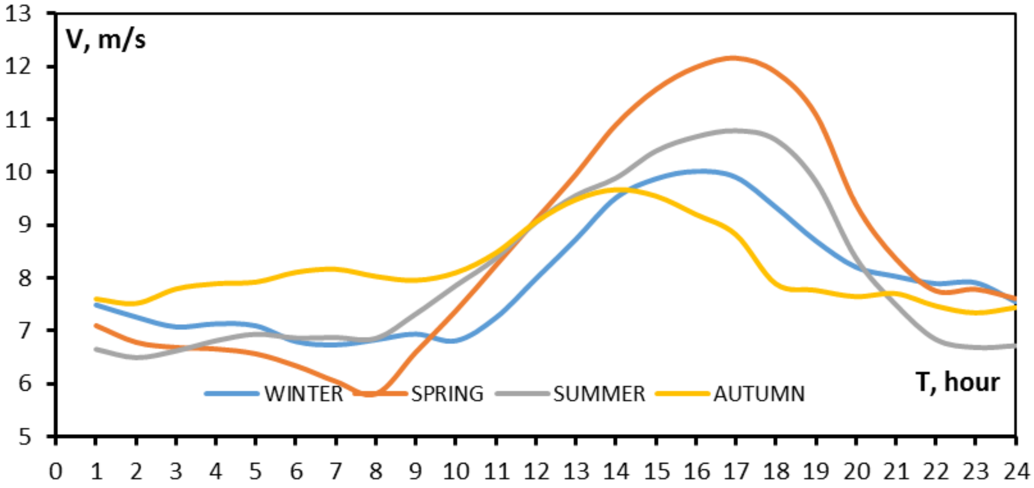
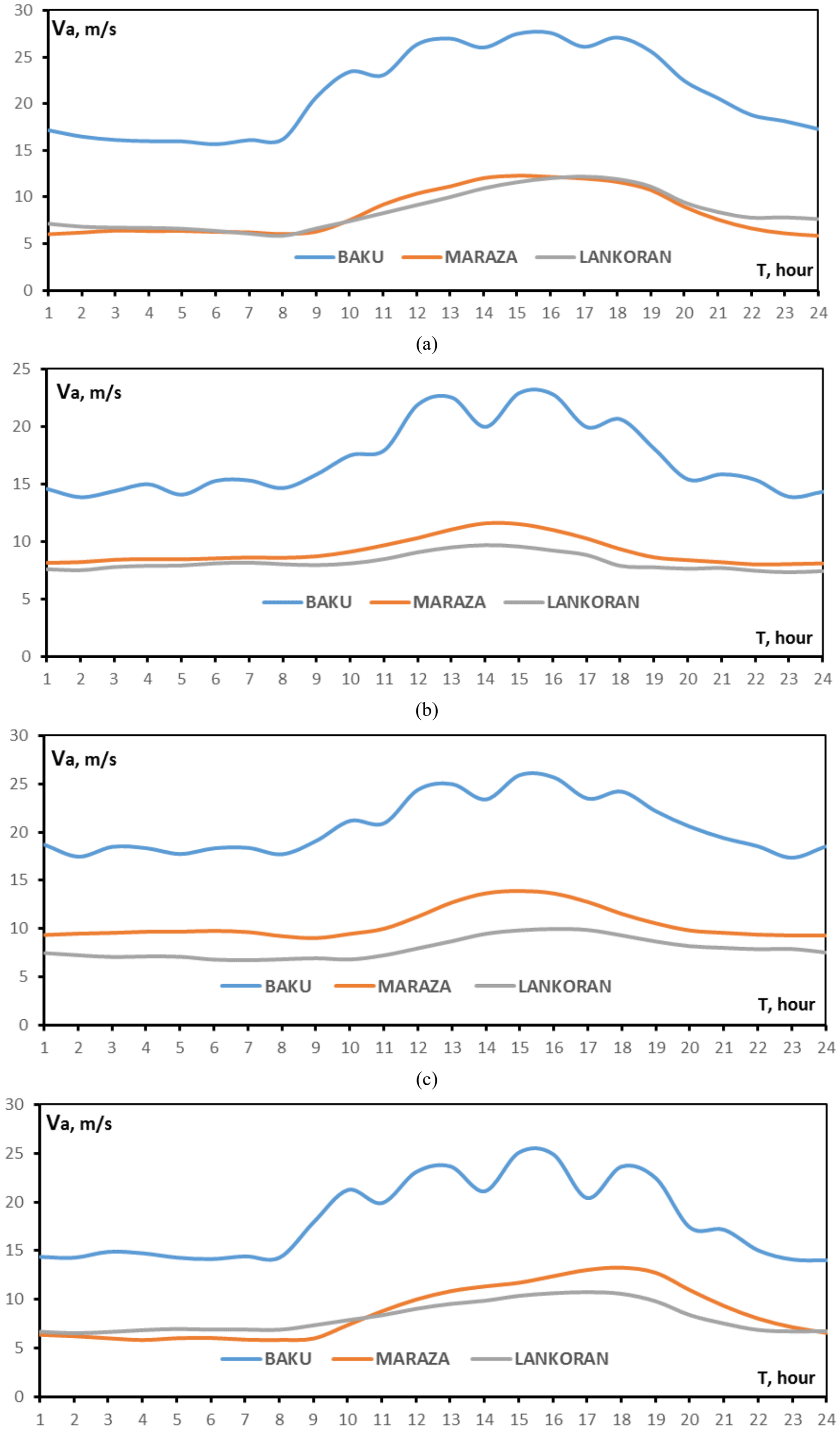


Fig. 6. Hourly changes in wind speed in the area of the Lankoran wind farm.



(a)

(b)

(c)

(d)

Fig. 7. Average seasonal wind speeds for selected areas: a – average wind speed in spring; b – average wind speed in autumn; c – average wind speed in winter; d – average wind speed in summer.

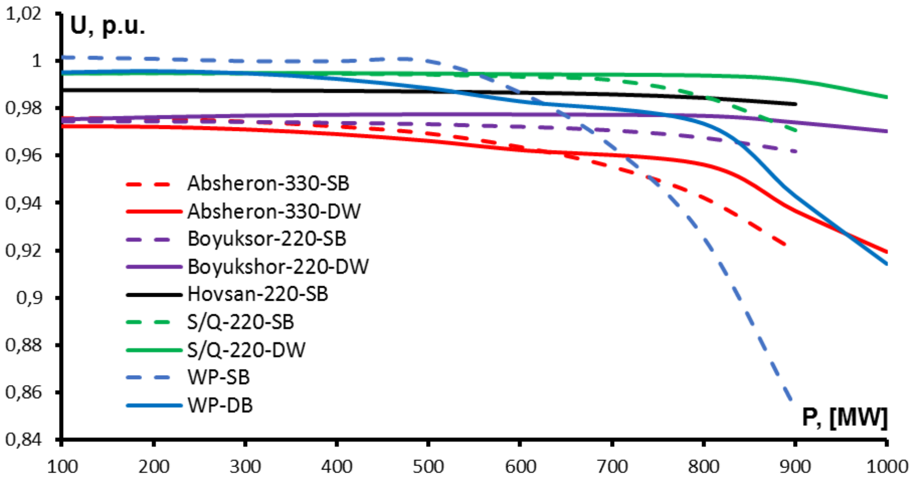


Fig. 8. The U–P relationship curves for power transmission along 220-330 kV power lines during evening peak load hours.

It is important to emphasize that if the total output from wind farms is reduced by 30–40%, i.e., by more than 85 MW, the power reserve will keep the voltage of the controlled power transmission line within the permissible critical values. Voltage collapse is possible only for one backbone line – the S/Q-220-SB line. To eliminate this risk of voltage instability, appropriate technical measures must be taken.

In addition, (Fig. 8), when the total integrated wind power is 700 MW (240+240+220 MW), voltage stability on power lines is maintained even for the S/Q-220-SB line (which is in a relatively heavy-load state) and voltage values higher than 0.97 U_{nom} are ensured. Therefore, at the first stage of integration of large powerful wind farms, the voltage stability condition is satisfied at all nodes of the power system.

V. CONCLUSION

1. The growing integration of renewable energy sources heightens the need for power reserve to cover the imbalance between power supply and demand. The stochastic variability of wind energy sources requires considering the influence of several factors when choosing the value of power reserve to compensate for the imbalance. These are the errors in the prediction of power generation from wind farms and solar power plants and the errors in the calculation model of balancing reserves, which affect the limit value of the reserve for balancing the deviation between total generation and consumption.

2. The paper proposes an approach to estimating the reserve for balancing active power in a system with a dominant share of renewable energy sources in a 30-minute interval of stochastic changes in power generated from wind turbines, stochastic load changes, and random emergency failures of conventional generators and power lines of the supply network. The proposed approach factors in the dynamics of changes in balancing power depending on the error in prediction of the discrepancy between the power generated by RES and power consumed.

3. The computational and experimental studies in a real-world power system have revealed the opportunity to significantly reduce the need for power reserve by increasing the number of wind farms connected to the backbone network at its different nodes. The effects of wind farms of identical power at different points of the power system diagram can be different and the amount of balancing power required depending on these effects can vary significantly.

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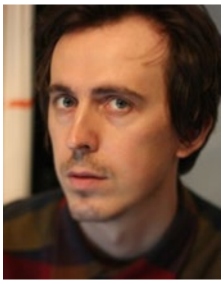

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