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ACTIVE POWER REGULATION IN WIND TURBINES

Purpose. To develop a methodology and determine rational parameters of wind energy installations with doubly fed induction generator to ensure maximum efficiency, taking into account changes in wind flow speed and power regulation to maintain stable and efficient operation of the installation.

Methodology. This study used a combination of theoretical analysis and mathematical modeling. Analytical models for estimating wind turbine power were developed through regression analysis, incorporating key parameters such as wind speed, blade pitch angle, and the generator's synchronous rotation speed.

Findings. Parameters and conditions ensuring maximum power of a wind turbine with a doubly fed induction generator were established and analyzed. It was determined that the efficiency of the wind turbine installation with a doubly fed induction generator depends on the nature of the wind flow. Active power regulation allows for an increase or stabilization of output power with changes in wind speed. The established dependencies allowed for determining the optimal conditions for ensuring maximum power. Mathematical modeling confirmed the theoretical conclusion regarding the increase in electricity generation efficiency with the rational selection of the specified parameters of the wind turbine.

Originality. The influence of key wind turbine parameters on the conditions for realizing the maximum power mode as well as the possibilities of using the speed regulation range of the wind turbine to limit excessive mechanical loads during wind gusts were determined. The study enhances the understanding of how synchronous torque affects the stability of wind generator operations, emphasizing the need for its control to maximize output power under various wind load levels.

Practical value. The established dependencies between key parameters of the wind turbine and their impact on operational efficiency allow for more allow for more precise tuning of wind turbines to achieve maximum productivity during wind gusts. This is crucial during the design and operational phases. The developed methodology for regulating the rotor speed can help reduce operational costs by ensuring stable operation of wind turbines over a wide range of wind speed. The data obtained may also facilitate the development of control systems that automatically adapt wind turbine parameters to changing conditions. This will contribute to increased efficiency of wind energy use and reduced impact of wind turbines on the stability of the power grid.

Keywords: *wind turbine, doubly fed induction generator, power regulation, wind turbine parameters*

Introduction. The consumption of energy from fossil fuels has serious global environmental consequences, including atmospheric pollution and climate change, which exacerbate the risk of their rapid depletion. This underscores the urgent need for a transition to alternative energy sources. Wind energy, as one of the leaders in the field of renewable energy production, is characterized by rapid growth and potential, with an average annual growth rate of installed wind turbine capacity worldwide of about 15 % [1].

The active increase in the capacity of the wind energy installations significantly affects the overall stability of power systems [2], necessitating in-depth scientific research to improve the management of these installations and increase their energy efficiency. The use of mathematical modeling methods serves as an effective tool for creating accurate mathematical models of wind energy systems and facilitating the optimization of their operation.

Wind, with its unpredictable changes in speed and direction, significantly affects the quality and stability of the generated electricity. This forces wind power plants to adapt to strict quality standards to ensure their effective integration into the power system without compromising its reliability and performance [3].

The active increase in the capacity of wind energy installations significantly affects the overall stability of power systems, requiring in-depth scientific research to improve the management of these installations and increase their energy efficiency. One of the promising technologies in this direction is the use of doubly fed induction generators (DFIG), which allow flexible regulation of active and reactive power, optimizing the use of wind resources and reducing mechanical loads on wind turbine components. The use of DFIG contributes to the stability of the grid and the quality of electricity generated by wind energy systems, ensuring their effective integration into the power system.

In the context of these challenges, this work focuses on aspects of power regulation of the wind turbine, which is key to ensuring maximum and stable output power over a wide range of wind speeds. Special attention in this context is given to the study of the properties of the DFIG. DFIGs provide the ability to regulate rotational speed, allowing optimal use of wind energy under various meteorological conditions.

Literature review. In the field of wind energy, the issue of effective management of active and reactive power of doubly fed induction generators remains relevant. The study [4] deeply analyzes the problem of power regulation in DFIGs installed in wind energy conversion systems and proposes a model for implementing a field-oriented control algorithm, which was confirmed through modeling in the Matlab/Simulink environment.

Significant contributions to the optimization of wind energy installations are made by modern technologies, particularly machine learning. The work [5] illustrates how machine learning methods can be applied for precise control of the power generated by DFIGs integrated into the power grid. This approach opens up new possibilities for improving the accuracy and efficiency of power management, which is key to integrating wind energy into the overall power system.

Optimization and integration of wind energy systems require a deep understanding of the dynamics and properties of doubly fed induction generators. Analyzing the possibilities and challenges associated with integrating wind energy systems into the general infrastructure makes it evident that new management methods need to be developed to effectively address the issues of grid stability and energy quality.

The scientific work [6] demonstrates the use of modeling for analyzing the behavior of DFIGs during network disturbances, such as wind speed fluctuations. This approach allows not only a deeper understanding of the dynamic processes in the system but also the development of more accurate and effective control strategies to improve efficiency.

These and other scientific works form a solid foundation for developing effective management strategies for wind energy systems, promoting their widespread implementation and integration into the overall energy infrastructure.

Results. Methods used. The energy efficiency of a wind power installation depends on the ability to utilize the power of the wind flow for conversion into electrical energy supplied to the electrical grid. The relationship between the output power of a wind turbine and the rotation speed at a given wind speed is characterized by the presence of a maximum. The operation of the wind generator at the maximum power output of the wind turbine ensures the generation of the maximum electrical energy by the wind installation

Traditional types of wind energy installations with fixed and variable rotation speeds have certain advantages and disadvantages [7, 8] (Table 1).

In wind installations with fixed turbine speed, maximum power mode can be achieved by using a turbine with pitch control systems. The use of such systems in wind power installations has drawbacks that become more significant with increasing power [9]. The cost of a semiconductor converter whose power equals the installation power increases significantly, leading to higher costs and technical problems associated with filtering higher harmonics at the output of the power circuit. Losses in the converter noticeably affect the overall efficiency of the installation. Using a blade pitch control system reduces the reliability of high-power wind installations and increases the time constant of the pitch control system.

Table 1

Advantages and disadvantages of wind energy installations with fixed and variable rotation speeds

Aspect	Wind generators with variable speed	Wind generators with fixed speed
Energy efficiency	Higher over a wide range of wind speeds	Maximum efficiency only at a specific wind speed
Power quality	Improved through the use of power electronics	Limited control over power quality
Mechanical loads	Reduced due to smoother operation	Higher due to constant rotation speed
Reactive power control	Can generate or absorb reactive power, helping in voltage control	Usually require separate reactive power compensation
Cost	Higher initial cost due to power electronics	Lower initial cost, simpler design
Maintenance	Potentially higher maintenance costs due to more complex systems	Generally lower maintenance costs due to simpler systems
Noise	Lower noise levels at low wind speeds	Constant noise level regardless of wind speed
Grid interaction	Better interaction capabilities with the electrical grid	Can cause voltage stability issues without additional systems

More efficient are wind installations with doubly fed induction generators, which allow the electromechanical conversion of wind energy more efficiently with lower costs. One of the main advantages of using doubly fed generators is the ability to provide maximum output power mode using a semiconductor converter with a significantly lower power rating than the nominal power of the installation, which is also cheaper. A wind installation with a doubly fed generator has higher efficiency and reliability.

As shown in Table 1, modern developments are focused on improving the parameters of wind installations with variable rotor speed. Control approaches for such installations vary depending on the control area [10].

Given the dependence of the electrical power produced by the wind generator on current wind conditions, three operating zones of the wind installation can be identified [11].

At low wind speeds $v < v_{\min} = 3{-}4$ m/s, the wind installation is not activated.

The start-up of the wind installation occurs at wind speeds $v > v_{\min}$. Conditions are created in which the conversion of wind energy into electrical energy becomes effective, one of which is the rotation of the wind turbine at the necessary speed. As the rotation speed of the turbine increases at a certain wind speed $v = v_{nom}$ and higher, the nominal power of the wind installation P_{nom} can be achieved. At any wind speed $v = v_i$ at a certain turbine rotation speed ω_{Ti} (or generator rotor ω_i), the installation power has a corresponding maximum value P_{maxi}. This provides the possibility of obtaining the maximum installation power in the wind speed range from $v_{\min}$ to v_{nom}, a doubly fed induction generator maintains the maximum power mode most effectively and economically.

With further increases in wind speed, P_{maxi} exceeds the nominal power, making the use of the maximum power mode impossible. At such wind speeds, nominal output power should be maintained, and when the maximum allowable wind speed is reached, the turbine blades should be moved to a safe feathering position, ceasing wind energy conversion.

When operating in parallel with the grid, the regulation of active and reactive power in wind installations with doubly-fed induction generators is achieved by regulating the respective components of the voltage applied to the generator rotor circuit.

In a doubly fed induction generator within an electrical cascade with a frequency converter in the rotor circuit, two components of the electromagnetic torque are formed – synchronous and asynchronous. As a result, such a generator can be considered a synchronous generator with a cylindrical rotor, with the influence of the asynchronous torque component. The asynchronous torque component damps rotor oscillations but at the same time imposes limitations on the speed regulation range. If the rotor speed in the synchronous mode of a doubly fed machine corresponds to a slip that exceeds the critical relative to the synchronous rotation speed of the magnetic field, the rigidity of the asynchronous torque component characteristic turns positive and can cause rotor oscillations. Therefore, in wind installations with doubly fed generators, it is advisable to use a speed regulation range within ±33 % of the synchronous rotation speed of the field.

In static modes, the operation of a wind generator installation is described by a family of characteristics in the form of the dependence of power on the generator rotor speed at different wind speeds.

To regulate the output power, it is necessary to select a wind generator with parameters that allow for such regulation.

The output power of the wind installation [12, 13] is

$$P_g = \frac{1}{2} C_p(Z,\beta)\eta\rho R^2 V^3, \qquad (1)$$

where C_p is the power coefficient; Z – speed ratio, $Z = \frac{\omega R}{V}$; β – blade pitch angle; ω – generator rotor rotation speed; R – rotor radius; ρ – air density; V – wind speed.

Considering (1) and data provided in [14, 15], the active output power of the wind generator installation is generally determined as a function of the installation parameters and the wind flow. This function is the static characteristic of the wind generator's output power

$$P_g = f(\omega, \beta, \eta, \rho, R, V, i),$$

where i is the gear ratio.

With changes in wind speed, the mechanical characteristic of the wind turbine changes, and the installation transitions from one steady state to another [16].

Using the dependencies of the wind generator installation power on the generator rotor speed [17, 18], wind speed, and rotor radius, a family of characteristics $P_g = f(\omega, V, R)$ for the generator with different rotor radii ($R_1 = 25$, $R_2 = 35$, $R_3 = 45$ m) in the wind speed range $V = 5$–3 m/s was obtained (Fig. 1).

As shown in Fig. 1, for different wind speeds, maintaining the maximum power mode for different turbine radii values is ensured in different ranges of rotor rotation speed. Considering the above-mentioned limitations of the speed regulation range for a doubly fed generator, maintaining the maximum power mode is possible with asynchronous machines with different synchronous speeds (the number of poles), chosen based on the required generator's nominal power, turbine blade length, and wind speed range inherent to the location where the wind installation will operate. Essentially, choosing the number of generator poles considering the size of the wind turbine and gear ratio means determining the wind speed range within which speed regulation of the wind installation with a doubly fed generator in the power regulation mode can be performed.

To carry out calculations and solve the problem of choosing the set of parameters of the wind installation, using regression analysis methodologies, a mathematical model of the power characteristic with minimal error in the range of values included in the regression equations was obtained

$$P = \beta_0 + \left(\sum_{i=1}^{n} V^i \sum_{k=1}^{m} \omega^k \right) \beta_{ik};$$

$$M = \delta_0 + \left(\sum_{i=1}^{z} V^i \sum_{k=1}^{p} \omega^h \right) \delta_{ik}.$$

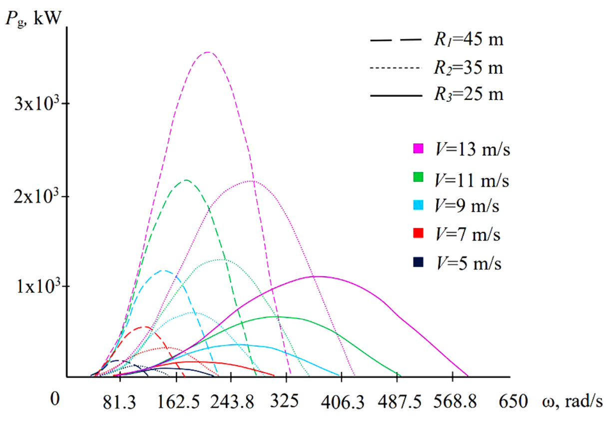

Fig. 1. Family of characteristics of $P_g(\omega, V, R)$

This methodology allows solving the problem of choosing parameters for a wind installation intended to operate in a given wind speed range:

1. The number of generator poles.
2. The maximum and minimum power provided at the boundaries of the wind speed range, which can be realized when regulating in the maximum power mode.
3. The length of the wind turbine blades.

When choosing the number of generator poles, the range of rotor radius values for which the maximum power of the wind generator can be obtained within the given wind speed range, equal to its desired nominal power, should be considered. The extreme points of the curve segment $P_{max} = f(\omega)$, $R_i = \text{const}$ within the given wind speed range should be within the allowable speed regulation range of the doubly fed generator. It is necessary to select such a combination of the machine's pole number and turbine radius for which the desired maximum power and the largest regulation range P_{max} can be achieved at a given wind speed.

If achieving $P_{max} = P_{nom}$ with an increase in wind speed occurs at a rotor speed lower than the permissible limit, it is possible to stabilize the generator's power when the wind speed exceeds the threshold by increasing the rotation speed of the installation within the allowable limits. As mentioned, this reduces the mechanical load on the elements of the wind installation structure.

The choice of the gearbox transmission ratio also affects the results of solving the mentioned problems. Its selection depends on the generator's rotation speed, the turbine rotor speed, and the wind speed. The gearbox ratio influences the dynamic processes during wind turbine speed regulation. In many cases, the gearbox ratio in wind installations is close to 100. If necessary, it can be clarified after analyzing the transient processes.

To assess the choice of rational values of the wind generator installation parameters based on the characteristics $P_g(\omega, V, R)$, graphs of the dependence of the maximum possible power P_{max} on wind speed $V = 5$–3 m/s (Fig. 1) are built with transmission ratios $i = 100$ (Fig. 2, *a*), $i = 75$ (Fig. 2, *b*) and $i = 50$ (Fig. 2, *c*), and synchronous rotation speeds $\omega_{s1} = 104$, $\omega_{s2} = 157$, $\omega_{s3} = 314$ rad/s he regulation boundaries at synchronous speed ω_{s1} are shown in green, at ω_{s2} in red, and at ω_{s3} in blue for radii $R_1 = 45$, $R_2 = 35$, $R_3 = 25$ m.

For each wind speed value, there is a specific rotation frequency at which the maximum turbine power is ensured. The summary data is provided in Table 2, which allows for evaluating the efficiency of choosing the synchronous speed, rotor radius, and nominal generator power according to the set task.

Using the graphical dependencies (Fig. 1) and Table 2 for given initial conditions, it is possible to establish the ranges of wind speed values and the range of maximum power values that are provided by speed regulation at a certain wind turbine radius.

As follows from the characteristics of the wind turbine's output power (Fig. 1), to achieve the maximum power of the wind installation, a certain rotation speed must be ensured depending on the wind flow speed. A doubly fed induction generator allows achieving this by appropriately regulating the frequency f_2 of the voltage applied to the generator's rotor circuit from the frequency converter.

The maximum power of the wind turbine P_{max} and the turbine rotation speed at which it occurs increase with the rise in wind flow speed V. When selecting the parameters for a doubly fed induction generator using the obtained dependencies illustrated in Fig. 2, the number of poles and synchronous rotation speed are determined. Subsequently, the ranges of generator speed and slip values to be used for achieving the maximum power of the wind turbine are also determined. Based on this, the frequency values f_2 corresponding to the wind flow speed within the regulation range are also established.

For a wind installation with a nominal power of 1 MW to maintain maximum power within the wind speed range of 5 to

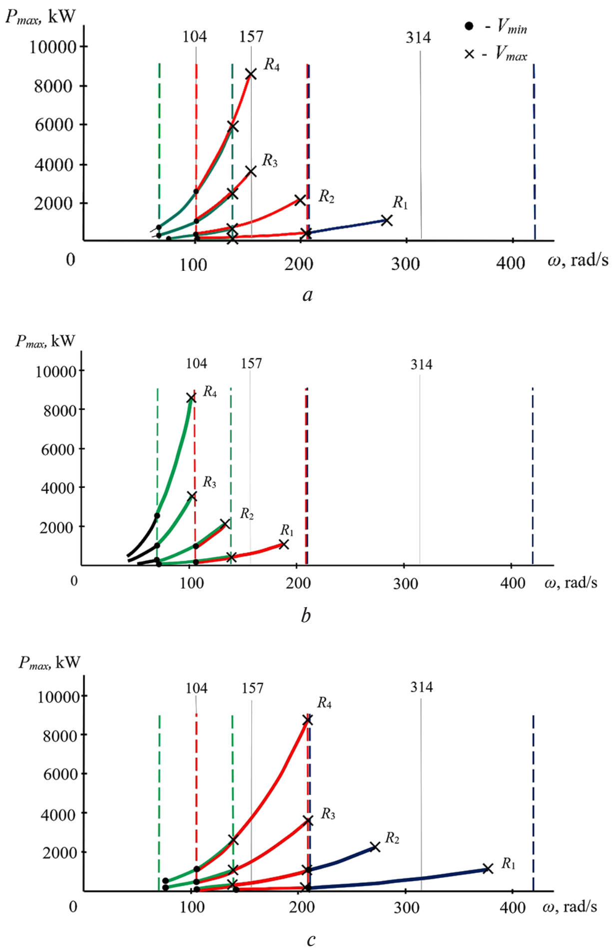

Fig. 2. Graphs of the dependence of $P_{max}(V, \omega, R)$, for:
a – i = 100, b – i = 75, c – i = 50

10 m/s, as shown in Fig. 2, it is advisable to choose a generator with a number of poles $2p = 4$ and a turbine with a blade length of 35 meters. Given the slip range s = ±0.33, which can be used for power regulation of the wind installation within the specified range of V, the angular speed of the generator rotor ranges from 105 to 208 rad/s. In these slip and wind speed ranges, the necessary regulation of f_2 from –16 до +16 Hz is performed (Fig. 3). Positive values of f_2 correspond to the phase sequence of the additional voltage introduced into the rotor circuit, which coincides with the phase sequence of the stator winding, while negative values correspond to the opposite phase sequence. To excite the machine at $f_2 = 0$ the rotor is powered by direct current.

When additional voltage with frequency f_2 is applied to the rotor circuit, the rotor speed and slip are determined by the equations

$$\omega = \frac{2\pi}{p}(f_1 - f_2); \quad s = \frac{f_2}{f_1}.$$

The rotational speed of the resulting magnetic field remains constant and is given by

$$\omega_0 = \frac{2\pi f_1}{p}.$$

It is necessary to investigate the conditions under which stable processes of the wind generator installation with a doubly fed induction generator in the maximum power mode are ensured. In a steady-state operation, the equilibrium equation of the torques acting on the shaft of the doubly fed induction machine [19, 20] has the form

$$M_t + M_a + M_s = 0, \quad (2)$$

Table 2

Obtained data for evaluating the choice of wind turbine parameters

R, m		V_{min}, m/s	V_{max}, m/s	P_{max}, kW
$i = 100$				
25	ω_{s1}	–	–	–
	ω_{s2}	5	6.9	175
	ω_{s3}	7.1	13	1,095
35	ω_{s1}	5	6.8	318
	ω_{s2}	5	10.2	1,075
	ω_{s3}	10.1	13	2,158
45	ω_{s1}	5	8.5	1,103
	ω_{s2}	6.5	13	3,500
	ω_{s3}	–	–	–
70	ω_{s1}	5	8.7	2,622
	ω_{s2}	6.6	13	8,640
	ω_{s3}	–	–	–
$i = 75$				
25	ω_{s1}	5	5.9	147
	ω_{s2}	5	9.2	4,166
	ω_{s3}	9.3	13	1,098
35	ω_{s1}	6.8	8.9	710
	ω_{s2}	7	13	2,143
	ω_{s3}	–	–	–
45	ω_{s1}	8.7	11.6	2,573
	ω_{s2}	8.6	13	3,551
	ω_{s3}	–	–	–
70	ω_{s1}	8.7	11.6	6,323
	ω_{s2}	8.7	13	86,207
	ω_{s3}	–	–	–
$i = 50$				
25	ω_{s1}	5	9.7	463
	ω_{s2}	6.9	13	1,090
	ω_{s3}	–	–	–
35	ω_{s1}	6.7	13	2,150
	ω_{s2}	10	13	2,150
	ω_{s3}	–	–	–
45	ω_{s1}	8.6	13	3,543
	ω_{s2}	–	–	–
	ω_{s3}	–	–	–
70	ω_{s1}	8.6	13	8,620
	ω_{s2}	–	–	–
	ω_{s3}	–	–	–

where M_t is the torque of the wind turbine; M_a is the asynchronous component of the torque of the doubly fed machine; M_s is the synchronous component of its torque. $M_a + M_s$ is the resultant torque of the doubly fed machine. Here, it is assumed that the positive direction of the torques coincides with the direction of rotation of the resultant magnetic field of the machine.

Based on the characteristics of the output power of the wind turbine and its maximum power under wind speed conditions within the given range (Figs. 1 and 2), it is possible to

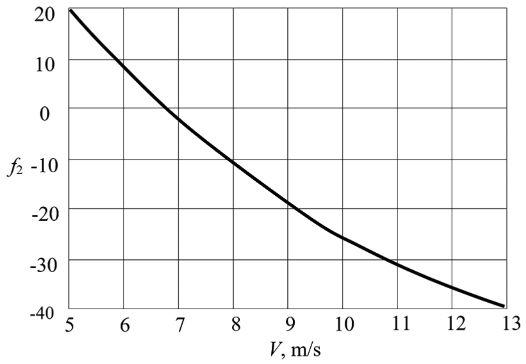

Fig. 3. Dependence of the frequency of the voltage introduced into the rotor circuit of the doubly fed machine on wind speed

construct graphs of the dependence of the maximum turbine torque on the slip (Fig. 4). The highest maximum torque of the turbine in the speed regulation range corresponds to the nominal power of the doubly fed generator.

To increase the accuracy of regulating the rotation speed of the wind turbine and wind generator to achieve maximum driving torque and power depending on the wind flow speed, it is advisable to use the synchronous mode of the doubly fed generator [21]. In this case, the rotor rotates at a constant speed corresponding to the frequency of the additional voltage in the rotor circuit, and the balance of torques is ensured by the synchronous component of the generator's torque. For this, it is necessary that the maximum synchronous torque of the doubly fed machine as a synchronous machine with a cylindrical rotor exceeds the synchronous torque required to balance the torques in the steady state in the presence of the turbine torque, which is determined by the required rotation speeds of the turbine and generator at a given wind speed.

The values of the turbine torque in the maximum power mode are determined as the torque $M_t + M_{tm}$ depending on the slip and wind speed (Fig. 5). The synchronous component of the torque of the doubly fed machine M_c is determined depending on the slip s based on the dependence $M_t = f(s)$ and the mechanical characteristic of the asynchronous component of the machine torque $M_a = f(s)$ according to the relationship (2). As can be seen from the graph, in the working range, the synchronous component of the torque at super-synchronous rotation speeds of the generator is mainly driving, compensating for the excessive braking asynchronous component of the torque. At sub-synchronous speeds, the synchronous component of the torque is braking, compensating for the driving asynchronous component, creating the required braking torque in the generator mode of the doubly fed machine.

The value of the synchronous torque determines the operating point on the angular characteristic $M_s = f(\theta)$. The angular characteristic of the synchronous torque of the doubly fed machine has the form of a sine wave, similar to a synchronous

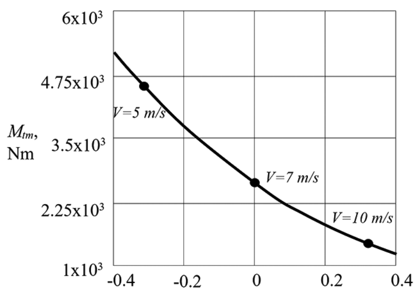

Fig. 4. Dependence of maximum turbine torque on slip of the rotor of the doubly fed generator with changes in wind flow speed

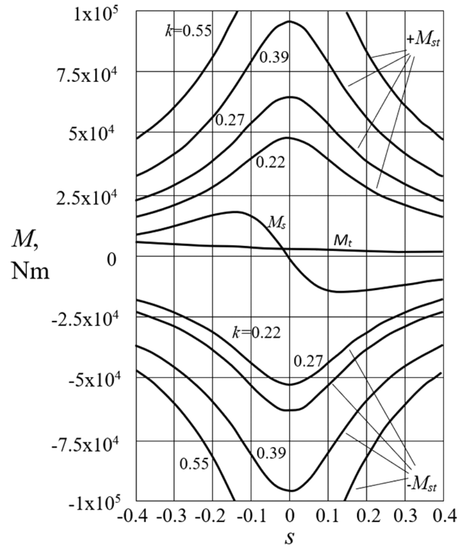

Fig. 5. Graphs of wind turbine torque M_t) and the synchronous component of generator torque (M_s, M_{st}) in maximum power mode

machine with a cylindrical rotor. However, in the doubly fed machine, the maximum torque depends not only on the voltage applied to the rotor circuit from the outside but also on the inductance of the rotor winding and the slip in the current operating mode. The maximum value of the synchronous component of the torque is achieved when $s = 0$ and the rotor is powered by direct current. The function $M_{st} = f(s)$ depends on the effective value of the voltage introduced into the rotor circuit (Fig. 5), i. e., on the ratio of the effective value of the voltage component introduced into the rotor phase, which coincides in phase or is in opposite phase with the rotor EMF and the phase voltage of the stator winding set by the grid with which the generator operates in parallel

$$\frac{U_2'}{U_1} = k.$$

The load angle for each slip value can be determined as

$$\theta = \arcsin\frac{M_s}{M_{st}}.$$

Based on the operating conditions corresponding to the graphs shown in Fig. 5, the curves of the dependence $\theta = f(s)$ Thus under the given conditions are constructed (Fig. 6). It is known that stable operation of the machine in steady and transient processes is ensured when $|\theta| \leq (25–30)$ electrical degrees. In this case, this condition is met at $k \geq (0.27–0.33)$

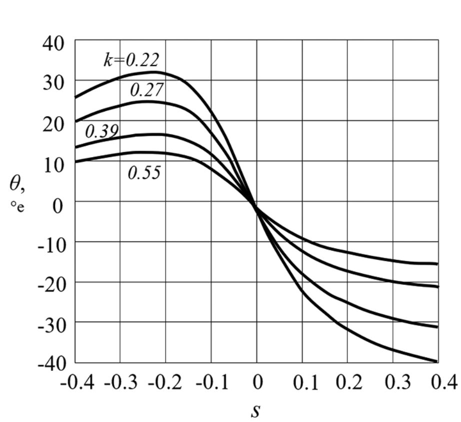

Fig. 6. Dependence of the load angle on the ratio of voltages U_2' and U_1

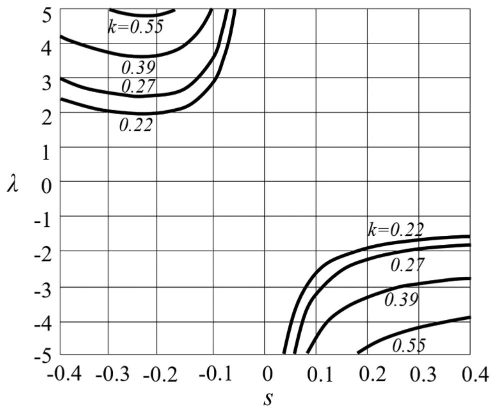

Fig. 7. Overload capacity of the doubly fed machine relative to the synchronous component of the torque

Based on the graphs of the angle θ, the dependence of the overload capacity of the doubly fed machine relative to the synchronous component of the torque $\lambda = f(s)$ is constructed, with the minimum value in the specified working range corresponding to the sub-synchronous speed mode and for the specified minimum values of $\lambda = 2.1-2.4$.

Thus, under the given conditions, to maintain the stable maximum power of the wind installation, the control system of the doubly fed generator should provide the required minimum voltage level applied to the rotor circuit. This level can be determined by the described method and is one of the parameters that should be specified in the technical task for creating the wind installation.

For reactive power control of the generator, the voltage introduced into the phase rotor circuit should have a component shifted in phase by $\frac{\pi}{2}$ relative to the rotor EMF.

Conclusions. The study investigated the task of determining the parameters and conditions for ensuring the maximum power of the wind generator installation with a doubly fed induction generator under changing wind flow speeds.

The efficiency of the doubly fed wind generator depends on the choice of its parameters, such as synchronous rotation speed, wind wheel radius, and gear ratio.

The maximum power of the wind generator installation depends on the synchronous speed of the generator, the gear ratio, and the radius of the wind wheel.

The analysis performed allows for selecting the optimal synchronous speed and wind wheel size that ensures the maximum power regulation mode within the necessary wind speed range for the location of the wind energy installation. The proposed approach formalizes and significantly simplifies the process of selecting wind installation parameters.

The stability of processes and more accurate maintenance of the maximum power of the wind installation are ensured in the synchronous mode of the doubly fed machine when voltage of frequency f_2 is applied to the rotor circuit in a phase corresponding to the rotor EMF, provided sufficient overload capacity is maintained. A method for determining the overload capacity of the doubly fed generator considering the operating conditions of the wind generator installation has been substantiated.

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Регулювання активної потужності вітроустановки

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Мета. Розробка методики й визначення раціональних параметрів вітроенергетичних установок з асинхронним генератором подвійного живлення для забезпечення максимальної ефективності, ураховуючи зміни швидкості вітрового потоку й регулювання потужності для підтримання стабільної та ефективної роботи установки.

Методика. Використана комбінація теоретичного аналізу й математичного моделювання. Аналітичні залежності для визначення потужності вітроустановок були отримані на основі регресійного аналізу, ураховуючи ключові параметри, такі як швидкість вітру, кут нахилу лопатей і синхронна швидкість обертання генератора.

Результати. Встановлені та проаналізовані параметри та умови, що забезпечують максимальну потужність вітроустановки з асинхронним генератором подвійного живлення. Визначено, що ефективність вітрогенераторної установки з асинхронним генератором подвійного живлення залежить від характеру вітрового потоку, а регулювання активної потужності дозволяє збільшити або стабілізувати вихідну потужність при зміні швидкості вітру. Встановлені залежності дозволили визначити оптимальні умови для забезпечення максимальної потужності. Математичне моделювання підтвердило теоретичний висновок щодо підвищення ефективності генерації електроенергії при раціональному виборі вказаних параметрів вітроустановки.

Наукова новизна. Визначено вплив ключових параметрів вітроустановки на умови реалізації режиму максимальної потужності, а також можливості використання діапазону регулювання швидкості вітроустановки для обмеження надмірних механічних навантажень при поривах вітру. Дослідження вносить вклад у розуміння впливу синхронного моменту на стабільність роботи вітрогенератора, підкреслюючи необхідність його контролю для максимізації вихідної потужності при різних рівнях вітрового навантаження.

Практична значимість. Установлені залежності між ключовими параметрами вітроустановки та їх вплив на ефективність роботи, що дозволяє точніше налаштовувати вітроустановки для досягнення максимальної продуктивності під час поривів вітру. Це має вирішальне значення на етапах проєктування та експлуатації. Розроблена методика регулювання частоти обертання ротора може сприяти зниженню експлуатаційних витрат шляхом забезпечення стабільної роботи вітроустановок у широкому діапазоні швидкості вітру. Можливість використання отриманих даних для розробки систем управління може дозволити автоматично адаптувати робочі параметри вітроустановок до змінних умов експлуатації. Це сприятиме підвищенню ефективності використання вітрової енергії та зменшенню впливу вітроустановок на стабільність роботи електромережі.

Ключові слова: *вітроустановка, асинхронний генератор подвійного живлення, регулювання потужності, параметри вітротурбіни*

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