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Development of a Control Unit for the Angle of Attack of a Vertically Axial Wind Turbine

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Abstract: This article presents the possibility of increasing the efficiency of a vertical-axis wind generator through the introduction of an automatic control system for the angle of attack of the blades. The calculation of the optimal position of the wind turbine blades for the maximum generation of electrical energy is given, and a developed scheme for controlling the blades using the sensors of the angular speed of rotation of the wind wheel by the anemometer and the current position of the blades is presented. The automatic control system implies the use of a PD controller. A comparison is made of two laboratory experimental models of vertical-axis wind turbines with and without the developed control system. This article focuses on optimizing the angle of attack and developing an automatic control system for vertical-axis wind turbines to increase their efficiency in generating electrical energy.

Keywords: wind generator; control system; wind wheel; output power; controller

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1. Introduction

Due to the volatility of electricity prices and environmental pollution, wind energy is a promising way to solve these problems. Renewable energy sources, in particular wind farms, are becoming more popular every year. According to IRENA, by 2040 many countries plan to completely switch to the use of alternative energy sources [1]. Today, wind energy has become so popular in many countries of the world that it competes with traditional energy sources. For example, in Spain and Denmark, the energy received from renewable sources exceeds in volume the energy that is generated in the traditional way [2]. Of all the renewable energy sources in Kazakhstan, wind power is the most significant. The possible potential of wind energy is calculated to be from 0.929 to 1.82 billion kWh per year [3], which corresponds to 3 billion kWh of energy per year. Comparison of the wind potential with the consumption of electricity in the country suggests that wind turbines are able to generate 15 times more electricity than Kazakhstan needs [4]. The most promising area for the placement of wind turbines is the Shelek corridor, Dzhungar gates, Akmola region, Zhambyl region, according to studies conducted under the UN Development Program on wind energy [5]. Also, it was found that in Kazakhstan there are more than 50 thousand square kilometer areas with an average annual wind speed of 6 m/s or more. Thus, the topic of wind energy development in Kazakhstan is relevant. The wind wheel converts the energy of the wind flow into rotational energy, then the rotational energy is converted into electrical energy using a generator system. The frequency of rotation of the generator and the wind wheel is constant when the power required to compensate

for the moment of resistance from the generator corresponds to the power expended by the wind wheel from the wind. If this condition is not met, the wind wheel starts to slow down. Vertical-axis wind turbines and horizontal-axis wind turbines are the two main types of wind-energy extraction devices, with horizontal-axis wind turbines widely used in commercial wind farms but which are facing logistical difficulties and complex control systems. Vertical-axis wind turbines offer advantages such as quick wake recovery, closer packing for higher power densities, and smaller size [6].

Today, there is a development of and improvement in the mechanical part and electronic control circuits of wind turbines and new methods of controlling them are emerging. For example, there are methods for controlling a wind generator at fixed rotor speeds [7]. The essence of this method is to switch the windings of the generator or change the gear ratio of the multiplier. There are also options for the operation of wind turbines at a variable speed, where control is carried out by changing the geometric parameters of the rotor, changing the angle of attack of the wind flow on the blades, or by using a power controller. The simplest method of controlling the output power of a wind turbine is the control method at a constant speed [8]. The disadvantages of this method are:

- the efficiency of the wind generator is possible in a limited range of wind speeds;
- there is a problem of protecting the wind generator when the nominal value of the wind speed is exceeded.

The method of convergence with the control method at a constant speed is also known, but in contrast to it, in this method, the output voltage of the generator changes depending on the value of the wind speed, which ensures the productive operation of the wind generator at various speeds [9]. The disadvantages of this method are:

- the need to apply wind speed measurement systems;
- low level of reliability of the electronic part of the wind generator due to the use of switching mechanisms for the winding of the generator;
- there is a problem of providing the wind generator with protective mechanisms when the nominal value of the wind speed is exceeded.

Another option for power output control is the method of changing the angle of attack on the blades by changing the parameters of the wind wheel. This method involves the use of various mechanisms, where the automated control of the mechanical part of the wind generator is performed in accordance with the change in the value of the wind speed [10].

The disadvantages of this method include:

- the need to use complex mechanisms and additional automation systems;
- higher costs for a wind power plant due to the complexity of the design and, accordingly, greater material consumption.

Adjustment of the wind power utilization factor is possible via turning the blade around the swing axis; changing the angle of attack of the blade produces a change in the proportion of energy taken from the wind. It follows that changing the angle of attack of the blade allows you to adjust the amount of energy taken from the wind, maintaining a balance of power and keeping the frequency rotation of the shaft of the wind wheel and the generator constant. To obtain the maximum energy from the wind generator at any wind speed, it is necessary to control the rotation speed in such a way that the turbine rotation speed corresponds to the optimal value at the current wind speed. Also, for each value of the speed of wind flow, there is a maximum power at the speed of rotation of the wind wheel [11]. Angle of attack control is crucial for vertical-axis wind turbines (VAWTs) to optimize their performance throughout the rotation [12]. VAWTs experience significant changes in their angle of attack as they rotate, and actively adjusting this angle allows for improved efficiency and power generation. The angle of attack refers to the angle between the oncoming wind direction and the rotor blade. It directly influences the lift and drag forces acting on the blades, which in turn affect the turbine's power output and overall performance [13]. By dynamically controlling the angle of attack, VAWTs can adapt to

varying wind conditions and extract more energy from the wind. There are several reasons why angle of attack control is necessary for VAWTs:

- Aerodynamic Efficiency—By adjusting the angle of attack, the turbine blades can be positioned optimally to harness the maximum amount of wind energy [14]. At a certain angle, the blades generate the highest lift and minimize drag, leading to improved efficiency and power production. As the wind direction changes with the turbine rotation, controlling the angle of attack allows the blades to maintain an optimal orientation and maximize energy capture [15];
- Start-Up and Cut-In Speed—VAWTs often face challenges during startup and at low wind speeds. By adjusting the angle of attack, the blades can be set to generate sufficient lift to initiate rotation even at low wind speeds [16]. Controlling the angle of attack allows VAWTs to start operating earlier and achieve their cut-in speed (the minimum wind speed required for the turbine to start generating power) more effectively;
- Performance at Different Wind Speeds—Wind speed is not constant, and it varies with height and atmospheric conditions. VAWTs experience changing wind speeds as the rotor rotates, which affects the angle of attack [17]. By actively controlling the angle, the turbine can optimize power production by adjusting to the wind speed changes. Higher wind speeds may require a lower angle of attack to prevent excessive loads on the blades, while lower wind speeds may require a higher angle of attack to maintain lift and power generation [18];
- Load Mitigation—VAWTs are subjected to cyclic loading as the blades pass through the wind stream [19]. These cyclic loads can lead to fatigue and structural damage over time. By adjusting the angle of attack, the turbine can manage the distribution of loads on the blades, reducing stress concentrations and extending the lifespan of the turbine [20].

To achieve angle of attack control, VAWTs employ various mechanisms such as blade pitching, twisting, or using airfoils with variable camber. These control systems continuously monitor wind conditions, rotor position, and other factors to determine the optimal angle of attack for each blade at any given moment [21]. This dynamic adjustment allows VAWTs to optimize their performance and extract the maximum energy from the wind, despite the substantial changes in the angle of attack during rotation.

By utilizing dynamic angle of attack control, vertical-axis wind turbines can optimize their performance throughout the rotation [22]. The angle of attack adjustment allows for improved aerodynamic efficiency, enabling the blades to capture the maximum wind energy. It also aids in the turbine's start-up and operation at low wind speeds, enhances performance across different wind speeds, and helps mitigate cyclic loads and potential structural damage [23]. These benefits are achieved through mechanisms like blade pitching, twisting, or using airfoils with variable camber, which continuously monitor wind conditions and adjust the angle of attack for each blade.

2. Materials and Methods

To begin with, the optimal position of the wind generator blades was determined, which allowed us to obtain maximum energy from the wind. The power P_k generated by the wind generator depended on the power of each blade of the wind generator in accordance with the formula [24]:

$$P_k = \sum_{i=1}^{4} P_i, \tag{1}$$

where P_i is the power of each of the blades.

To achieve maximum efficiency of the wind generator, its blades must create the optimal value of aerodynamic resistance, changing their position with changes in wind speed and direction in order to use the wind force F_B to the maximum extent in accordance with the formula [25]:

$$F_B = \frac{mV_B^2}{2} \tag{2}$$

where m is the mass of wind flow, V_B is the wind speed.

Figure 1 shows the optimal arrangement of the blades which will use the force of the wind to its maximum extent.

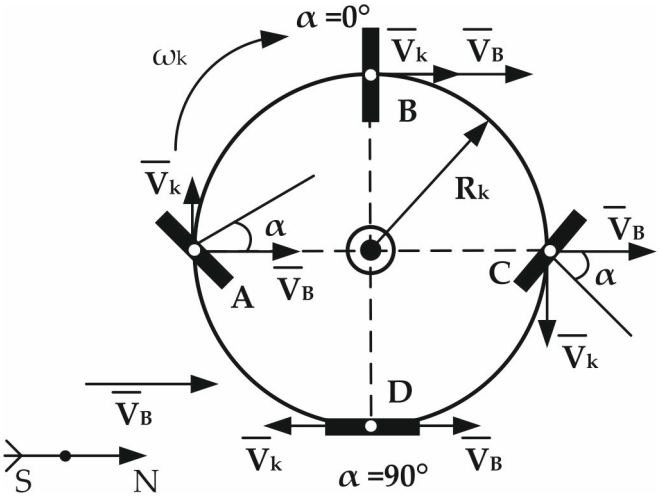


Figure 1. The position of the blades in accordance with the current direction of the wind and the angular velocity of rotation.

Since the wind speed and its direction are not constant values, it is necessary to develop a control system to ensure a given position of the blades with a changed wind direction $\overrightarrow{V_V}$ and a given rotor speed $\overrightarrow{\omega_K}$. In addition, for the effective operation of the automatic blade control system, it is necessary to have information on not only $\overrightarrow{V_V}$, $\overrightarrow{\omega_K}$, but also on the linear speed of the rotor $\overrightarrow{V_L}$, as well as the influence of these parameters on the current value of the angular position of the blades α. To do this, it is necessary to determine the power generated by the blades A and C, in accordance with the formula [26]:

$$P_{AC} = P_A + P_C = 2\frac{\rho S}{2}\left(V_V \cos\alpha - V_L\right)^2 * V_K\,, \tag{3}$$

where ρ is the air density, S is the area of the blade, V_L is the linear speed of the blade, and α is the angle between the direction of the wind flow velocity and a certain blade perpendicular to the plane.

Next, the partial derivative of the powers generated by the blades A and C with respect to the angular position of the blades is determined α [27]:

$$\frac{dP_{A,C}}{d\alpha} = \rho S * (V_V \cos\alpha - V_L) * V_L * \sin\alpha. \tag{4}$$

Next, the expression 4 is equated to 0 and the value of the angular position of the blades is expressed α:

$$\alpha = \arccos\left(\frac{V_L}{V_V}\right). \tag{5}$$

We considered the linear speed of the blade to be equal to:

$$V_L = \omega_K R, \tag{6}$$

where ω_K is the angular speed of the rotor, R is the radius of the wind wheel.

Thus, the final expression becomes:

$$\alpha = \arccos\left(\frac{\omega_K}{V_V} * R\right). \tag{7}$$

In accordance with expression (7), to install the blades A and C, it is necessary to adjust the control system using the sensors of the angular speed of rotation of the wind wheel, ω_K, according to the anemometer (wind speed device). Expression (7) determines the initial value of the position of the angle of the blades A and C. The rotation of the blades during the rotation of the wind wheel occurs relative to this angle with an angular velocity ω_K. When blades A and C are set at the angle calculated in accordance with expression (7), blade B should receive the maximum amount of wind flow, while the plane of the blade is perpendicular to the direction of the wind, and, accordingly, blade D should be parallel to V_V to ensure the minimum value of aerodynamic drag. When the wind direction changes, the automatic blade control system will change the control signal in time and the blades will turn according to the control signals ω_K, φ (the angle of change in wind direction). The control is performed in accordance with Figure 2 and Table 1 (time delay when changing the angle of attack of the blades when changing wind direction).

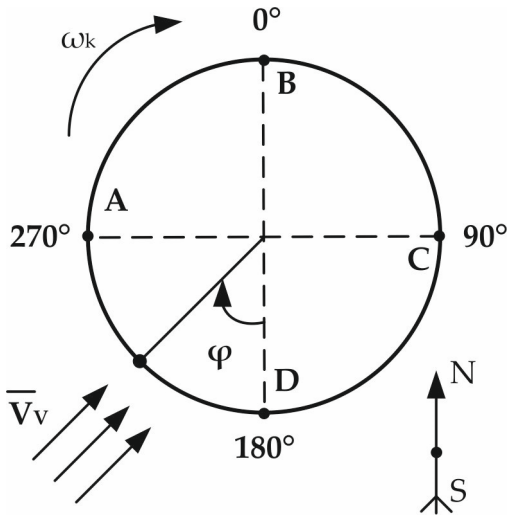


Figure 2. Changing the angle of wind direction by the angle φ.

To select the type of regulation, a study was conducted in the TIA Portal software environment. The block "CONT_C" was chosen, which is used in programmable logic controllers of technological processes of continuous inputs and outputs of variables (Figure 3).

To select the type of regulation, the regulator in the open state was considered. The necessary parameters for the study of the P-controller were set at GAIN = 1 and GAIN = 1.5. The results are shown in Figures 4 and 5.

Table 1. Time delay when changing the angle of attack of the blades with a change in wind direction.

Deviation of Wind Direction by Angle φ	Temporary Delay
0	t = 0
0 < φ < 90	t = ω/φ
90 < φ < 180	t = ω/(φ—90)
180 < φ < 270	t = ω/(φ—180)
270 < φ < 360	t = ω/(φ—270)

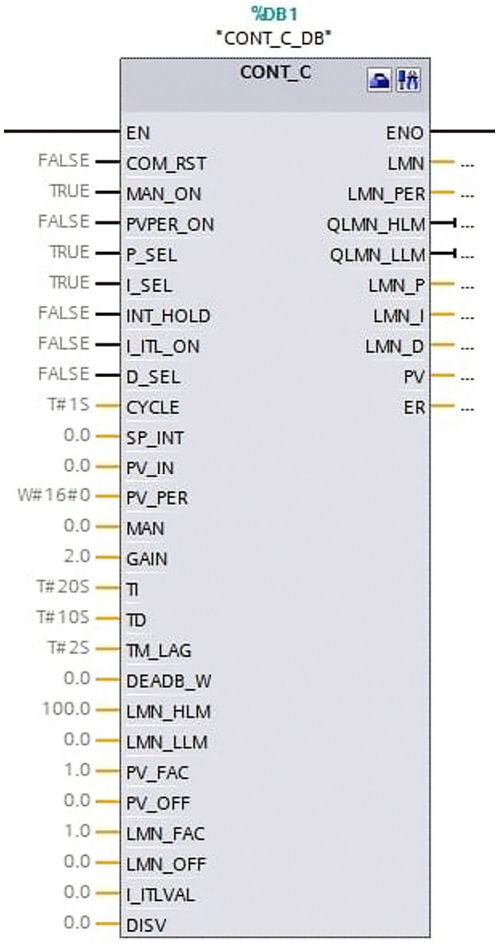


Figure 3. Block "CONT_C".

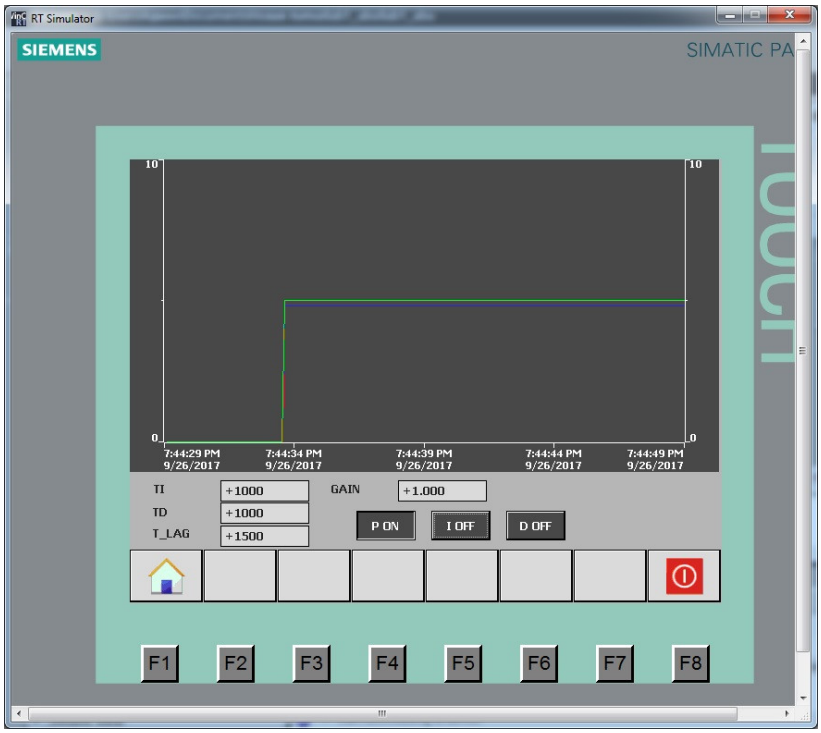


Figure 4. P-controller with GAIN = 1 red line is the control action, green line is the setting signal, blue line is the output control signal.

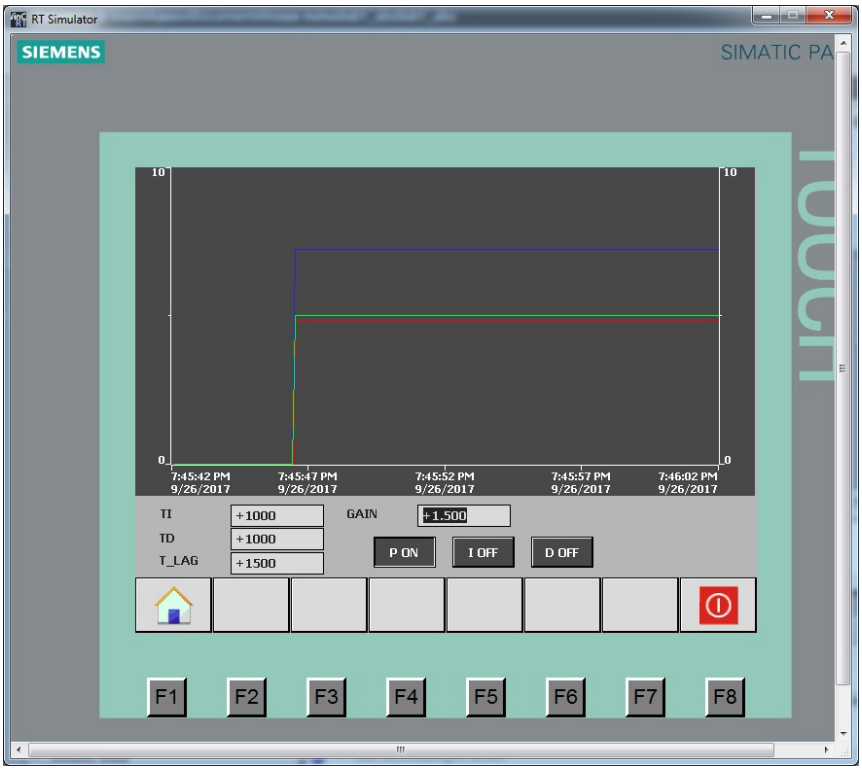


Figure 5. P-regulator with GAIN = 1.5: red line is the control action, green line is the setting signal, blue line is the output control signal.

Figures 6 and 7 show the I-controller at TI = 1 s and TI = 5 s, respectively.

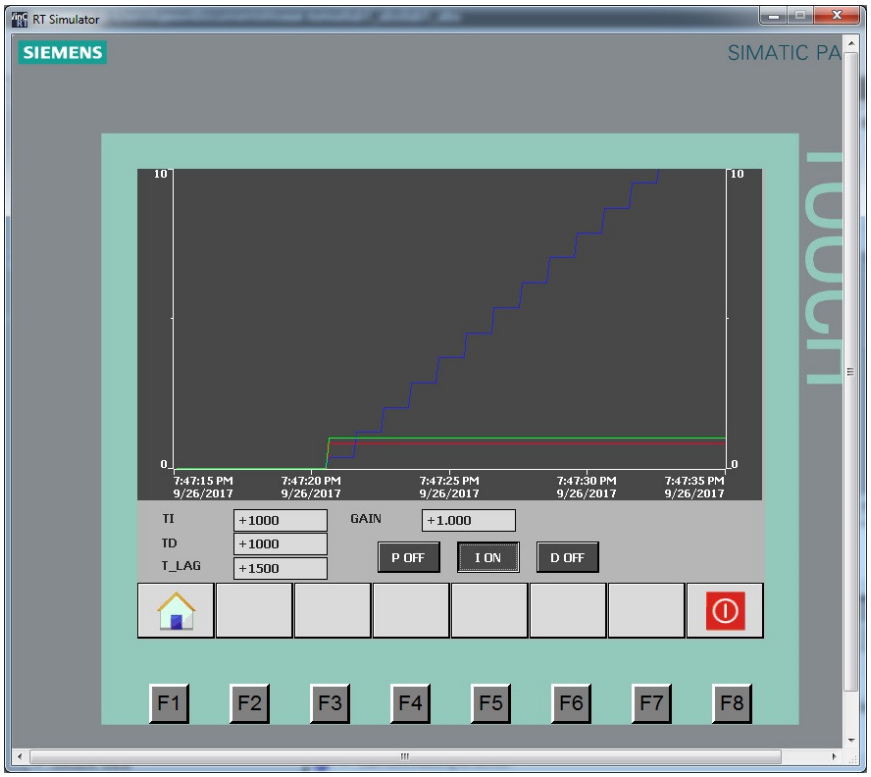


Figure 6. I-controller at TI = 1 s: red line is the control action, green line is the setting signal, blue line is the output control signal.

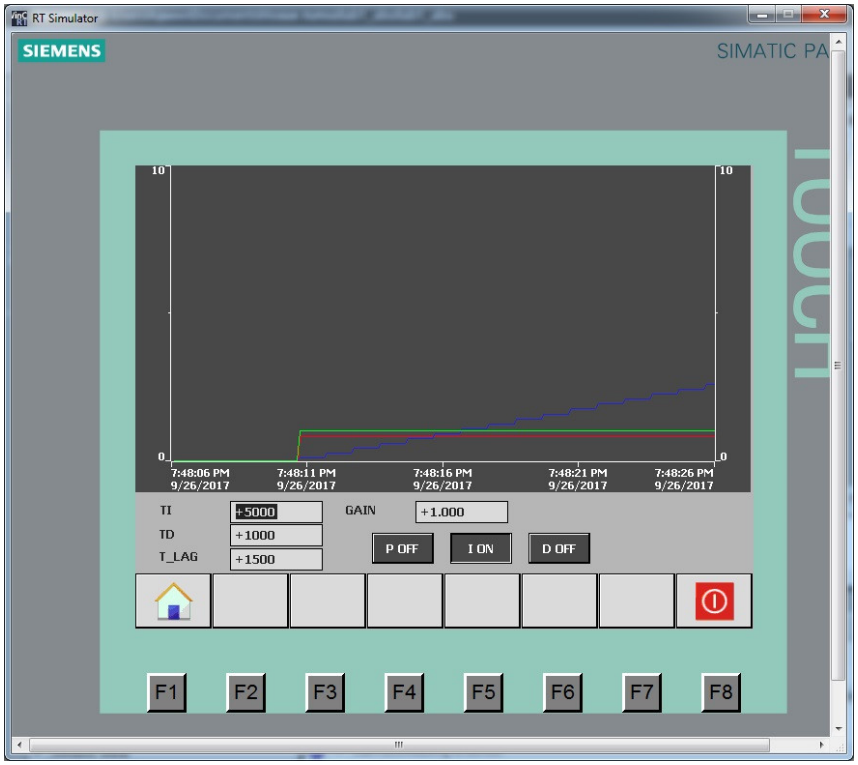


Figure 7. I-controller at TI = 5 s: red line is the control action, green line is the setting signal, blue line is the output control signal.

Figures 8 and 9 show the D-controller at TD = 2 s and TI = 5 s, respectively.

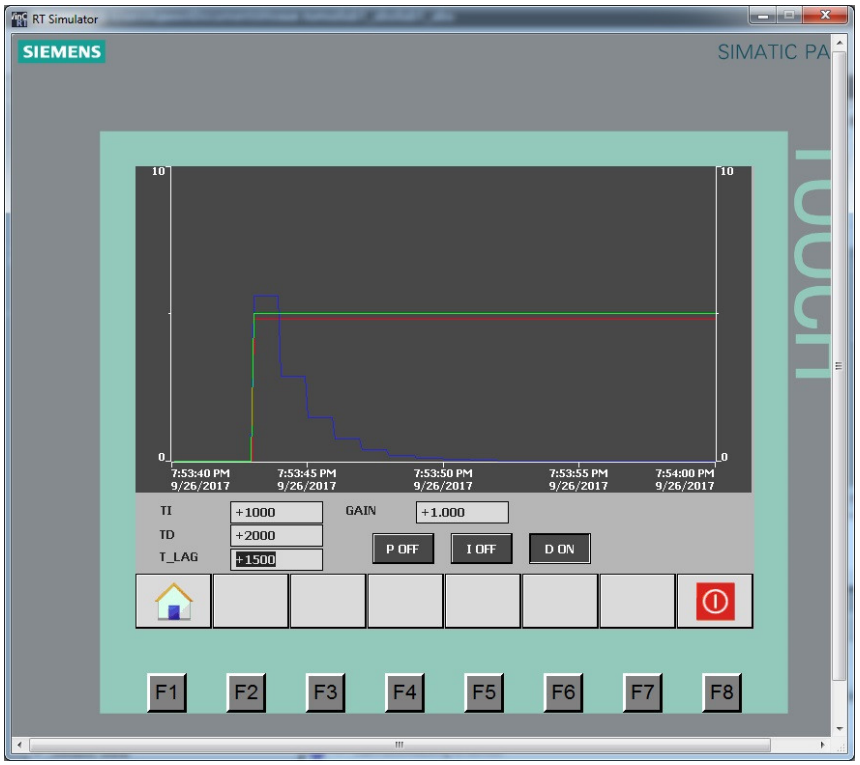


Figure 8. D-regulator at TD = 2 s: red line is the control action, green line is the setting signal, blue line is the output control signal.

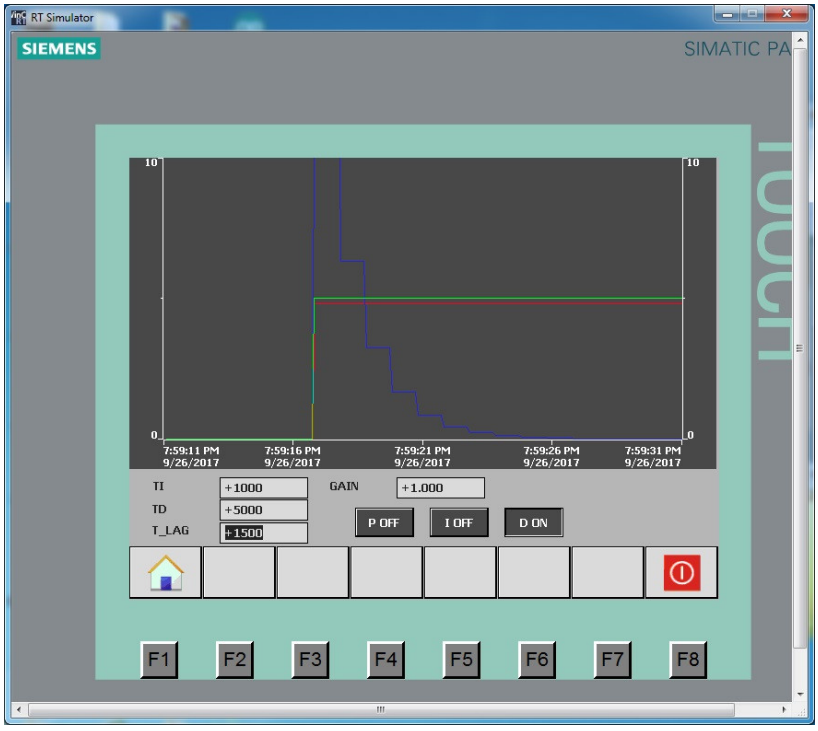


Figure 9. D-regulator at TD = 5 s: red line is the control action, green line is the setting signal, blue line is the output control signal.

Next, the behavior of the controller with a simulated aperiodic plant was studied. Figures 10 and 11 show the P-controller with GAIN = 2 and GAIN = 10, respectively.

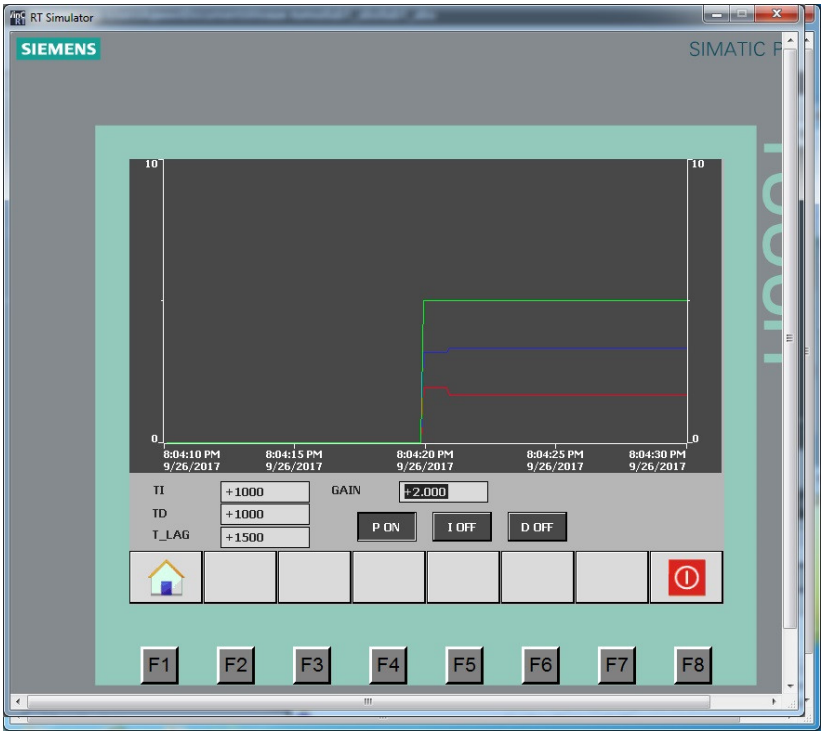


Figure 10. P-controller with GAIN = 2: red line is the control action, green line is the setting signal, blue line is the output control signal.

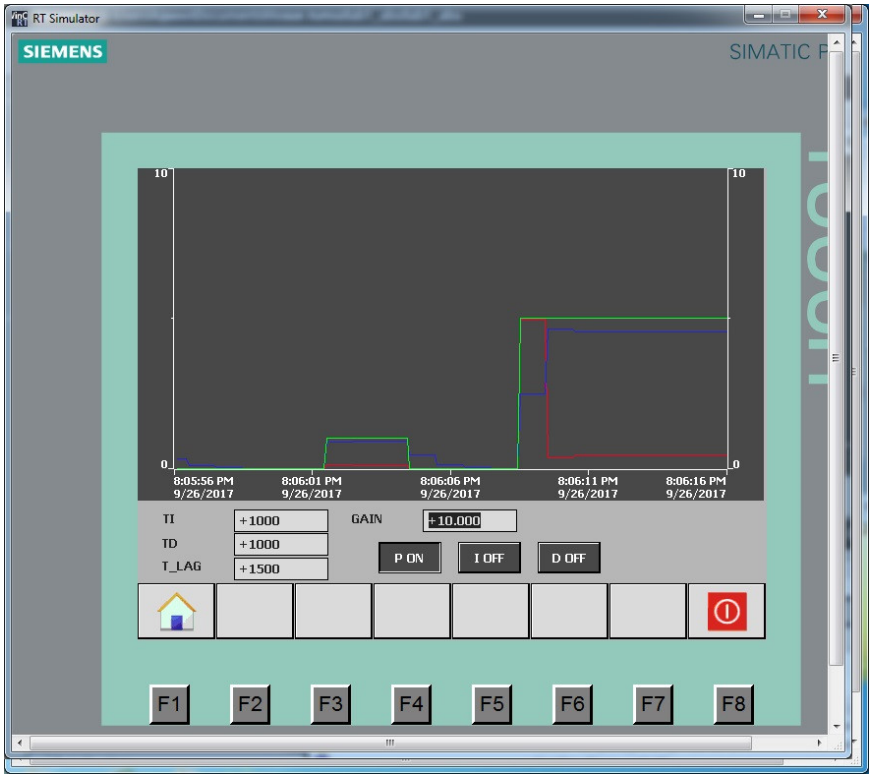


Figure 11. P-controller with GAIN = 10: red line is the control action, green line is the setting signal, blue line is the output control signal.

Figures 12 and 13 show the I-controller at TI = 1 s and TI = 10 s, respectively.

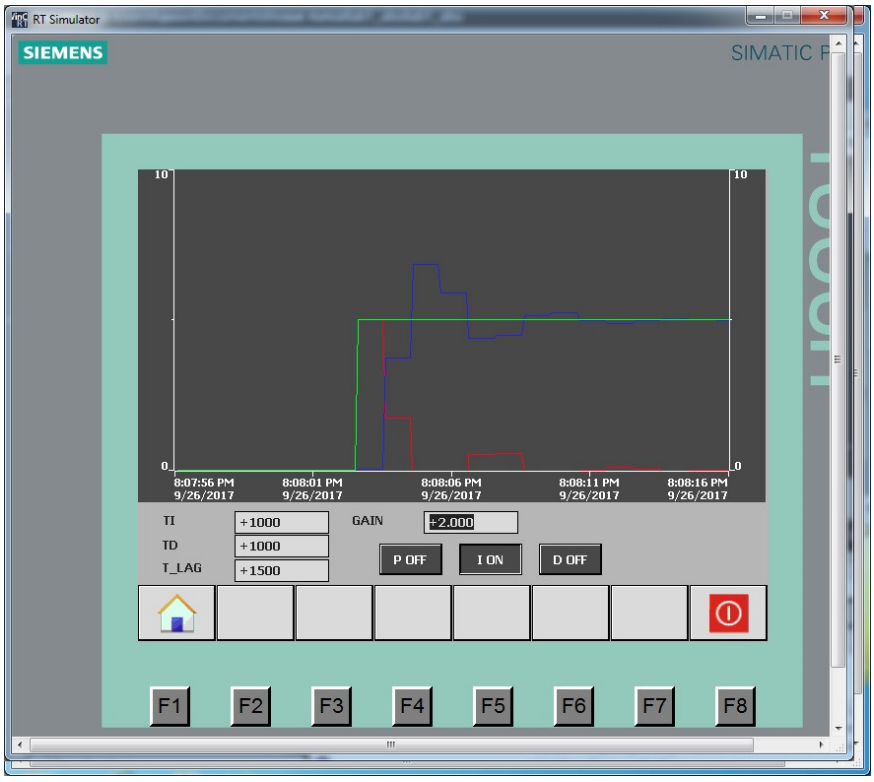


Figure 12. I-controller at TI = 1 s: red line is the control action, green line is the setting signal, blue line is the output control signal.

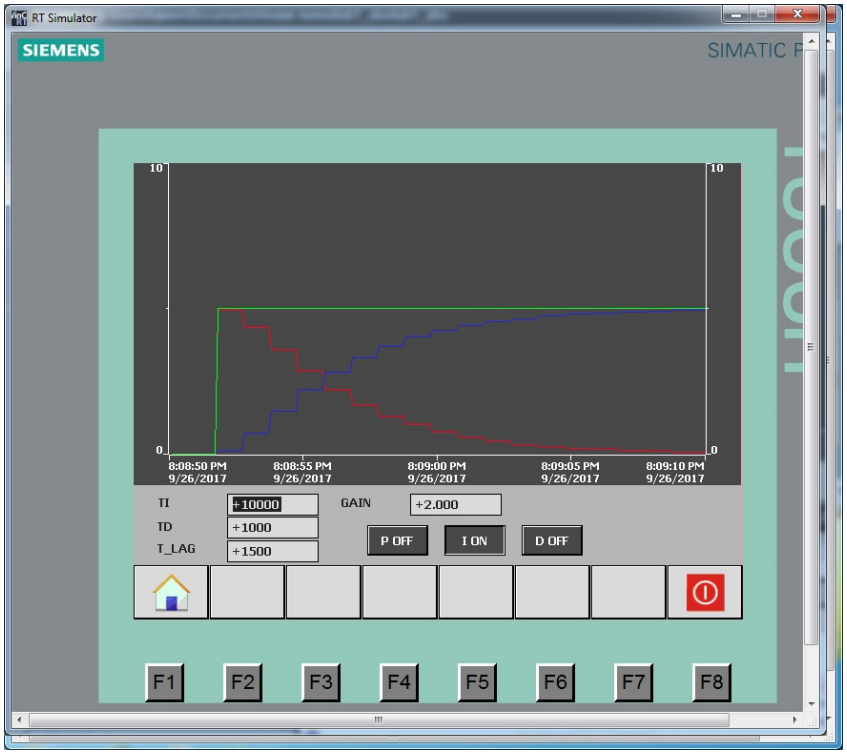


Figure 13. I-controller at TI = 10 s: red line is the control action, green line is the setting signal, blue line is the output control signal.

Figures 14 and 15 show the D-controller at TD = 1 s and TI = 10 s, respectively.

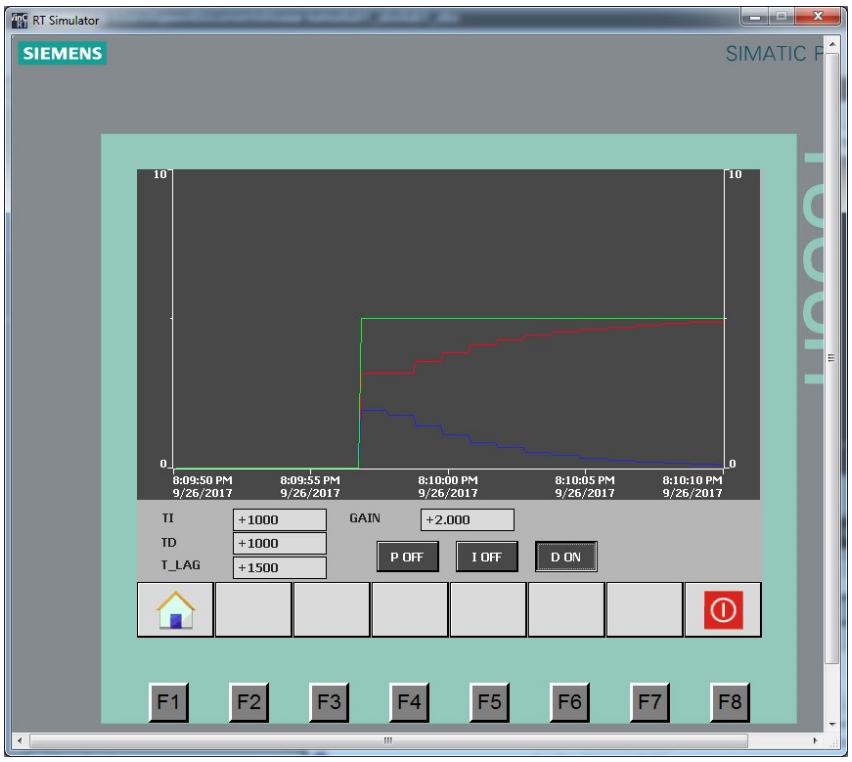


Figure 14. D-regulator at TD = 1 s: red line is the control action, green line is the setting signal, blue line is the output control signal.

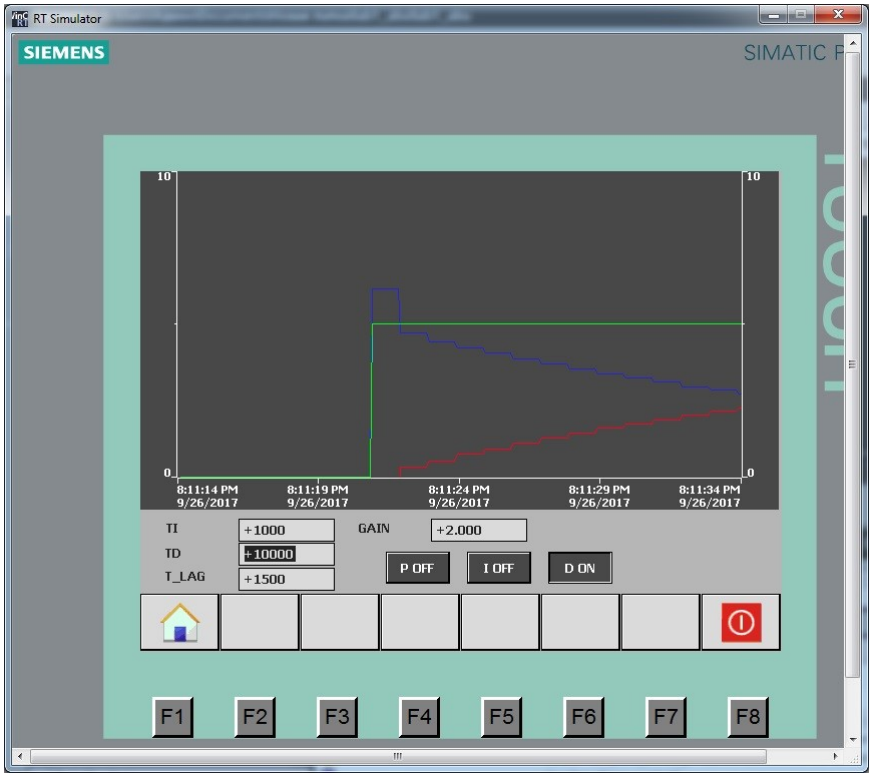


Figure 15. D-regulator at TD = 10 s: red line is the control action, green line is the setting signal, blue line is the output control signal.

The studies shown in Figures 4–15 show that the I-component allows you to compensate for the static error, and the D-component reduces the regulation time. An increase in the integration time leads to a slower rise in the I-component, and an increase in the differentiation time leads to an increase in the peak of the D-component. Thus, based on these results, the type of regulation was chosen and a scheme was developed.

Next, a mathematical model for controlling the angle of attack of the wind turbine blades was determined. In accordance with the calculations given above, a general functional diagram for controlling the blades of a vertical-axis wind generator was developed (Figure 16). Let us assume that the wind direction is south–north. The functional diagram includes 4 control channels for four blades A, B, C, and D. Setting the position of the blades depends on the direction of the wind flow, power calculation, angular speed of rotation of the wind generator, and wind speed. To take into account the above parameters, the use of sensors and setters in the feedback circuit is provided. Next, you need to determine the type of regulator and the law of regulation. Figure 17 shows a diagram of one channel for controlling the position of a wind turbine blade. In accordance with Figure 18, elements 1, 2, 3, and 4 set the desired position of the blade based on the values of the wind flow velocity and wind generator rotation. Next, it is necessary to determine the choice of control law, based on these parameters:

$$\delta_s = K_\alpha(\alpha - \alpha_s) + K_\alpha \alpha_x, \quad (8)$$

where δ_s is the servo angle, K_α is the conversion factor, α is the actual angle of rotation, α_S is the angle reference, and α_x is the blade angular velocity.

The value of the setting value of the angle was calculated in accordance with Formula (7) and Table 1 in block 4 in Figure 17. Next, a mathematical model of the blade attack angle control system was developed; for this, the MatLab/Simulink simulation environment was used, shown in Figure 18. The results of modeling the mathematical model are shown in Figure 19.

Figure 19 shows the simulation result of the developed wind turbine blade control system. As can be seen from it, the transition process setting time is 3 s, which is the optimal

value when controlling the wind turbine blades. As can be seen, the blade position control system is robotic.

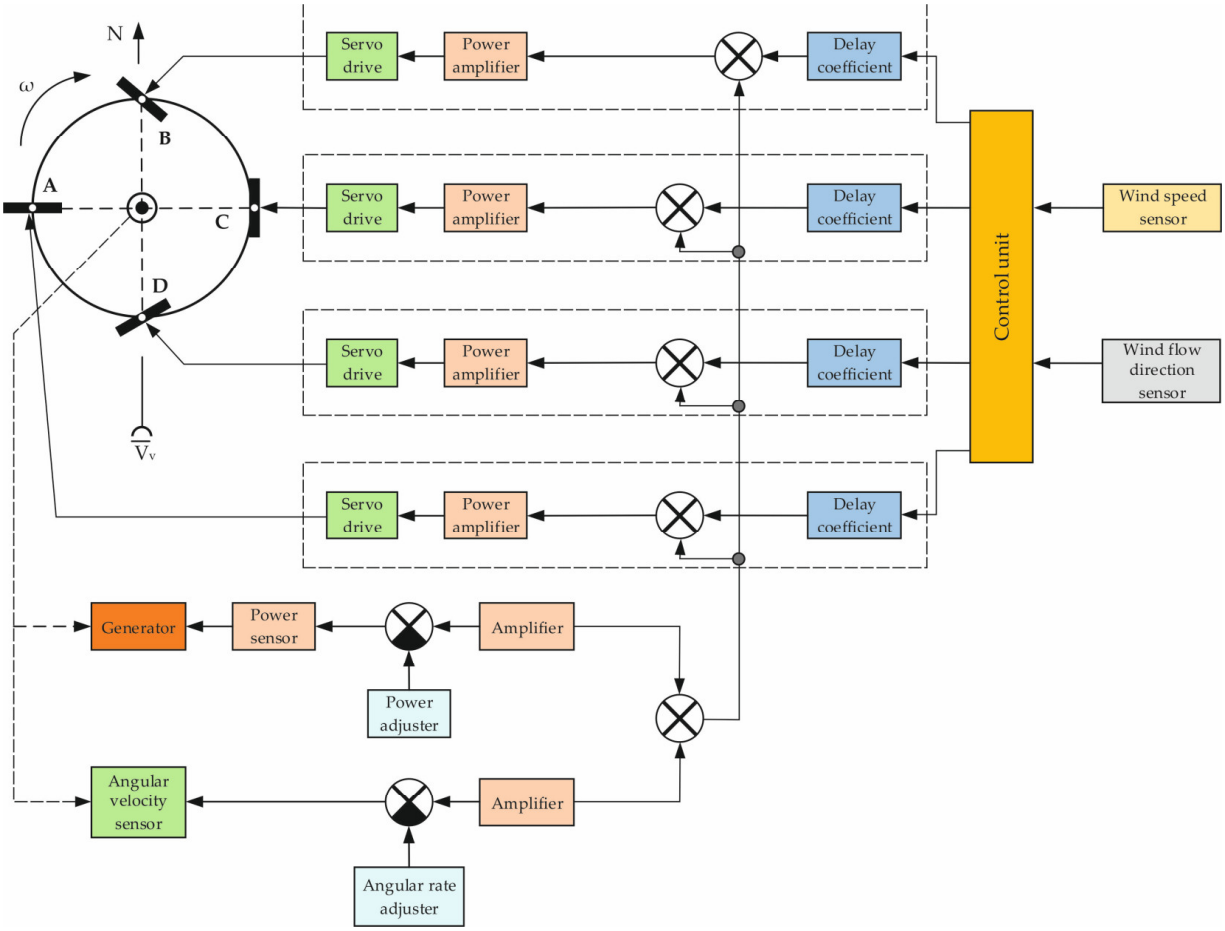


Figure 16. A general functional diagram of the blade control of a vertical-axis wind generator: A, B, C, D—control channels for four blades.

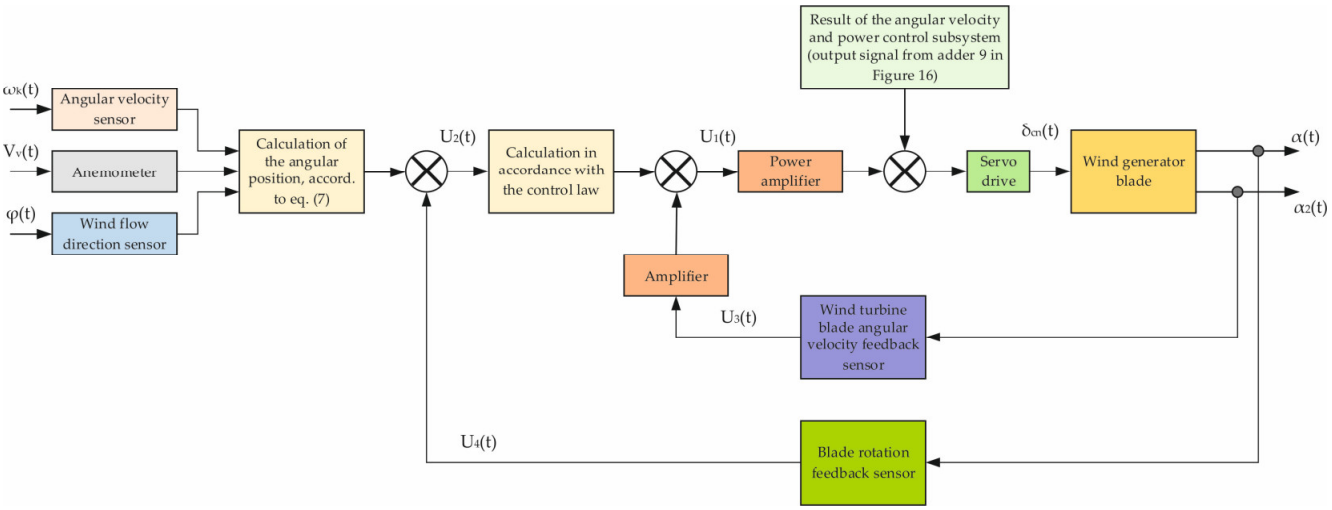


Figure 17. Scheme of one channel for controlling the position of the wind turbine blade.

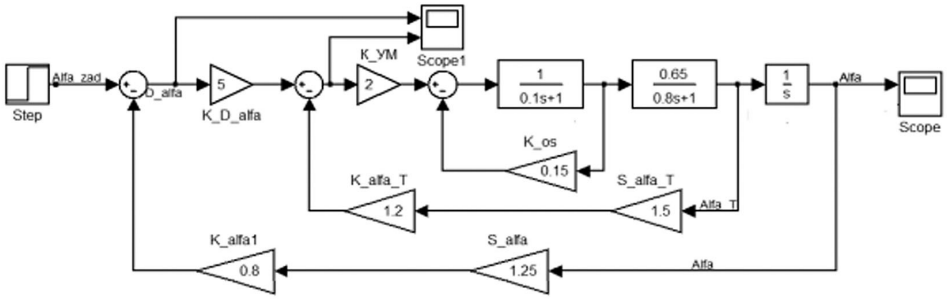


Figure 18. Mathematical model of wind turbine blade control.

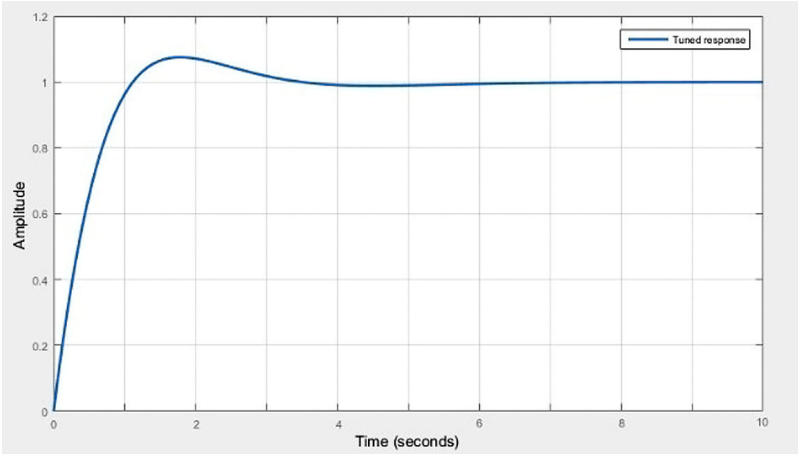


Figure 19. Simulation result.

3. Results

On the basis of the obtained calculations and mathematical models, two laboratory models were assembled that have the same characteristics in terms of dimensions and materials of manufacture. The model shown in Figure 20 does not have a blade position control system, while the model shown in Figure 21 includes the control system designed and described. A stepper motor was used as a generator for both models. MG996R servo drives were used as an actuator for controlling the wind turbine blades in the model with a control system (Figure 21).



Figure 20. Experimental model of a wind turbine without a control system.



Figure 21. Experimental model of a wind generator with a developed control system.

With the help of the laboratory software and hardware complex Petom-51 (Figure 22), the values of the output voltage for both models were obtained by supplying a wind flow at a speed of 25 m/s. Figure 23 shows the voltage output characteristic for a wind turbine model without a control system (Figure 20). Figure 24 shows the voltage output characteristic for a wind turbine model with a control system (Figure 21).



Figure 22. Software and hardware complex Petom-51.

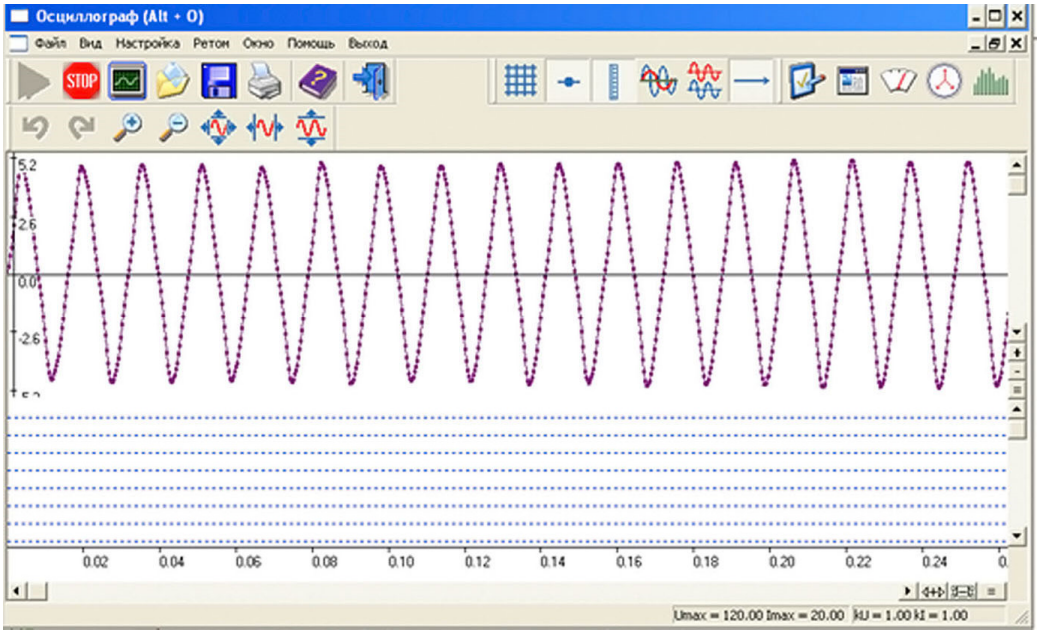


Figure 23. Voltage output signal from the laboratory model without the implementation of the developed control system (the vertical axis is the voltage amplitude V, and the horizontal axis is the time, s).

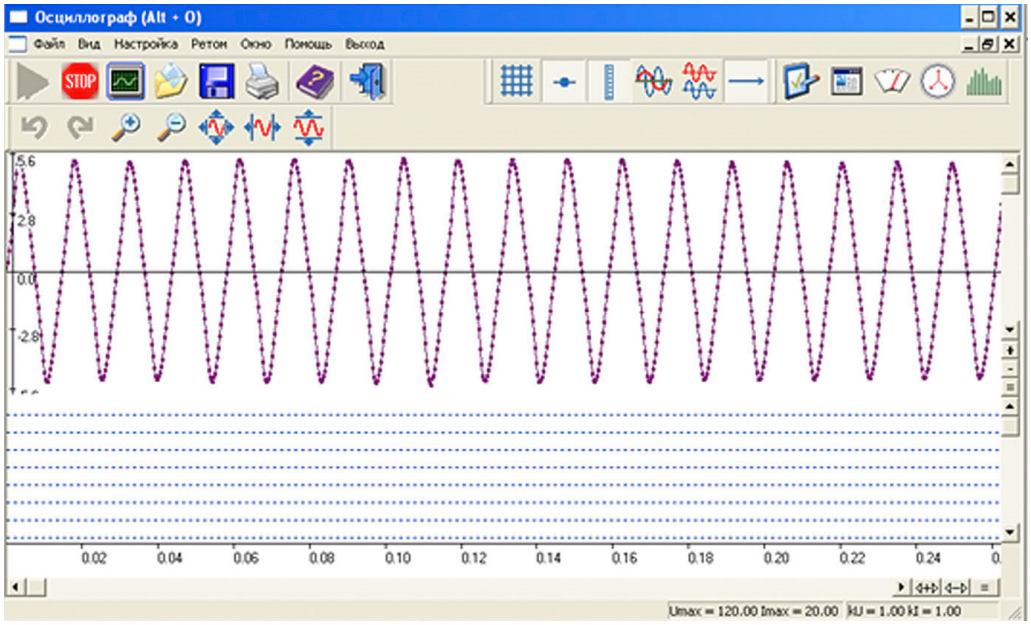


Figure 24. Voltage output signal from the laboratory model with the introduction of the developed control system (the vertical axis is the voltage amplitude V, and the horizontal axis is the time, s).

In the course of the work, a system for automatically controlling the angle of rotation of the blades of a vertical-axis wind generator was developed and tested. Figures 23 and 24 show the values of the output voltage amplitude for two wind turbine models. The voltage amplitude for the wind turbine model without a control system was 5.2 V. After the introduction of the control system described in this paper into the wind generator, the voltage amplitude became 5.6 V. The developed control system was able to increase the efficiency of vertically axial wind turbines. Thus, the efficiency of using the developed control system corresponded to 7.69%. The proposed calculation method does not pay attention to the losses in electricity associated with the rotation of the servos, since these losses can vary depending on factors such as materials, dimensions, and other characteris-

tics of wind turbines. The main purpose of this article is to develop and demonstrate the control system, as well as to test its performance. In this case, the main emphasis is on the practical implementation of the control unit and its effectiveness.

Further, to calculate the efficiency from the introduction of the control system, calculations were made of the generated value of the output power of two wind turbines with and without the developed control unit, taking into account the experimental and calculated data given earlier. Since it was found that the efficiency of a wind generator with an embedded control unit is 7.69% higher than that of a wind generator without a control system, the power generated by a wind generator with a control system can be found by the formula [28]:

$$P_2 = P_1 \cdot \left(1 + \frac{\eta}{100}\right) \quad (9)$$

where P_1 is the generated power of a wind generator without a control system, and η is the value of the increase in efficiency.

For comparison, a vertical-axis industrial wind generator with a nominal power of 4 kW was chosen, the instantaneous power data depending on the wind speed were taken from the literature [27], and, in accordance with the following expression, the values of the daily electricity generation by the wind generator were calculated [29]:

$$\mathrm{E} = \mathrm{P} \cdot \mathrm{t} \quad (10)$$

where P is the daily generation of electrical energy, and t is time (24 h).

The calculation data for the daily generation of electrical energy of a wind generator without a control system are shown in Table 2. The calculation of the daily generation of a wind generator with an embedded control unit is listed in Table 3.

Table 2. Characteristics of an industrial wind turbine without a control system.

Wind Speed, v, m/s	Instantaneous Power of Energy Industrial Wind Generator, W	Daily Generation of Electrical en from an Industrial Wind Generator, kW
4	200	4.7
5	400	9.5
6	700	16.7
7	1100	26.3
8	1700	40.7
9	2500	60
10	2900	69.5
11	3300	79.1
12	3400	81.5

Table 3. Characteristics of an industrial wind turbine with a control system.

Wind Speed, v, m/s	Instantaneous Power of Energy Industrial Wind Generator, W	Daily Generation of Electrical en from an Industrial Wind Generator, kW
4	215	5.0
5	430	10.2
6	754	17.0
7	1185	28.3
8	1831	43.8
9	2692	64.6
10	3123	74.8
11	3554	85.2
12	3661	87.2

For an example of calculating the effectiveness of the implementation of the control unit, let us take the value of electricity consumption per hour as equal to 390.8 kWh, or 390,805 Wh, and the value of the wind speed as 10 m/s. Thus, it is necessary to use 135 wind turbines with a nominal power of 4 kW or 41 wind turbines with a power of 10 kW.

Next, it is necessary to carry out a similar calculation for a wind generator with an embedded control unit. For the calculation, the wind speed is also taken as 10 m/s and the average consumption per hour is 390.8 kWh, or 390,805 W * h. Thus, it is necessary to use 126 wind turbines with a control unit with a rated power of 4 kW or 38 wind generators with a power of 10 kW. Figures 23 and 24 shows a comparison of the daily power generation of a vertical-axis wind turbine with and without an embedded control unit. Thus, from the introduction of a control unit into a wind generator with a vertical axis of rotation, the savings are three wind generators with a rated power of 10 kW.

4. Conclusions

As a result of studying the components of a standard PID controller and developing the wind turbine blade control system, an optimal control law for the blades was selected based on calculations and mathematical models. The developed control system underwent successful testing using a mathematical model in the MatLab program and conducting experiments. The obtained experimental data confirm the robotic capability of the developed wind turbine blade control system. By accurately positioning blades A and C through control system adjustments and utilizing sensors for angular speed of the rotor and an anemometer, optimal performance of the wind turbine was achieved. Blade B receives the maximum wind flow, while blade D is oriented parallel to the wind direction to minimize aerodynamic drag. The implementation of the automated control system resulted in a 7.69% increase in the efficiency of the wind turbine, based on experimental data. This demonstrates the potential of the developed system to enhance the operation of wind turbines and improve the energy efficiency of wind power installations. Based on the conducting calculations, the incorporation of a control unit in a vertical-axis wind generator yields savings equivalent to three wind generators with a nominal power of 10 kW. This highlights the significant impact and efficiency achieved through the implementation of control mechanisms in vertical-axis wind turbines.

Further research in the field of wind turbine blade control can focus on improving the accuracy of the control system, reducing the transient response time, and optimizing the generator's efficiency. Exploring alternative control algorithms and employing more accurate sensors can enhance the reliability and stability of the system. These advancements will continue to enhance the efficiency and reliability of wind power installations, contributing to sustainable development and environmental effectiveness in the renewable energy sector.

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