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A Motor Speed Control System Simulation

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ABSTRACT The article considers the features of building a motor speed control system using the SIMULINK environment. The model served as a demonstration of the effectiveness of the system design method based on a specialized environment. The model implements three types of automatic control systems: closed and open automatic control systems, as well as a closed software automatic control system in which the set point changes according to a sinusoidal law. A user interface has been developed to change the parameters of the automatic control system elements and control the start of a DC motor using GUIDE tools. The results of experimental studies of the system with different forms and values of the set point, as well as when disturbing factors act on the controlled object are presented.

KEYWORDS DC motor; Simulink; pulse-width modulation; control system; simulation; Arduino; MATLAB.

I. INTRODUCTION

The field of research on the regulation and stabilization of the speed of rotation of the shafts of DC motors is widely popular due to their use in many areas of science and technology, such as industry, electronics and transport [1]. DC motors play an important role in robotic complexes, as well as in the design of high-precision automation and computing devices [2, 3].

- The main advantages of DC motors include the simplicity and reliability of their design, relatively simple speed control, and a variety of dimensions - from very small (in camera drives, medical equipment) to massive motors in drives of industrial installations.

It is these advantages that determine the use of DC motors in various devices where high speed of change of the shaft rotation speed and its highly effective stabilization are required. Depending on the type of motor, different speed control methods are used. These methods have their own advantages and disadvantages, which makes it possible to maximally satisfy the requirements of the device for the operation of which the speed of the drive is required [4–21].

The main task when using DC motors is to ensure high speed and stabilization of the speed of rotation of its shaft. For this purpose, hardware and software-hardware complexes are being developed that allow:

- to minimize the error of speed regulation;
- to ensure stable operation under the influence of external disturbances;
- to provide convenient control by the user.

Automatic control systems [22] are used to control the speed of rotation of the motor shaft. Such systems ensure the stability of the set speed of rotation of the motor shaft, and also allow changing the speed according to some previously known program. Today, open-loop and closed-loop systems are used to control the speed of rotation of motor shafts. In open-loop systems, the value of the controlled variable is set using a control influence, however, in such systems there is no feedback, which makes it impossible to correct the controlled variable in cases of its change caused by the action of external environmental factors. In addition, the accuracy of maintaining the controlled value in such systems depends on the stability of the static characteristics of the elements that make up the system. The advantages of open-type systems include their high speed.

In closed-type systems, due to the implementation of feedback during the system operation, the controlled value is corrected in the direction of achieving its values close to the values of the set value. The main disadvantage of closed-type systems is that when certain values of the parameters of the elements that make up their composition are reached, such systems enter an unstable operating mode.

In closed-type systems, regulators are used in the

feedback loop, which are necessary to form the control effect and ensure the required control accuracy. To ensure the specified operating characteristics of the system, preliminary synthesis of the regulator parameters is required.

In motor shaft rotation speed control systems, microprocessor devices (controllers) are used, with the help of which algorithms are executed that implement certain control laws (for example, PI or PID laws) [23-25]. Controllers, together with peripheral devices (sensors, converters, actuators), provide the ability to control the speed of rotation of the motor shaft. Development of systems at the controller level requires additional implementation of interfaces for changing system parameters, as well as displaying information that characterizes the state of the system at certain points in time.

Connecting the controller to a specialized development environment simplifies the creation of algorithms and interfaces for the controller. System development at the specialized environment level can be implemented using the example of the Matlab software package, which also includes the Simulink modeling environment. Simulink allows developing a model of an automatic control system and deploy it on the controller using software and hardware. At the same time, Simulink and the model deployed on the controller exchange data in real time, which allows changing system parameters and observe changes in the system state. The apabilities of the Simulink software are not limited package provides tools for developing users own blocks that implement certain functions on the end equipment. It is these advantages for modeling the motor shaft rotation speed control system that led to the choice of the design method at the Simulink specialized environment level [26-29].

II. BLOCK DIAGRAM OF THE MOTOR SHAFT ROTATION SPEED CONTROL SYSTEM

When developing the motor shaft rotation speed control system the design method at the specialized environment level was used. In this case, the Matlab software package, or more precisely the Matlab and Simulink programs, is used as a specialized environment.

The main elements of the block diagram (Fig. 1) are as follows:

- Matlab is used for intermediate calculations and implementation of the user interface, which is necessary for convenient change of model parameters in Simulink.

- Simulink is a development environment for a model that is deployed on a controller (in this case, Arduino Mega). At the same time, after deploying the model on a controller, the structural diagram in Simulink becomes an interface for the program that is executed by the controller. Changing the parameters in Simulink blocks provides a change in the parameters of the executed program.

- Arduino Mega [29–31] is used as a bridge between the experimental setup and the Simulink environment. A Simulink environment model is deployed on it, which provides signal processing from the tachometer and performs the control process (control signals are supplied to the DC motor driver).

The block diagram of connecting the equipment elements for the motor shaft speed control system investigation is shown in Fig. 2.

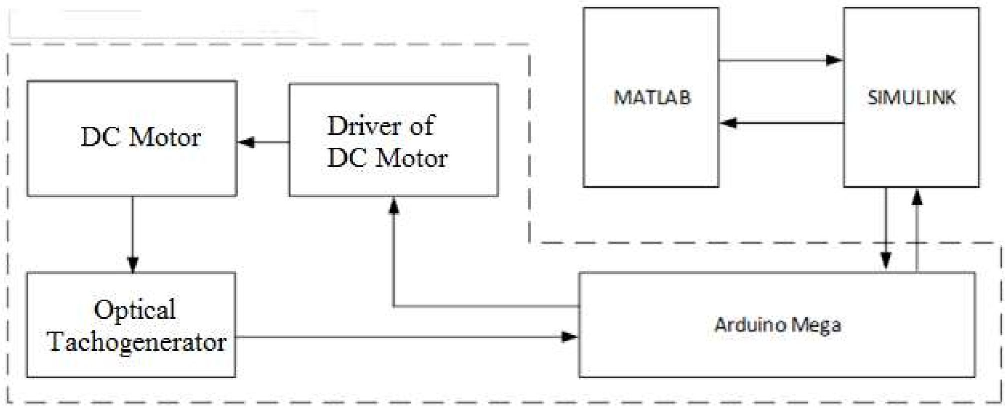

Figure 1. Block diagram of the motor shaft speed control system.

Arduino Mega ports purpose is as follows:

- 2 – output to which the signal from the tachogenerator is applied;

- 3 – output is the output of the generator pulse-width modulator;

- 22, 23 – motor state control outputs.

The principle of the system operation is as follows. The logic level signal from the digital outputs "*22*" and "*23*" of the Arduino Mega board is fed to the inputs "*IN1*" and "*IN2*" of the *L298N* driver [32]. This signal changes the state of the motor (start, stop, change of the shaft rotation direction). From output "*3*" the pulse width signal (*PWM*) of the microcontroller generator signal is fed to the input "*ENB*". This makes it possible to control the motor speed by changing the duty cycle of the PWM signal [33–40]. From the output "*Signal*" of the tachogenerator, a signal in the form of pulses is fed to input "*2*" of the Arduino board. Input "*2*" is programmed for external interrupts. The function that will be called upon an external interrupt is a pulse counter. As a result, after simple mathematical calculations, there is obtained the numerical value of the motor shaft rotation speed in the number rpm per minute.

The model allows changing the principle of the motor shaft rotation speed controlling in real time by switching the connections of the created subsystems. In Fig. 3 there is shown a model of the motor shaft rotation speed control system using the Simulink environment.

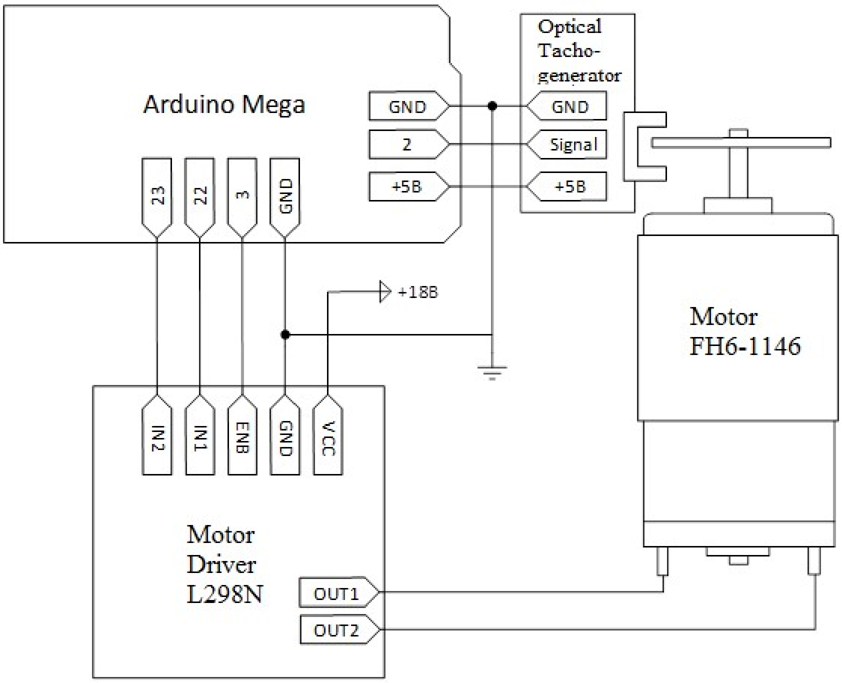

Figure 2. Block diagram of the motor shaft rotation speed control system studying.

The model uses subsystem blocks with activation (*Enabled Subsystem*), which are activated only when there is a high-level signal at the *Enable* input. This allows to implement several algorithms for controlling a physical object within one model, and include them only when necessary.

The constant blocks (*EnablePID*, *EnableSIN*) ensure the activation of the corresponding subsystem, and the *Switch signal* block switches the output of the active subsystem, the signal from which is fed to the "*Real Object*" subsystem. The constants *IN1* and *IN2* control the state of the motor, or rather, their value is converted into the corresponding signal level ("*0*" or "*1*") and fed to the corresponding inputs of the L298N motor driver.

The "*Real Object*" subsystem (Fig. 4) contains the blocks of the Arduino support package library. The blocks allow to control digital inputs and PWM output. The *Tachometer optical* block [41-42] allows to obtain the actual value of the motor shaft rotation speed based on the signal from the output of the optical tachogenerator.

The "*Motor speed stabilisation*" subsystem (Fig. 5) allows to implement two types of automatic control systems (ACS):

- closed-loop control system or rather, a motor speed control system. The control system must provide a constant value of the controlled variable (*Y*) at the output of the control object: *Y= const*;

- open-loop control system, in which control is carried out without controlling the result, based only on the model of the controlled object embedded in the control system.

Switching the control method is carried out using the "*Multiport Switch*" block.

The "*activatePID*" variable block generates such a level signal value that is necessary to reset the PID controller values.

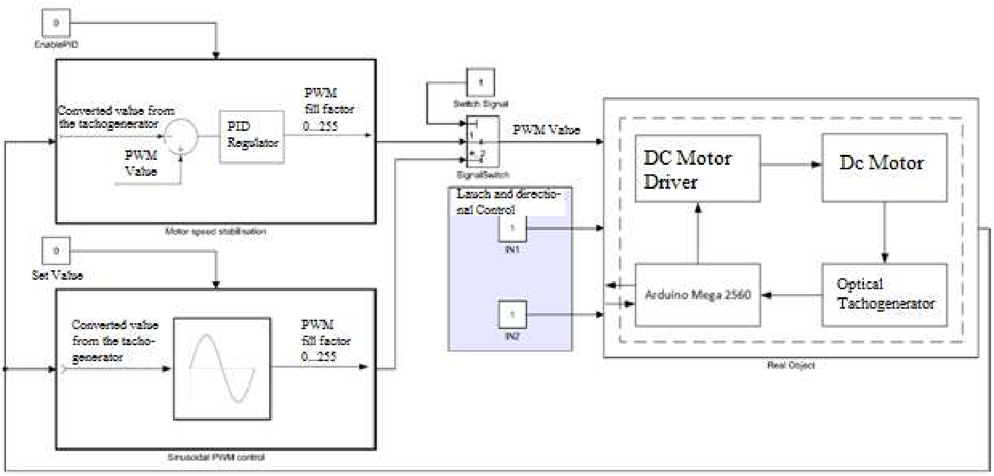

Figure 3. The model of the motor rotation speed control system

In a closed control system, the PID controller block is included in the feedback loop, the type of which can be changed if necessary (to *P, I, PI, PD*). In this case, the controlled variable is the motor shaft rotation speed (number of rpm).
The following values are highlighted in the system model:

- the setpoint value of the controlled variable. It there is formed by the "*Desired Speed*" block, the value of the setpoint value can be changed via the user interface. The value of this value is set in rpm.

- the converted value of the controlled value is formed by the "*Tachometer_optical*" block and fed into the subsystem through the "*TachometerValue*" input. This value is the actual value of the controlled value and is measured in rpm.

- the signal of discrepancy between the set and actual values of the controlled value is formed by the "*SUM*" block, and the "*Error saturation*" block sets the error limits, i.e., forms the so-called "*dead zone*", which is the actual error value of the optical tachogenerator used. The magnitude of this error is 24 rpms of the motor shaft at the period of data collection from the tachogenerator output, which is equal to 0.1 seconds.

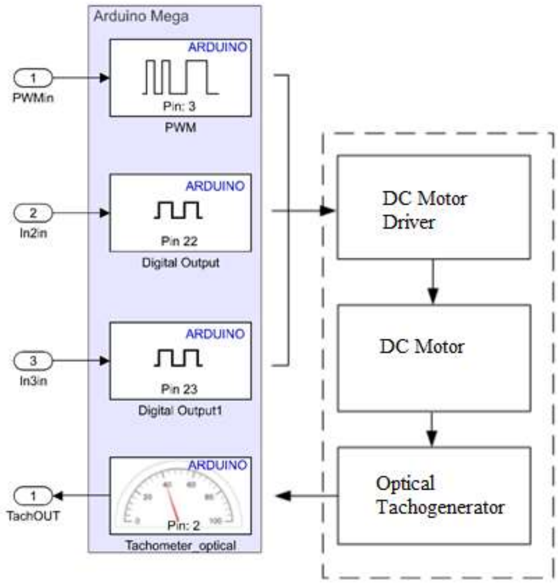

Figure 4. The “Real Object” subsystem

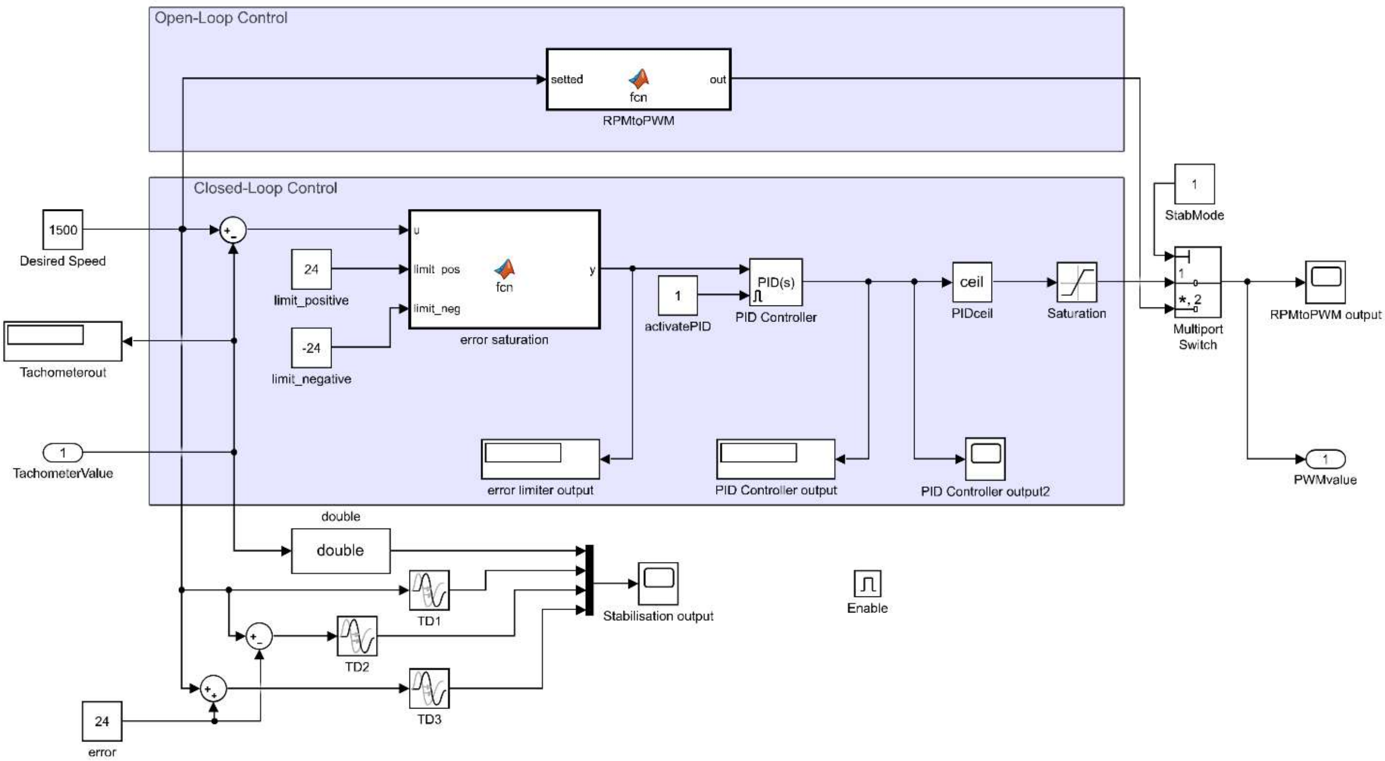

Figure 5. “*Motor speed stabilisation”* subsystem

- control influence there is formed by the PID controller based on the mismatch signal and the selected control law. The output value of the controller is the input value for the PWM generator of the Arduino microcontroller board.

- The "*Saturation*" block sets the permissible limits of the PWM pulse width modulator value "0...255" in order to prevent abnormal operating modes of the PWM generator.

The control system allows to keep the motor shaft rotation speed within the specified value with an error of 24 rpm.

In the open-loop control system for the motor shaft rotation speed of the SAK, the value of the set value (in rpm) is fed to the *RPM to PWM* block (Fig. 6), which converts the value of revolutions per minute into the corresponding parameter value for the PWM generator of the microcontroller.

The *RPM to PWM* block is a MATLAB function that, based on the interpolation of the motor speed characteristic by the set value of the shaft rotation speed, finds the corresponding value of the pulse width modulator parameter, which is fed to the motor driver.

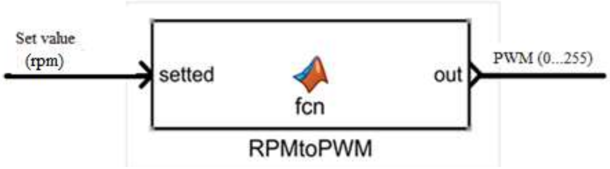

Figure 6. RPM to PWM block in Simulink environment

The "*Sinusoidal PWM control*" subsystem (Fig. 7) implements a closed-loop automatic control software system (that is with feedback), which provides a change in the controlled quantity according to a given program: *Y= var*. In this case, the program change occurs according to the sinusoidal law.

The system uses a feedback link, which is built by analogy with the feedback link of the "*Motor speed stabilisation*" subsystem.

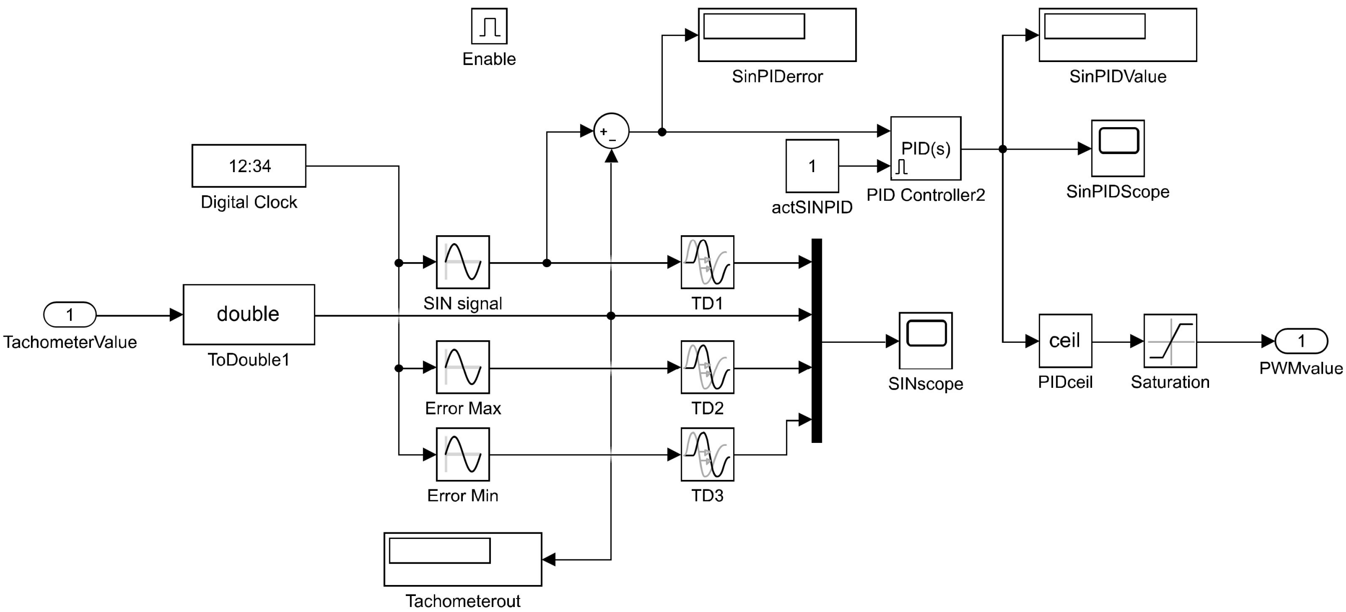

Figure 7. The "*Sinusoidal PWM control*" subsystem

In this case, the value of the setpoint changes according to a sinusoidal law, and the control effect is formed by the *PI* controller based on the error between the setpoint and the value obtained at the output of the "*Tachometer_optical*" block.

The setpoint changes according to a sinusoidal law. The "*SIN Signal*" block forms a sinusoidal signal with parameters specified via the user interface, i.e.,:

- oscillation amplitude (*Amplitude*);
- bias (*Bias*);
- number of samples per period (*Samples per period*).

The relationship between the *Amplitude* and *Bias* parameters and the maximum/minimum value of the motor shaft rotation speed is given by the formulas as follows:

$$Amplitude = 0.5(Max.value \quad Min.value)\ (turns\ per\ minute)\ (1)$$
$$Bias = (Amplitude + Min.value)\quad (turns\ per\ minute)\ (2)$$

The "*Error Max*"/"*Error Min*" blocks form sinusoidal signals that are shifted up and down relative to the main control signal. In this case, the block parameters are similar to the parameters of the "*SIN Signal*" block, except for the bias parameter (*Bias*), which is calculated by the formulas as follows:

$$Bias_{max} = (Amplitude + Min.value + Error)(turns\ per\ minute)(3)$$
$$Bias_{max} - (Amplitude + Min.value - Error)(turns\ per\ minute)(4)$$

These signals are used to display the error limits on the graph (*Scope*). The "*Digital Clock*" block is an external signal source for the sine wave shaping blocks.

III. MOTOR SPEED CHARACTERISTIC OBTAINING

To ensure control in an open system, a model of the controlled object is required. In this case, the motor is controlled using pulse-width modulation, that is, the speed of rotation of the motor shaft depends on the duty cycle parameter of the PWM signal. The characteristic of the dependence of the motor shaft speed on the duty cycle of the signal is used in an open-loop AC system. To obtain it, the PWM generator parameter of the microcontroller was changed in the range 0…255 (8-bit PWM), with a step of 5. The range of the PWM generator parameter change 0…255 corresponds to 0…100% of the duty cycle of the PWM generator output signal. At each step of changing the duty cycle parameter, the motor shaft rotation frequency was measured. For this, a model (Fig. 8) was used in Simulink to specify the duty cycle parameter of the PWM signal.

The experimentally obtained speed characteristic of the motor is shown in Fig. 9.

A. OPEN-LOOP CONTROL SYSTEM

To measure the response characteristic of the open-loop automatic control system, there were two experiments conducted, i.e.:

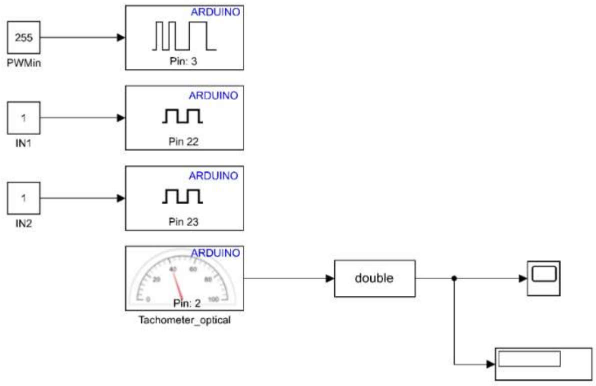

Figure 8. Simulink model for the motor speed characte-ristic measuring

- at a motor shaft rotation speed of 1500 rpm, a step change of the setpoint value was performed to the level of 400 rpm.
- at a motor shaft rotation speed of 1500 rpm, a step change of the setpoint value was performed to the level of 2200 rpm.

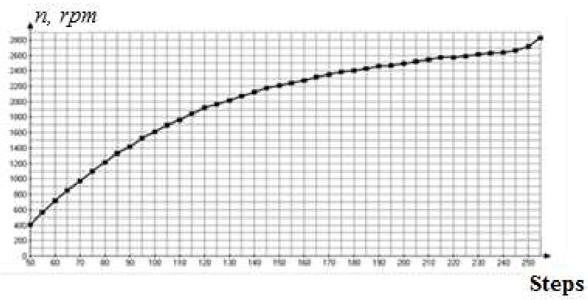

Figure 9. Motor speed characteristic

The response of the open-loop system during the first experiment is shown at the Fig. 10. The dashed-dotted line shows the limits of the permissible error, which is 24 rpm. As can be seen from the figure, after the completion of the transient process, the speed of rotation of the motor shaft stabilized, however, its value did not enter the specified error zone.

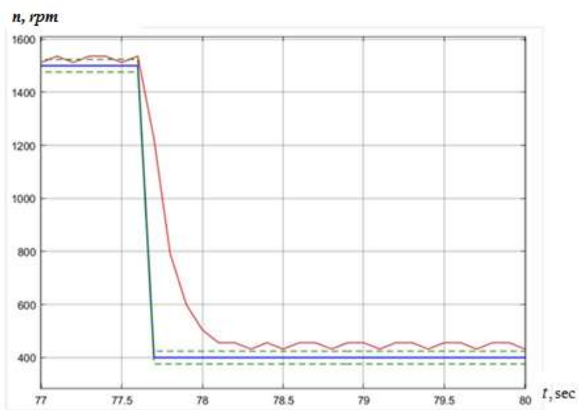

Figure 10. Response of an open-loop system when changing the setpoint from 1500 to 400 rpm

The response of the open-loop system during the second experiment is shown at the Fig. 11. As can be seen, at high speeds close to the maximum (maximum motor shaft rotation speed 2850 rpm) the deviation of the motor shaft rotation speed in steady-state mode from the setpoint increased. In both cases, such deviations of the motor shaft rotation speed from the setpoints are due to the fact that the motor does not provide a linear conversion of the duty cycle of the input signal into the motor shaft rotation speed (see Fig. 9).

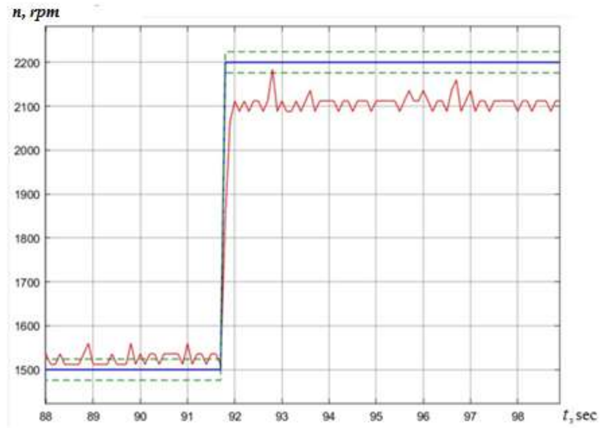

Figure 11. Response of an open-loop system when changing the setpoint from 1500 to 2200 rpm

The response of the open-loop system to disturbances there is shown at the Fig. 12. As can be seen, after the disturbance on the system is over, the controlled variable returns to its original value. There is no overshoot, which is a feature of the operation of an open-loop system, but the control error remains a drawback.

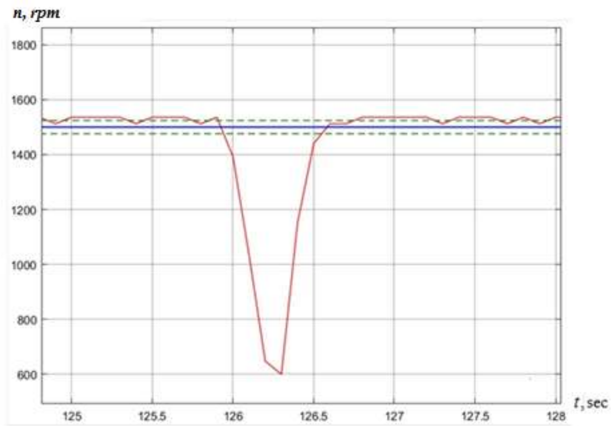

Figure 12. Reaction to disturbances of an open-loop control system

B. CLOSED-LOOP CONTROL SYSTEM

To measure the response characteristics of a closed-loop automatic control system, a stepwise change of the setpoint from 1500 rpm to 400 rpm was performed at different values of the PI controller parameters. The system characteristics were measured using the PI control law. In the parameters of the "*PID Controller*" block of the Simulink model, the PID control law parameters were replaced by the PI control law parameters. The controller parameters were changed according to Table 1.

Table 1. The controller parameters

Parameter number	Proportional law (P) K_p	Integral law (I) K_i
1	0.001	0.1
2	0.01	0.1
3	0.001	0.05
4	0.01	0.05

The response of a closed-loop controller with parameters number 1 (Table 1) is shown at the Fig.13.

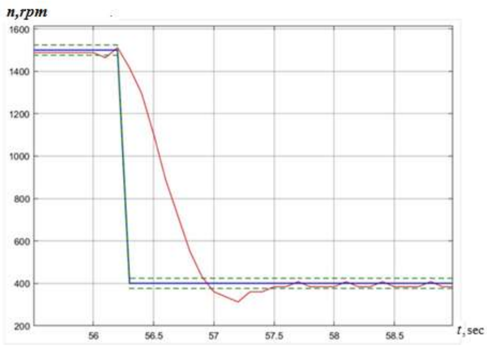

Figure 13. Response of a closed-loop controller (K_p=0.001, K_i = 0.1)

The figure shows that the response time is 1.25 seconds, but there is a slight overshoot, which is equal to 156 turns. At the same time, after the transition process is completed, the speed is set to the set value. The dashed-dotted line shows the limits of the permissible error, which is equal to 24 rpm.

With parameters number 2, a shorter response time is observed compared to the case number 1, as well as there is no overshoot. The response time of the control system (Fig. 14) is equal to 1 second.

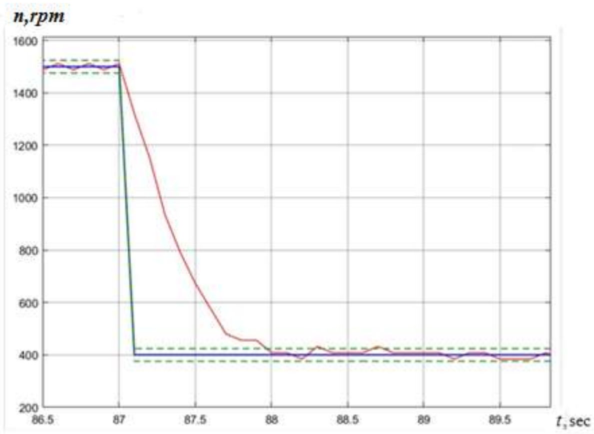

Figure 14. Response of the closed-loop controller with coefficients K_p = 0.01, K_i = 0.1

With parameters number 3 and 4 there is an increase in the response time of the automatic control system (Fig. 15 and Fig.16).

Among the above mentioned four experiments, the most qualitative characteristic of the system response was obtained with coeficients K_p = 0.01, K_i = 0.1.

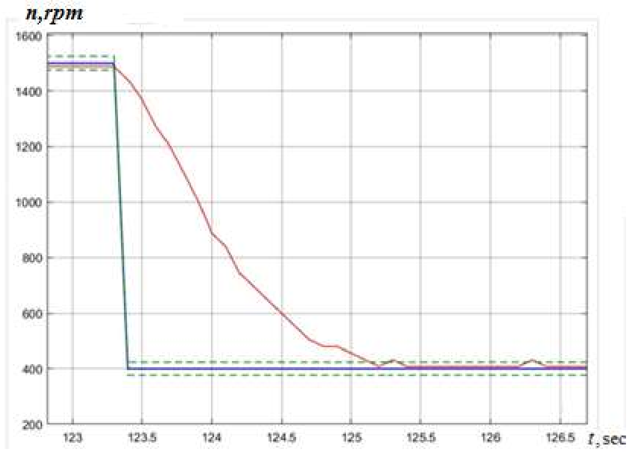

Figure 15. Response of the closed-loop controller with coeficients K_p = 0.001, K_i = 0.05

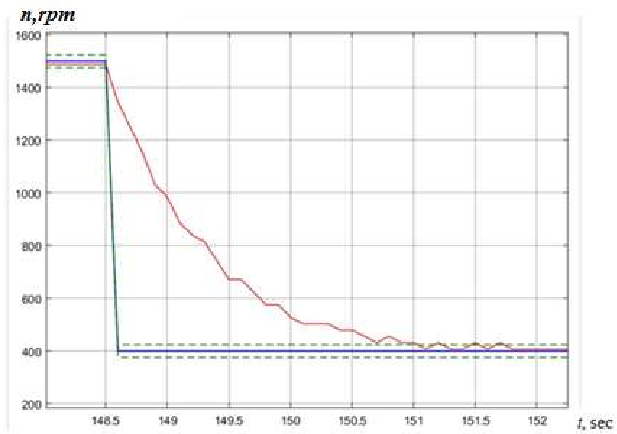

Figure 16. Response of the closed-loop controller with coeficients K_p = 0.01, K_i = 0.05

The response to perturbations of the closed-loop controller with coefficients K_p = 0.01, K_i = 0.1 is shown at the Fig. 17.

According to the obtained characteristics, it can be assumed that the use of a *PI* regulator in a closed-loop control system ensures its high-quality operation in both dynamic and static operating modes.

C. Programing closed-loop control system

As mentioned above, the closed-loop programing control software system provides a change in the controlled variable according to a sinusoidal law, and the created model allows to change a number of its parameters.

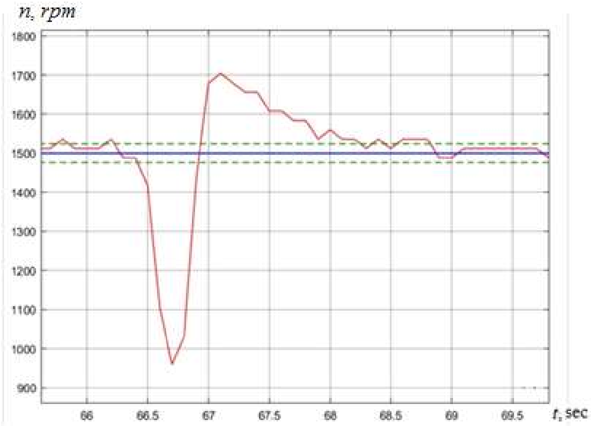

Figure 17. Response to disturbances of the closed-loop controller with coefficients $K_p = 0.01,\ K_i = 0.1$

The graph (Fig.18) shows the software control system operation at the specified parameters. Three sinusoids show the setpoint and permissible deviation limits of the controlled variable, and the curve in the form of a broken line shows the actual values of the controlled variable during the system operation. In this case, a *PI* controller was used. The controller parameters were set via the user interface.

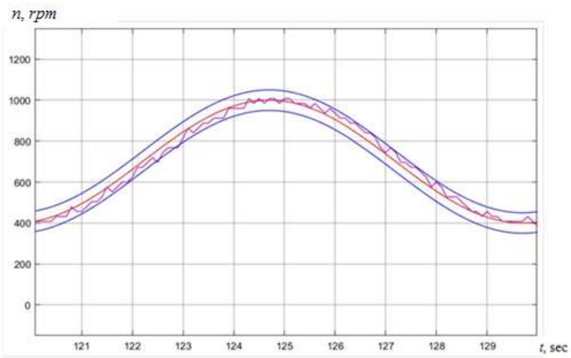

Figure 18. The closed-loop control system according to a sinusoidal law operation graph (coefficients $K_p = 0.01,\ K_i = 0.1$)

The graph (Fig.19) shows the schedule of the system response to the disturbances of the software control system. As can be seen from the figure, the controlled variable returns to the specified value after the disturbance action ends.

Based on experimental studies, it can be concluded that the software automatic control system satisfies the set conditions, namely:

- ensuring the necessary speed for timely response to a change in the control influence;
- returning the controlled value to the specified limits under the action of an external disturbance;
- deviation of the controlled value from the specified value within the specified error.

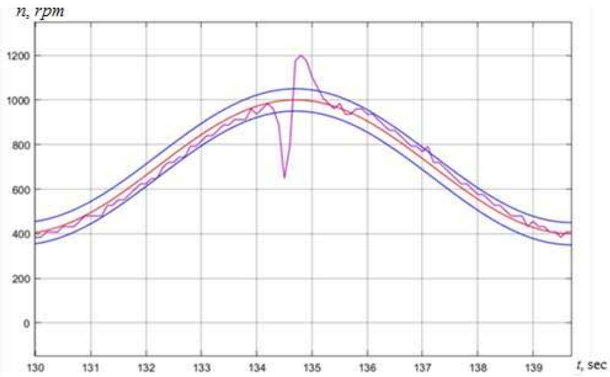

Figure 19. The closed-loop control system according to a sinusoidal law response to disturbances graph (coefficients $K_p = 0.01,\ K_i = 0.1$)

IV. CONCLUSIONS

The developed model:

- provides stabilization of the motor shaft rotation speed with a stationary error of 24 rpm;
- implements process control in the facility using open and closed signal transmission loops.
- implements software control system, in which the change in the controlled quantity occurs according to a sinusoidal law;

The error of the motor shaft rotation speed control system of 24 rpm is due to the accuracy of the optical tachogenerator, as well as the sampling step (sample time), which is equal to 0.1 second. To achieve better results in terms of error and sampling step, it is necessary to use more accurate, and in turn more expensive tachogenerators. However, even with such results of error and sampling step, it was possible to achieve qualitative characteristics of the system.

The hardware capabilities of the Arduino Mega development board allowed the successful development and debugging of the model. This is due to the peculiarities of the model's functioning in the "external mode", which allowed real-time monitoring of the state of all systems running on the controller. For convenient management of all parameters of the control systems implemented in the model, a user interface (GUI) was applied of GUIDE tools.

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