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STUDYING TRANSIENT CHARACTERISTICS OF ELECTRICAL CIRCUITS IN ROBOT DRIVES

The article deals with the issues of mathematical analysis, mathematical modeling, creating an analytical foundation for constructing hardware and algorithmic support for the drive device for launching aircraft by robots in order to determine the optimal choice of structure and parameters of the control loop. The article examines equivalent circuits for control loops in the form of RL circuits and RLC circuits. Mathematical modeling for the drive functioning is carried out by considering first- and second-order differential equations. The article determines the transient characteristics of control loops as a response to the supply of a single step function and estimates the time parameters for reaching a steady state mode when using P and PID controllers. The article adopts an equivalent circuit for a DC motor in the form of a series circuit of active resistance R and inductance L and uses typical ratings R and L of the motor and power source E in conjunction with regulator type. The article presents recommendations for choosing engine type for launching an aircraft and choosing regulator type.

Keywords: robotics, control, regulator, DC motor, RL circuit, RLC circuit, transient processes, transient response, aperiodic processes, oscillatory processes, mathematical model, mathematical modeling.

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ДОСЛІДЖЕННЯ ПЕРЕХІДНИХ ХАРАКТЕРИСТИК ЕЛЕКТРИЧНИХ КІЛ В ПРИВОДАХ РОБОТА

Розглянуті питання математичного аналізу, математичного моделювання, створення аналітичного обгрунтування для побудови апаратурного і алгоритмічного забезпечення пристрою приводу запуску літальних апаратів роботами, з метою визначення оптимального вибору структури і параметрів контура регулювання. Розглянуто схеми заміщення контурів управління у вигляді RL-кіл і RLC-кіл, здійснено математичне моделювання функціонування приводу шляхом розгляду диференційних рівнянь першого і другого порядків, визначені перехідні характеристики контурів управління як реакцію на подачу одиничної ступеневої функції, оцінені часові параметри виходу на сталий режим при використанні П і ПІД регуляторів. Прийнята схема заміщення двигуна постійного струму у вигляді послідовного кола активного опору R і індуктивності L, використані типові номінали R і L двигуна і джерела живлення E в сукупності з використовуваним типом регулятора. Представлені рекомендації для вибору типу двигуна привода запуску літальних апаратів і вибору типу регулятора.

Ключові слова: робототехніка, управління, регулятор, двигун постійного струму, RL-коло, RLC-коло, перехідні процеси, перехідна характеристика, аперіодичні процеси, коливальні процеси, математична модель, математичне моделювання.

Introduction. The relevance of using robots in the modern world is beyond doubt. Such robots are used in places that are either dangerous to humans or inaccessible to humans. In any case, the positioning accuracy and accuracy of the robot’s actions directly affect the efficiency of performing the tasks assigned to the robot.

The object of study was a robot used in robotics competitions. An image of this robot is shown in Fig. 1.

Considering that this device is used in robotics competitions, which are traditionally held in the United States and other countries around the world, similar devices are widely used in various industries, military and agriculture. Therefore, the importance of studying the presented object and the processes occurring in it is beyond doubt.

The presented robot contains seven DC motors and each of them is equipped with an individual drive (a gearbox system for transmitting rotations from the motor to the actuators):

- four wheel drive motors (one motor per wheel);
- two motors for the robotic arms;
- one engine for launching a drone (aircraft).

The study of transient processes in an object is based on the study of transient characteristics of electrical circuits in a robot. Transient characterization involves studying the behavior of electrical circuits when transitioning from one state to another, for example, when a robot motor starts, stops or changes direction [1].

To control DC motors, each motor drive contains a gearbox system and an electrical control system. P (proportional component), PI (proportional and integrating components), PID (proportional, integrating and differentiating components) regulators are used as regulators in control systems [2].

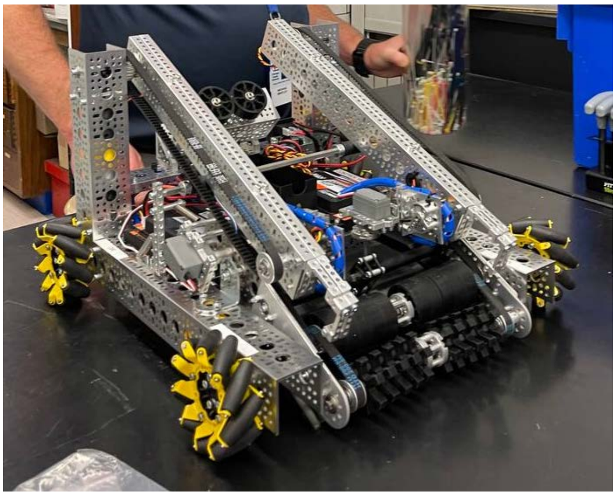

Fig. 1. Research object image – a robot

The research work analyzes the engine control system for launching a drone (aircraft). The operation of the drone launch drive is demonstrated in Fig. 2.

The final actuator element for the drone launch drive is two wheels, which eject the aircraft by counter-rotation. These two wheels acquire counter-rotation from a DC motor through a gearbox system.

Fig. 2. Drone launch drive operation

The actuating elements themselves, their look and design are presented in Fig. 3 and Fig. 4.

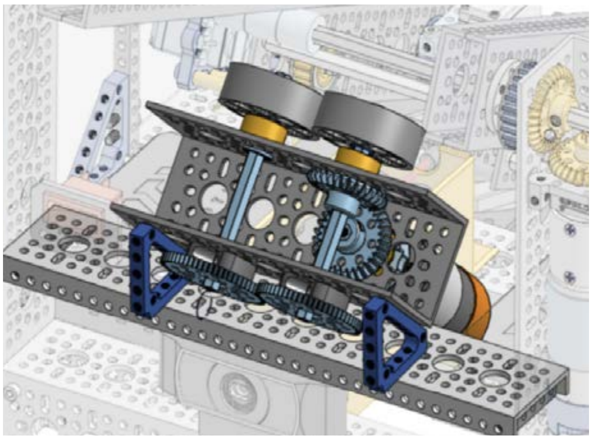

Fig. 3. Design of of the actuating elements

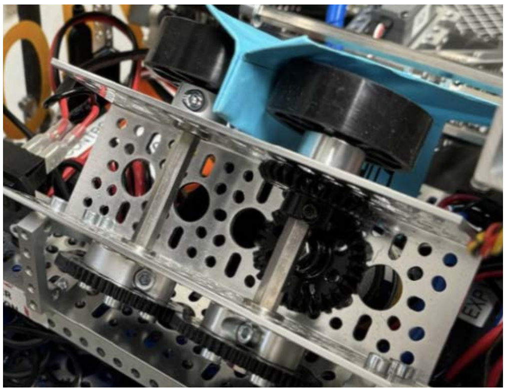

Fig. 4. Appearance of the actuating elements

Research purpose and methods. The control system is equipped with a P-regulator to fulfill the condition of maximum performance (minimum reaction time to start the engine and minimum time to reach a steady state).

A generalized block diagram of the object control channel is shown in Fig. 5 [2].

The scheme (Fig. 5) shows:

X – input signal;

Y – output signal;

R – regulator;

P – regulation object (DC motor).

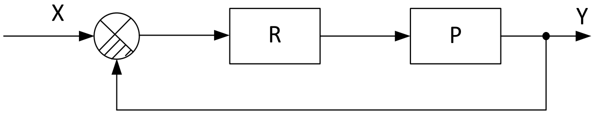

Fig. 5. Control channel block diagram

Parameters estimation of the electrical control circuit is possible through mathematical analysis and mathematical modeling. That would require replacing the real control circuit with a corresponding equivalent circuit. Only after this the mathematical apparatus can be used and data verification and conclusions can be made [3].

To analyze the parameters of the electrical circuit during transient processes in the drive of the drone launcher, an equivalent circuit of the electrical control circuit was used, which is shown in Fig. 6.

The equivalent circuit of the electrical control circuit was used (Fig. 6) to analyze the parameters of the electrical circuit during transient processes in the drive of the drone launcher.

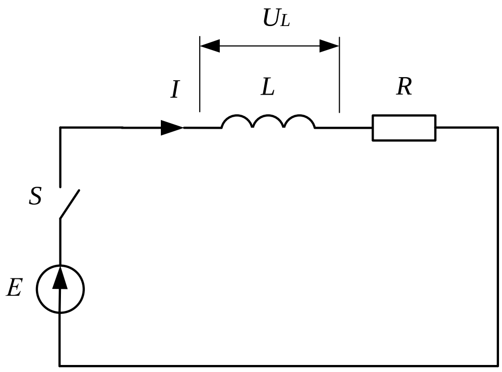

Fig. 6. Control scheme of equivalent circuit for the drone launching device drive

Fig. 6 illustrates the following symbols:

E – electrical power supply;

L, *R* – a DC motor equivalent circuit that includes a resistor *R* and an inductor *L*;

S – a key for supplying electrical voltage to the DC motor;

I, U_L – electric current in the electric circuit and electric voltage on element L of the electric circuit *RL*, respectively.

Fig. 6 shows the diagram where initial parameter values are determined:

$$E = 2.5\ \text{V};\ L = 0.2\ \text{H};\ R = 100\ \Omega.$$

The purpose of analytical research is to analyze the transient characteristics of electric current *I* and electric voltage U_L (Fig. 6) in the electric circuit *RL* after closing the key *S* and, accordingly, applying electric voltage *E* to the electrical circuit of the drive.

The classical method of transient processes is used as a research method, based on differential equations taking into account the laws of commutation. The transient characteristic is the time response of the electric current I parameters and electric voltage U after applying a unit step function $1(t)$ to the circuit input. A differential equation is an equation that can be used to describe any physical processes occurring in nature.

Analysis of transient processes in the control scheme of equivalent circuit for the drone launching device drive by a robot.

Using a first order differential equation. According to Kirchhoff's second law [4], the sum of the circuit voltages in Fig. 6 is equal to zero.

The voltage across the resistor is determined by Ohm's law [4]:

$$U_R = IR,$$

where I – value of electric current in the circuit;

U_R – value of the electrical voltage drop across the resistance R.

Inductor voltage [4]:

$$U_L = L\frac{dI}{dt},$$

where U_L – value of the electrical voltage drop across the inductor (V);

L – inductor inductance value (H);

t – time (sec).

Based on [5], the diagram presented in Fig. 6 can be described by a differential equation of the form:

$$L\frac{di}{dt} + iR = E, \quad (1)$$

where i – instantaneous value of electric current in a series circuit of a simplified equivalent circuit (Fig. 6).

Formula (1) describes the processes in the circuit in Fig. 6 and is basic for describing RL electrical circuits [6] and is a first-order linear inhomogeneous differential equation.

The authors analyze how electric current behaves when the power is turned on depending on the circuit parameters R and L. It requires solving the differential equation (1) with respect to the variable i. The solution to this equation, in general form, is the current, which has two components:

$$i = i_1 + i_2, \quad (2)$$

where i_1 – particular solution of a non-homogeneous differential equation. The physical meaning is the current value that is established after the end of transient processes;

i_2 – general solution of a homogeneous differential equation. The physical meaning is the change in current during a transient process.

To solve equation (1), the corresponding homogeneous equation is defined in the form:

$$L\frac{di}{dt} + iR = 0.$$

Hence

$$L\frac{di}{dt} = -iR.$$

After separating the variables, integrating and taking the logarithm of the resulting equation:

$$\frac{di}{dt} = -\frac{R}{L}dt \;\rightarrow\; \int\frac{di}{i} = -\frac{R}{L}\int dt \;\rightarrow\; \ln|i| = -\frac{R}{L}t + c\,,$$

we get an expression for the corresponding homogeneous equation.

To do this, we perform the transformations:

$$i(t) = e^{-\frac{R}{L}t + c} = e^{-\frac{R}{L}t}\cdot e^{c}.$$

Then we obtain the solution to the corresponding homogeneous equation in the form:

$$i(t) = c\cdot e^{-\frac{R}{L}t}.$$

Using the method of varying an arbitrary constant, we look for a solution to the corresponding inhomogeneous equation:

$$i(t) = c(t)\cdot e^{-\frac{R}{L}t}. \quad (3)$$

We perform a number of transformations:

$$\frac{di}{dt} = c'e^{-\frac{R}{L}t} - \frac{R}{L}A(t)e^{-\frac{R}{L}t},$$

$$Lc'e^{-\frac{R}{L}t} - Rce^{-\frac{R}{L}t} + cRAe^{-\frac{R}{L}t} = E.$$

Hence

$$\frac{dc}{dt} = \frac{E}{L}e^{\frac{R}{L}t},$$

$$c(t) = \frac{E}{L}\int e^{\frac{R}{L}t}dt = \frac{E}{L}\cdot\frac{L}{R}e^{\frac{R}{L}t} + A. \quad (4)$$

Substituting (4) into (3) we get:

$$i(t) = \left(\frac{E}{R}e^{\frac{R}{L}t} + A\right)e^{-\frac{R}{L}t} = \frac{E}{R} + Ae^{-\frac{R}{L}t}.$$

According to (2):

$$i_1 = \frac{E}{R},\; i_2 = Ae^{-\frac{R}{L}t}.$$

The final solution of equation (1), as the sum of the particular and general solutions (forced and free components), has the form:

$$i = \frac{E}{R} + Ae^{-\frac{R}{L}t}. \quad (5)$$

To determine the constant A of the free component in (5), it is necessary to use the initial conditions.

According to the first law of commutation [7]:

$$i(0-) = i(0+),$$

where $i(0–)$ – instantaneous value of the electric current in the electrical circuit (Fig. 6) immediately before the closure of the key S at some point in time t;

$i(0+)$ – instantaneous value of the electric current in the electrical circuit (Fig. 6) immediately after closing the key S at some point in time t.

Since before the closure of the key S (at $t = 0$) the electric current in the RL electrical circuit (Fig. 6) was absent, meaning it was equal to 0, then:

$$i(0-) = i(0+) = 0,$$

which means that immediately after closing the key S and, accordingly, turning on the drive motor of the drone launcher, the electric current in the RL electrical circuit is:

$$i(t) = 0.$$

Hence

$$i(0+) = \frac{E}{R} + A,$$

$$A = i(0+) - \frac{E}{R}.$$

Then expression (5) takes the following form:

$$i = \frac{E}{R} - \frac{E}{R} e^{-\frac{R}{L}t}. \qquad (6)$$

To obtain the value of the electric voltage on the inductor, we take the derivative of the electric current (6) and multiply by L:

$$u_L = L\frac{di}{dt} = L\frac{E}{R}\frac{R}{L} e^{-\frac{R}{L}t} = Ee^{-\frac{R}{L}t}. \qquad (7)$$

Expressions (6) and (7) characterize the instantaneous value of electric current i and electric voltage u_L in the RL circuit in general form. To determine the behavior of the variables i and u_L in the control scheme of the robot’s drone launching drive, it is necessary to substitute known parameters of the robot into expressions (6), (7).

Then expressions (6), (7) will take the form:

$$i = \frac{2.5}{100} - \frac{2.5}{100} \cdot e^{-\frac{100}{0.2}t} = 0.025\left(1 - e^{-500t}\right), \qquad (8)$$

$$u_L = 2.5 \cdot e^{-\frac{100}{0.2}t} = 2.5e^{-500t}. \qquad (9)$$

The transient process in electrical circuits is completed within five time constants τ [8]. For RL circuits, the time constant τ is defined as

$$\tau = \frac{L}{R} = \frac{0.2}{100} = 0.002 \text{ sec}.$$

Table 1 summarizes the data for i_L and u_L for real values of E, R, L of the control scheme circuit of the drone launcher drive for the time range [τ, 5τ].

According to the results of Table 1, the transient characteristics $i = f(t)$, $u_L = f(t)$ are made, which reflect the speed at which the control channel elements of the device drive under study reach the steady state of operation (Fig. 7, 8).

Table 1 – Calculation data by formulas (8), (9)

τ	1τ	2τ	3τ	4τ	5τ
t	0.002	0.004	0.006	0.008	0.01
u_L	0.920	0.338	0.124	0.046	0.017
i_L	0.016	0.022	0.024	0.025	0.025

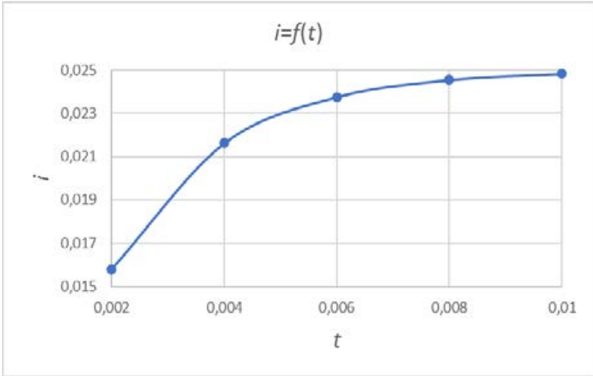

Fig. 7. Transient characteristic $i = f(t)$

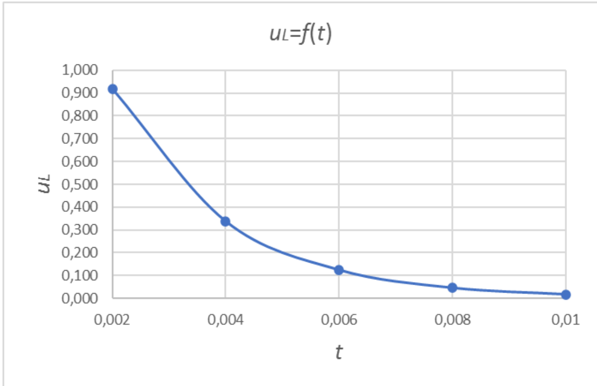

Fig. 8. Transient characteristic $u_L = f(t)$

Using a second order differential equation. In the equivalent circuit under consideration in Fig. 6, conditions were set for using the P-regulator and neglecting the presence of capacitance in the electrical circuit of the engine. However, taking into account the motor capacitance or using a PID controller will allow us to consider a more complex DC motor drive equivalent circuit. Such an equivalent circuit will have three electrical parameters – R, L, C.

The equivalent circuit taking into account capacitance C is shown in Fig. 9.

In the scheme:

$E = 2.5$ V; $L = 0.2$ H; $R = 100$ Ω; $C = 4 \cdot 10^{-6}$ F.

The equation that describes the circuit in Fig. 9 has the form [9]:

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt = E,$$

where L – value of inductor inductance (H);

C – capacitor value (F);

i – instantaneous value of electric current (A);
R – resistor value (Ω);
E – power supply voltage (V);
t – time (sec).

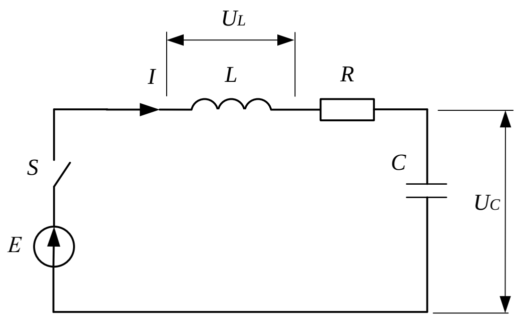

Fig. 9. Simplified equivalent circuit for the control scheme of the drone launching drive taking into account the capacitive component

In this equation:

$$i = C\frac{u_C}{dt}, \; u_C = \frac{1}{C}\int i dt,$$

where u_C – instantaneous value of the voltage drop across capacitor *C*.

We take the derivative with respect to *t* on the right and left sides of the equation. Hence

$$L\frac{d^2 i}{dt^2} + R\frac{di}{dt} + \frac{1}{C} = 0.$$

This is a second order differential equation that describes the equivalent circuit in Fig. 9. This equation is transformed by dividing the left and right sides by 1/*L*. Hence [10]:

$$\frac{d^2 i}{dt^2} + \frac{R}{L}\frac{di}{dt} + \frac{1}{LC} = 0. \qquad (10)$$

Based on (10), we form the characteristic equation:

$$p^2 + \frac{R}{L}p + \frac{1}{LC} = 0.$$

This equation is quadratic. We find its roots.
Discriminant:

$$D = \left(\frac{R}{L}\right)^2 - 4\frac{1}{LC}.$$

Roots:

$$p = \frac{-\frac{R}{L} \pm \sqrt{\left(\frac{R}{L}\right)^2 - 4\frac{1}{LC}}}{2} =$$

$$= -\frac{R}{2L} \pm \frac{1}{2}\sqrt{\left(\frac{R}{L}\right)^2 - \frac{4}{LC}} = -\frac{R}{2L} \pm \sqrt{\frac{1}{2^2}\left(\frac{R}{L}\right)^2 - \frac{1}{4}\frac{4}{LC}}.$$

$$p_{12} = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}.$$

The general solution to equation (10) is presented as:

$$i = A_1 e^{p_1 t} + A_2 e^{p_2 t}. \qquad (11)$$

A_1, A_2 are determined from the laws of commutation [7]:

$$\begin{cases} u_C(-0) = u_C(+0); \\ i_C(-0) = i_C(+0). \end{cases}$$

Hence

$$\begin{cases} A_1 + A_2 = E; \\ A_1 p_1 + A_2 p_2 = 0. \end{cases} \qquad (12)$$

Solving a system of equations (12):

$$A_1 = -A_2 - E,$$

$$(-A_2 - E)p_1 + A_2 p_2 = 0, \; -A_2 p_1 - Ep_1 + A_2 p_2 = 0,$$

$$-A_2(p_2 - p_1) = Ep_1, \; A_2 = \frac{Ep_1}{p_2 - p_1}.$$

$$A_1 = -\frac{Ep_1}{p_2 - p_1} - E.$$

$$A_1 = -\frac{Ep_1}{p_2 - p_1} - \frac{E(p_2 - p_1)}{p_2 - p_1} = \frac{-Ep_1 - Ep_2 + Ep_1}{p_2 - p_1} =$$

$$= -\frac{Ep_2}{p_2 - p_1}.$$

Thus:

$$A_1 = -\frac{Ep_2}{p_2 - p_1}, \; A_2 = \frac{Ep_1}{p_2 - p_1}.$$

Let us substitute the obtained data into (11) taking into account $p_1 p_2$, we obtain:

$$i = \frac{E}{L(p_1 = p_2)}e^{p_1 t} - \frac{E}{L(p_1 = p_2)}e^{p_2 t} =$$
$$= \frac{E}{L(p_1 = p_2)}\left(e^{p_1 t} - e^{p_2 t}\right) \qquad (13)$$

We find u_L, u_C.

$$u_L = \frac{di}{dt} = \frac{E}{p_1 - p_2}\left(p_1 e^{p_1 t} - p_2 e^{p_2 t}\right). \qquad (14)$$

$$u_C = \frac{1}{C}\int i dt = \frac{E}{LC(p_1 - p_2)}\int_0^t \left(e^{p_1 t} - e^{p_2 t}\right)dt + E.$$

$$u_C = \frac{E}{LC(p_1 - p_2)}\left(\frac{1}{p_1}e^{p_1 t}\Big|_0^t - \frac{1}{p_2}e^{p_2 t}\Big|_0^t\right) + E =$$

$$= \frac{E}{LC(p_1 - p_2)}\left(\frac{1}{p_1}e^{p_1 t} - \frac{1}{p_2}e^{p_2 t} - \frac{1}{p_1} + \frac{1}{p_2}\right) + E =$$

$$= \frac{E}{LC(p_1 - p_2)}\left(\frac{p_2 e^{p_1 t} - p_1 e^{p_2 t}}{p_1 p_2}\right) -$$

$$- \frac{E}{LC(p_1 - p_2)}\left(\frac{p_1 - p_2}{p_1 p_2}\right) + E .$$

Since $p_1 p_2 = 1/(LC)$ [11], then

$$u_C = \frac{E}{p_1 - p_2}\left(p_2 e^{p_1 t} - p_1 e^{p_2 t}\right) + E . \qquad (15)$$

In the equivalent circuit in Fig. 9 there are two possible options for transient characteristics:

- aperiodic (condition $R \geq 2\sqrt{\frac{L}{C}}$);

- oscillatory (condition $R < 2\sqrt{\frac{L}{C}}$).

Considering that for the case under consideration:

$R = 100$, $L = 0.2$, $C = 4 \cdot 10^{-6}$, then

$$100 < 2 \cdot \sqrt{\frac{0.2}{4 \cdot 10^{-6}}} \rightarrow 100 < 447.214.$$

Therefore, the transient response has an oscillatory character.

To form graphical dependencies $i = f(t)$, $u_L = f(t)$, $u_C = f(t)$ and further time analysis of transient processes in the diagram in Fig. 9, we present equations (13), (14), (15) in a more convenient form. To do this, we use the algebraic and trigonometric form of representing these equations.

To write equations (13), (14), (15) more compactly, we introduce the following symbols:

$$\omega_0 = \frac{1}{\sqrt{LC}}, \ \delta = \frac{R}{2L}, \ \omega = \sqrt{\frac{1}{\sqrt{LC}} - \frac{R^2}{4L}},$$

$$\beta = \operatorname{arctg}\frac{\frac{R}{2L}}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L}}} .$$

Then equations (13), (14), (15) can be represented as:

$$i = \frac{E}{\omega L} e^{-\delta t} \sin(\omega t), \qquad (16)$$

$$u_L = E\frac{\omega_0}{\omega} e^{-\delta t} \sin(\omega t + 90 + \beta), \qquad (17)$$

$$u_C = E\frac{\omega_0}{\omega} e^{-\delta t} \sin(\omega t - 90 - \beta). \qquad (18)$$

Let us determine the numerical parameters ω_0, δ, ω, β.

$$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.2 \cdot 4 \cdot 10^{-6}}} = 1118.034 ,$$

$$\delta = \frac{R}{2L} = \frac{100}{2 \cdot 0.2} = 250 ,$$

$$\omega = \sqrt{\frac{1}{\sqrt{LC}} - \frac{R^2}{4L}} = \sqrt{\frac{1}{0.2 \cdot 4 \cdot 10^{-6}} - \frac{100^2}{4 \cdot 0.2^2}} = 1089.725 ,$$

$$\beta = \operatorname{arctg}\frac{\frac{R}{2L}}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L}}} = \operatorname{arctg}\frac{\delta}{\omega} = \operatorname{arctg}\frac{250}{1089.725} = 12.898.$$

Finally, the equations for constructing graphs, in accordance with (16), (17), (18) have the form [12]:

$$i = \frac{E}{\omega L} e^{-\delta t} \sin(\omega t) = 0.011 e^{-250t} \sin(1089.725t) . \ (19)$$

$$u_L = E\frac{\omega_0}{\omega} e^{-\delta t} \sin(\omega t + 90 + \beta) =$$
$$= 2.565 e^{-250t} \sin(1089.725t + 102.898) . \qquad (20)$$

$$u_C = E\frac{\omega_0}{\omega} e^{-\delta t} \sin(\omega t - 90 - \beta) =$$
$$= 2.5 + 2.565 e^{-250t} \sin(1089.725t - 102.898). \qquad (21)$$

Based on equations (19), (20), (21), the Table 2 is filled out.

Table 2 – Calculation data by formulas (19), (20), (21)

t	0.002	0.004	0.006	0.008	0.01
i	0.005	–0.004	0.001	0.001	–0.001
u_L	–1.534	0.404	0.284	–0.346	0.135
u_C	2.210	3.361	2.009	2.523	2.664

According to the Table. 2 we build graphs that are transient characteristics.

According to the obtained graphs (Fig. 10–12) it is clear that the transient process, although with fluctuations, takes half as much time. And this is very important for increasing the speed of the robot's response to the launch command. Thus, it is obvious that the capacitance in the equivalent circuit of the robot drive as well as the use of a PID controller can reduce the robot's response time to the start command to 0.004–0.006 sec.

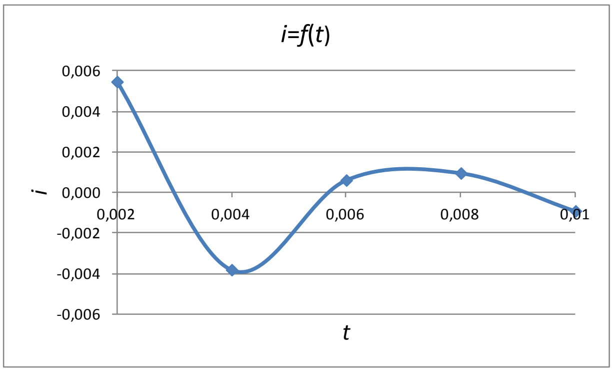

Fig. 10. Transient characteristic $i = f(t)$

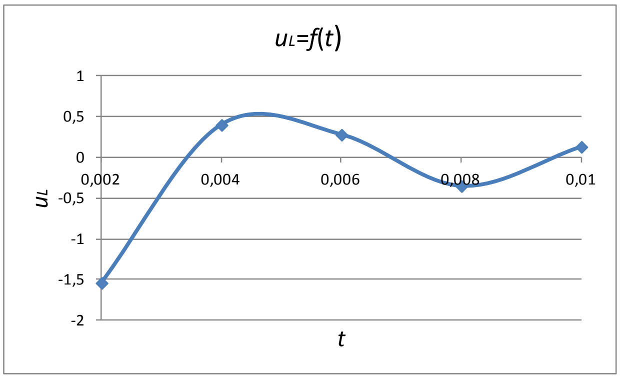

Fig. 11. Transient characteristic $u_L = f(t)$

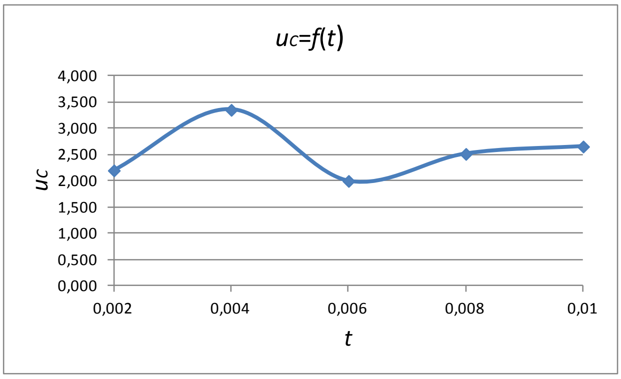

Fig. 12. Transient characteristic $u_C = f(t)$

Research results. The transient processes that occur in the electrical circuits in the control scheme of the robot's drone launching drive are analyzed in these studies. This drive is necessary to eject the drone (aircraft) at maximum speed. To do this, it is necessary to ensure the fastest possible transitions of the electric current *I* and electric voltage *U* in the DC motor, which is the executive element of the specified drive, to new steady-state values [13].

Considering that the drone (aircraft) is launched by pressing a button, it is equivalent to applying a single step function 1(*t*) to the input of the drive control circuit. The output characteristic of the drive control circuit is the transient characteristic; it is the response of the drive device to a single step function. For the successful functioning of the control scheme of the robot's drone launching drive, the transient characteristic must be as steep as possible, the transition to a new state must be minimal in time [14].

The transition from the initial state to the specified state in terms of electric current *I* and electric voltage *U* occurs in 0.01 seconds in the robot under study. Note that such a transition occurs along an aperiodic trajectory. Examining the obtained formulas (8) and (9) it is easy to see that an even steeper transient characteristic occurs with an increase in *R* or a decrease in *L* [15]. The implementation of this condition occurs due to correct selection of a DC motor (with the necessary parameters) in drone launching drive.

Another way to increase the transient characteristic for i_L and u_L i_L is to use PID controllers. In this case, capacitance *C* appears in the equivalent circuit of the drive electrical control circuit, which can lead to transition to a new steady-state value of the electric current *I* and electric voltage *U* along an oscillatory path. And such a trajectory can reduce the time of the transition process.

However, the presence of capacitance in an equivalent circuit leads to an increase in the order of the differential equation that describes such circuits. Considering and analyzing a second-order linear differential equation is much more difficult.

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