Simulation of the electric starter system of the internal combustion engine start-up to study the impact on its operation of the pre-start battery discharge

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Abstract.The article is devoted to the actual problem of starting an automobile engine in conditions of low negative temperatures. To increase the likelihood of starting the engine when using autonomous means of pre-heating, it is necessary to optimally distribute the battery energy to the pre-start and start-up discharges. As a part of the creation of a system, an automated pre-start thermal preparation of an automobile engine the need arises to conduct research on the influence of the battery starting-up discharges on the parameters characterizing the functioning of the electric starter system.
Research methods. A mathematical model of the electric starter system for starting the internal combustion engine is presented. The model is implemented using the software Mathcad 15.
Results. As a result of the simulation of the start-up system, the dependencies of the crankshaft rotation speed on time have been obtained for various values of battery discharge and temperature. According to the frequency of rotation of the crankshaft and the coefficient of dynamism of the battery discharge and the temperature of the electrolyte are also derived.
Findings. As a result of analyzing the data obtained in mathematical modelling it was determined that with decreasing electrolyte temperature the effect of the pre-discharge of the battery on the rotational speed of the crankshaft increases significantly. The ratio of the maximum rotational speed to the rotational speed of the crankshaft at the end of the start-up is almost independent of the degree of the battery discharge.

Keywords: starter battery, car engine start, electric starter start system, battery pre-start discharge, and volt-ampere characteristics

1. Introduction

In winter, in cold climates, the operation of road transport is significantly hampered; one of the main problems arising from this is the start of the cold engine [1, 2].

A large number of research papers by domestic and foreign researchers Roberts A., Brooks R., Shipway P., Lou D., Kan Z., Hu Z., Cao Z. [3, 4]. Indicate the relevance of the problem.

Studies on a similar topic were conducted by Ramadhas A.S., Xu H., the results were published in the scientific journal International Mobility Conference, SIIMC in the article "Influence of Coolant Temperature on Cold Start Performance of Diesel Passenger Car in Cold Environment". In the them authors analyze main factors affecting the success of the start of the diesel engine [5]. Alvaro Canto Michelotti, Jonny Carlos da Silva, in the scientific journal Journal of the Brazilian Society of

Mechanical Sciences and Engineering, well revealed the topic of modeling an electric starter system to start a car engine in dynamics, using models with lumped parameters [6].

The results of the study of the influence of low temperatures, the thermal state of the engine and the state of the battery on the operation of the electric starter system for starting automobile engines, in particular, are given in Hu Z., Xie Y., Kan Z., Lou D, Deng Y., Liu H., Zhao X., Jiaqiang E., Chen J. [7, 8].

Due to the increased requirements for minimum starting temperatures of internal combustion engines for vehicles operating in cold climates, these vehicles are often equipped with autonomous or non-autonomous means of facilitating cold engine starting [9, 10]. Starting aids have an effect on various engine systems and usually change their temperature state [11, 12]. Depending on the methods and tools used, conducting pre-thermal preparation allows reducing the moments of resistance to the movement of engine parts during start-up, increasing the energy capabilities of the starting system, improving the conditions for the formation and ignition of air-fuel mixtures [13].

Autonomous liquid pre-heaters have been widely used in the operation of vehicles. With their help, preheating of the engine is carried out, which helps to reduce the moment of resistance to cranking the crankshaft and leads to an increase in the frequency of its cranking during start-up. However, these devices for pre-starting thermal preparation of the engine for the period of their work consume the electric power of the rechargeable battery, and its pre-start discharge occurs, which affects the energy capabilities of the start-up system [13].

An option is possible when, after pre-warming the engine, the energy potential of the battery will be lower than that required for rotating the crankshaft with a frequency higher than the minimum starting frequency under these conditions. Repeated unsuccessful attempts to start the engine can lead to a deep discharge of the battery.

At present, maintenance-free batteries using lead-calcium alloys have become widespread. Along with the advantages [14, 15] of such batteries there is a serious drawback. After several deep discharges, the energy characteristics of such batteries deteriorate dramatically and irreversibly [13].

In this regard, there is a need for an automated control system for pre-start thermal preparation of the engine in an autonomous mode.

The main tasks of the proposed control system for pre-start heat treatment of the engine will be: optimal distribution of battery energy between the means of pre-start thermal preparation and the start-up system to ensure maximum probability of starting the engine at low negative temperatures and preventing deep discharge of the battery. Optimization of the energy distribution should be made taking into account the fact that, with an increase in energy consumption for pre-start thermal preparation of the engine, the energy costs for the subsequent start-up decrease, but the energy supply of the battery, which can be used to rotate the crankshaft, also decreases.

The search for the optimal variant of the energy distribution of the battery in the given conditions should be based on information on the viscosity-temperature characteristics of the engine oil, as well as on the characteristics of the friction pairs of a particular engine. As an objective function during optimization, it is advisable to choose the difference between the calculated crankshaft rotation speed and the minimum crankshaft rotation speed.

If in these conditions, as a result of searching for the optimal combination of battery energy distribution with all combinations of variable parameters, the objective function remains negative, then this indicates a low probability of starting the engine under these conditions and the need to use additional external energy sources to carry out pre-start thermal preparation of the engine and battery.

2. Formulation of the problem

To create the proposed automated control system for pre-start thermal preparation of the engine, it is necessary to conduct studies of the effect of prestart discharges of a starter battery of varying intensity in different conditions on the parameters characterizing the operation of the electric starting system of the automobile engine. To carry out such research, it is necessary to develop a mathematical model of the electric starting system of the automobile engine suitable for achieving the set goal. The level of complexity of the model should provide the opportunity to study the process of scrolling the crankshaft during engine start-up and taking into account the dynamic properties of the battery.

3. Theory

Electric starting system of the internal combustion engine provides a forced rotation of the engine crankshaft at the required speed. The main elements of this start-up system are: a chemical current source - a rechargeable battery, an electric starter and a gearbox of a drive mechanism [16].

An autonomous source of energy in electric starting systems for internal combustion engines is a starter lead-acid rechargeable battery. The block diagram of the battery in the discharge mode as an object of study is shown in Fig. 1. Input parameters – x are: load resistance – R_l ; load connection duration – t. The internal parameters of the object of the study are – z: ohmic resistance - R_o; polarization resistance – R_p; equilibrium EMF – E; discharge capacity – C_d; energy storage – W_e; electrolyte density – ρ; T_{el} – electrolyte temperature; degree of discharge – ΔD_b; the time constant of the EMF of polarization is τ. The parameter of the impact of external factors - w is the ambient temperature – T_a. Output parameters – y are: discharge voltage – U_v ; discharge current – I_c; the power developed by the battery in the external circuit – P_b.

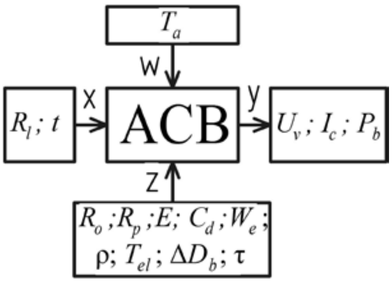

Figure 1. Block diagram of the storage battery as an object of study

For the starter discharge mode of the battery, the characteristic connecting the battery with the operating characteristics of the electric starter motor is the volt-ampere characteristic [16]. Also, the time response has a significant effect on the electric starter process.

Volt-ampere characteristic of the battery depends on a large number of factors and can be obtained experimentally or presented as an analytical dependence. Usually, when calculating the electric start-up system, the current – voltage characteristic is represented as a straight line, cutting off the coordinate axes of the segments proportional to the initial discharge voltage – U_{dv} short-circuit current – I_+ per one positive plate, which allows analyzing the volt-ampere characteristics of batteries of different capacity. Volt-ampere characteristic is represented in the form of equations [17]:

$$U_v = m\,(2.02 + 0.00136\,T_{el} - 0.001\,\Delta D_b)(1 - \frac{I_c}{I_+ n_+}) \tag{1}$$

where m is the number of batteries in the battery;
n_+ number of positive electrodes in the battery

$$I_+ = a + bT_{el} - C\Delta D_b - d(z_n - 1) - e(t_n - 10)(z_n - 1). \tag{2}$$

where a, b, C, d, e, are coefficients;
z_n – the number of attempts to start;
t_n – the duration of the attempt to start, p.

The analytical dependences (1), (2) expressing the volt-ampere characteristic do not take into account the presence of a transient polarization process during discharge.

When creating engine starting systems, the method of calculating the current-voltage characteristics during discharge is applied, taking into account the design features of the battery, as well as the phenomenon of polarization during discharge [18]. The basic equation for determining the voltage is:

$$U_v = 0.125\,[E - E_P(1-e^{-0.5t}) - I_c R_o]\cdot\left\{\frac{\ln\left[\left(15-\frac{250}{t_k}\right)\cdot\left(1-\frac{t}{t_k}\right)+1\right]}{\ln\left(4-\frac{50}{t_k}\right)}+6\right\} \tag{3}$$

where E_p is the polarization potential, V;
t is the duration of the discharge, with
t_k is the permissible duration of discharge by the starter mode current, p.

Variables entering into equation (3) can be conveniently viewed as functional:

$$E = f(\rho, \Delta D_b). \tag{4}$$
$$E_n = f(T_{el}, I_c). \tag{5}$$
$$R_o = f(\rho, T_{el}, \Delta D_b). \tag{6}$$
$$t_k = f(I_c, T_{el}, \Delta D_b). \tag{7}$$

Wherein

$$E_p = R_p I_c \tag{8}$$

The polarization resistance is non-linear; it can be represented as a functional $R_p = f(I_c, T_{el})$.

Pre-starting discharge of a battery to start-up devices is usually carried out by relatively small currents – (0.03-0.2)C_{20}. The degree of discharge of the battery after the pre-discharge can be calculated by the formula:

$$\Delta D_{b2} = \Delta D_{b1} + \left(\frac{\int_0^t I_c(t)dt}{C_{20}}\right)\cdot 100\% \tag{9}$$

where ΔD_{b1} - the initial degree of discharge of the battery, %;
ΔD_{b2} - the degree of discharge of the battery after pre-discharge by current I p (t) during time t,%.
C_{20} - rated battery capacity, A·h.

The electric starter includes a starter electric motor, a traction relay and a drive mechanism. As a starter motor used DC motors with sequential, mixed or independent excitation from permanent magnets [16]. The block diagram of a starter motor with sequential excitation as an object of study is shown in figure 2.

Input parameters – x are: voltage – U_v; armature current – I_a; power input – P_i. The internal parameters of the object of study – z are: the resistance of the armature winding – R_a; excitation winding resistance – R_c; starter network resistance – R_{sn}; voltage drop in the brush-collector contacts – ΔU_b; electric machine constants - C_e, C_m; winding temperature – T_w; magnet ic flux passing through the air gap and the anchor – Φ; back anchors' EMF – E_a; Motor efficiency – η_{st}; electromagnetic moment – M_{em}; electromagnetic power – P_{em}. The parameter of the impact of external factors - w is the ambient temperature – T_a. Output parameters – y are: armature rotation frequency – n_a; effective torque on the motor shaft – M_s; effective power – P_s.

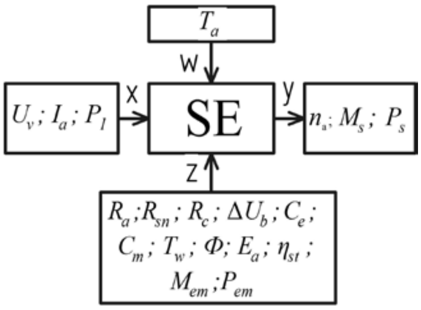

Figure 2. Structural diagram of the starter motor as an object of study

The back EMF of the armature and the electromagnetic moment are calculated by the formulas [16]:

$$E_n = C_e n_a \Phi \,, \tag{10}$$

$$M_{em} = C_m I_a \Phi \tag{11}$$

The voltage applied to the motor from the power source [16]:

$$U_v = E_a + I_a(R_a + R_{sn} + R_c) + \Delta U_b \tag{12}$$

In electric motors with sequential excitation, the magnetic flux of the motor Φ is a certain function of the armature current $\Phi = f(I_a)$. The nature of this function is determined by the load on the engine. There are nonlinear and almost linear portions of the function [16]; in the case of experimental determination of the dependence of the magnetic flux on the armature current, these fractions can be approximated separately. The nonlinear segment with an acceptable accuracy is approximated by a third-order polynomial, the linear segment, respectively, by a linear approximation.

$$\Phi = \begin{cases} (kI_a + w), & I_a > (0.8...0.9)I_n \\ aI_a^3 + bI_a^2 + cI_a + d, & I_a \le (0.8...0.9)I_n \end{cases} \tag{13}$$

Where a, b, c, d, k, w - coefficients;
I_n - is the rated armature current.

When calculating electric starter start systems, the average moment of resistance and the average rotational speed of the crankshaft are used for the calculation. There are a large number of empirical expressions relating the moment of resistance, viscosity of engine oil and the frequency of rotation of the crankshaft. The average moment of resistance is determined by [19]:

$$M_e = 0.795 \cdot V_h \cdot \left(0.24 + 0.033 \frac{n_e}{100}\right) \cdot \nu^{0.37} \,. \tag{14}$$

Where V_h - engine capacity;
n_e - engine crankshaft rotation speed, min-^{1};
ν is the viscosity of engine oil;

Dependence of kinematic viscosity of engine oil on temperature $\nu = f(T)$ in the temperature range T = 233…293 K with sufficient accuracy can be approximated by a fourth-order polynomial [19]:

$$\nu = aT^4 + bT^3 + cT^2 + gT + k. \tag{15}$$

The block diagram of an internal combustion engine together with a reducer in the mode of forced rotation of a crankshaft as an object of study is shown in figure 3. Input parameters – x are: effective torque on the motor shaft – M_s; anchor rotation frequency – n_e; useful power of the starter motor – P_s; crankshaft cranking duration – t. The internal parameters of the object of study – z are: gear ratio – i; Gearbox efficiency – η_z; engine oil viscosity – ν; working volume – V_h; moment of inertia of moving parts – J_e. The parameter of the impact of external factors – w is the ambient temperature – T_a. The output parameters – y are: engine crankshaft rotational speed – n_e; crankshaft scrolling resistance moment – M_e; the power absorbed by the engine during the forced rotation of the crankshaft – P_e.

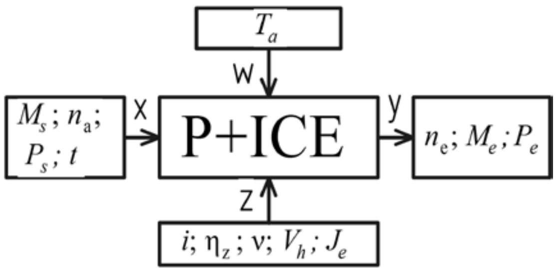

Figure 3. Structural diagram of the internal combustion engine together with the gearbox in the mode of forced rotation of the crankshaft as an object of study

The block diagram of the electric starter system of the internal combustion engine is shown in figure 4.

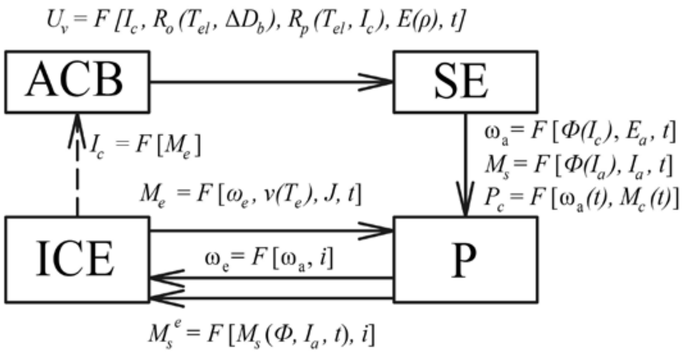

Figure 4. Structural diagram of the electric starter start system of the internal combustion engine

The equation of equilibrium moments during rotation of the engine crankshaft by an electric starter has the form [16]

$$M_s^e = M_e + J\frac{d\omega_e}{dt}, \tag{16}$$

Where M_s^e is the starter moment, reduced to the engine taking into account the gear ratio and the efficiency of the gearbox, n · m;

J is the m-oment of inertia of rotating and progressively moving masses of the “electric starter – engine” system, reduced to the engine crankshaft, kg·m^2;

ω_e is the angular velocity of rotation of the crankshaft, c^{-1}.

The mathematical model of the electric starting system was implemented using the Mathcad 15 software product. As an example for modelling an electric starter starting system for a D-245 diesel engine was used consisting of the electric starter ST142B, a low-maintenance rechargeable battery with a nominal capacity of C_{20} = 190 A·h with a rated voltage of U = 24 V with calcium conductors. The viscosity-temperature characteristic of engine oil $\nu = f(T)$ was adopted for SAE 5W30 oil. The duration of the start-up attempt for a diesel engine according to the normative literature is t_n = 15 s.

The parameters characterizing the operation of the electric start system were taken at the end of the start attempt – n_{15} and the start dynamic factor - K_d, which allows estimating the intensity of the reduction in rotation frequency during the engine start. The equation of equilibrium moments during rotation of the engine crankshaft by an electric starter has the form.

$$K_d = \frac{n_{\max}}{n_{15}}. \tag{17}$$

Where n_{max} is the maximum rotational speed of the crankshaft during start-up, min^{-1} .

4. Results of experiments

The results of the engine cranking simulation when starting from an electric starter are shown in the form of graphs of the engine crankshaft speed versus time with varying degrees of battery discharge and electrolyte temperature shown in figure 5.

From the presented graphical dependences it is seen that at the beginning of the start-up there is an intensive increase in the rotational speed of the crankshaft up to n_{max}, and then with the scrolling a gradual decrease in the rotational speed occurs. The decrease in the frequency of the crankshaft rotation during start-up can be explained by the presence of a transient polarization process, as well as an increase in the internal resistance of the battery due to intense passivation of the electrodes during starter discharge [16]. When the electrolyte temperature is T_{el} = 233 K and the degree of discharge ΔD_b = 40% when cranking the crankshaft, the discharge voltage of the battery drops below the allowable value, therefore the dependence $n_e = f(\Delta C_d, t)$ was not determined at this temperature.

Figure 6 shows the graphs of the crankshaft rotation frequency and the start-up dynamic coefficient versus the electrolyte temperature and the degree of the battery discharge.

5. Discussion the results of the investigation

As a result of the analysis of the obtained data, it was found that with a decrease in the electrolyte temperature, the effect of the pre-discharge of the battery on the rotational speed of the crankshaft increases significantly. The coefficient of dynamic start-up increases with decreasing electrolyte temperature and practically does not depend on the degree of discharge of the battery at the temperature of the electrolyte T_{el} > 243 K.

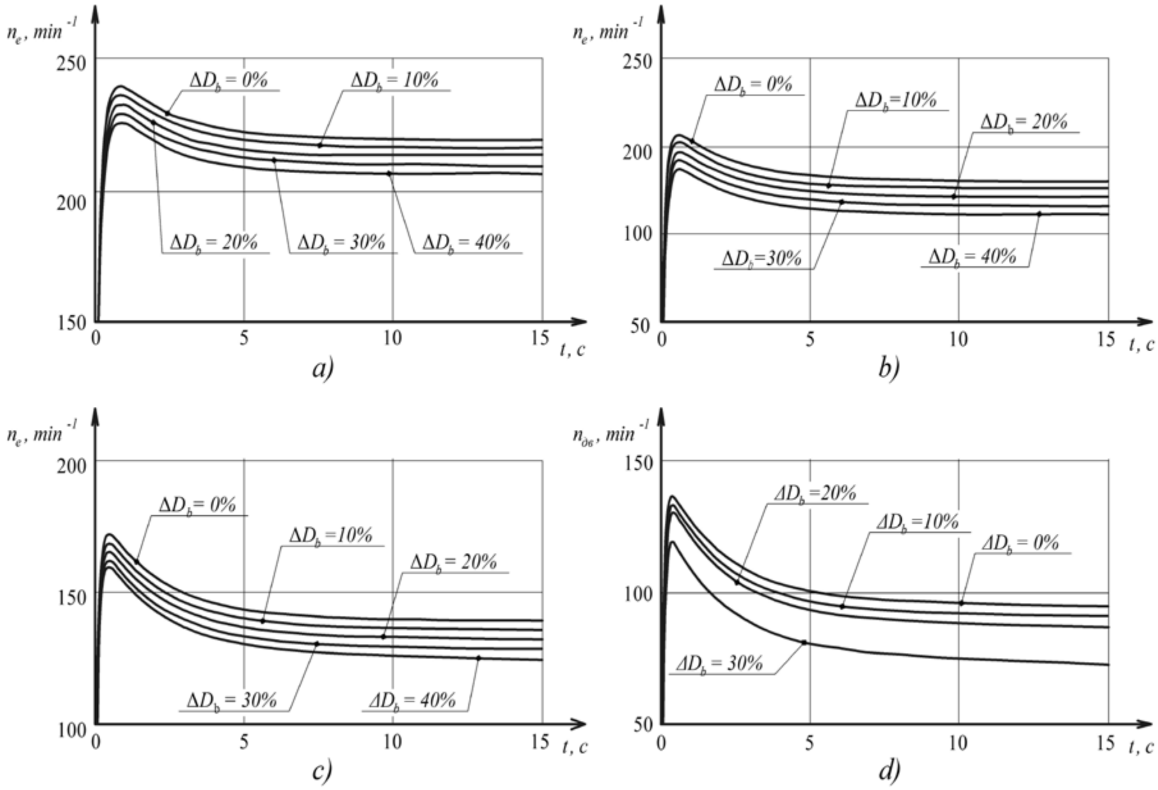

Figure 5. Graphs of the crankshaft rotational speed versus time with varying degrees of battery discharge
a) T_{el} = 263 K, b) T_{el} = 253 K, c) T_{el} = 243 K, d) T_{el} = 233 K

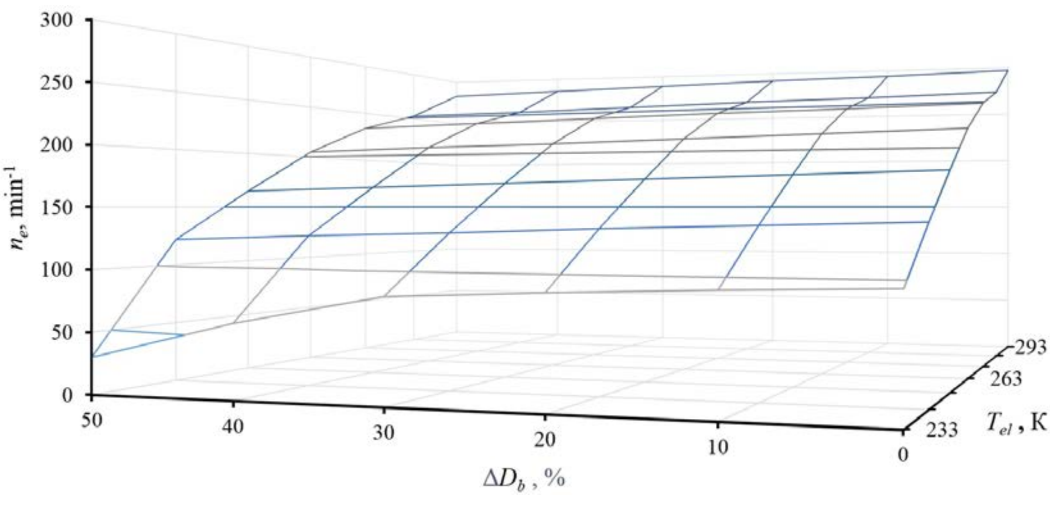

Figure 6. Dependence of the crankshaft rotation frequency on the degree of the battery discharge - ΔD_b and electrolyte temperature – T_{el}

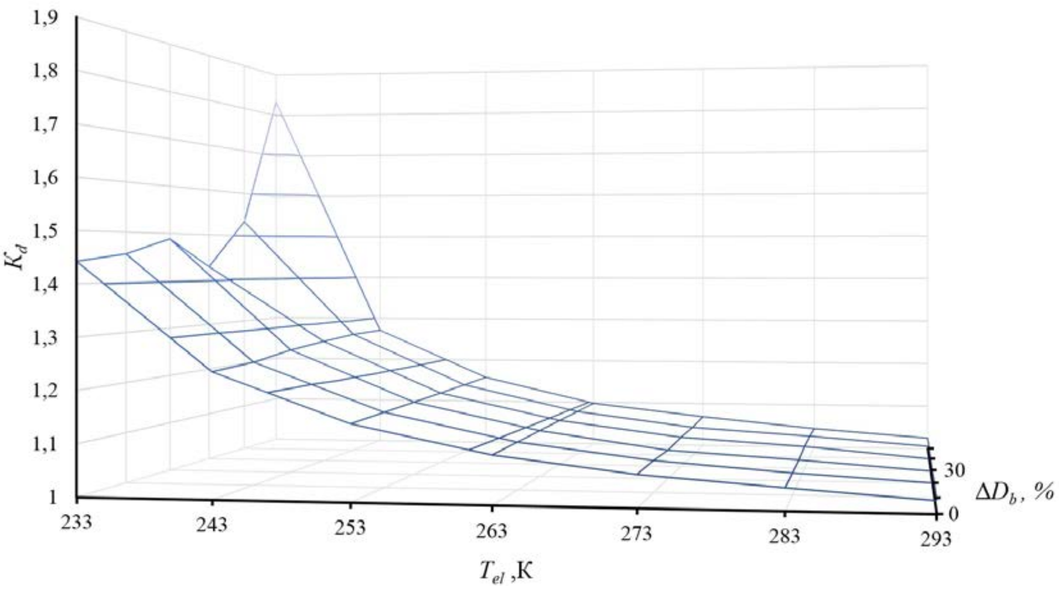

Figure 7. A graph of the dependence of the dynamic start-up K_d on the degree of discharge crankshaft on the degree of discharge – ΔD_b battery and electrolyte temperature – T_{el}

6 Conclusions and resumes

To study the effect of starting-up discharges of a starter battery on the parameters characterizing the operation of an electric starter system for starting an internal combustion engine, a mathematical model was developed that takes into account the dynamics of a starter electric drive, as well as transient polarization processes when a battery is discharged. As a result of mathematical modelling, the dependencies of the engine's rotational speed on time with varying degrees of battery discharge and electrolyte temperature, the dependence of the crankshaft speed and starting coefficient on the electrolyte temperature and degree of discharge are obtained. The obtained information will be used to create an automated control system for pre-thermal preparation of an internal combustion engine.

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