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ENERGY EFFICIENT START MODES OF TRACTION ELECTRICAL SYSTEMS OF MINE ELECTRIC LOCOMOTIVES

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Purpose. Research of the energy consumption process observed in TEM in the starting mode and development the optimum way of control are the relevant task. **Methodology.** mathematical modeling, analytical research, analysis, synthesis. **Findings.** The question of power losses reducing in direct current traction electric motors in mine electric locomotives was considered. The comparative analysis of the methods of traction motors connecting at the electric start of electric locomotive was conducted. The results of starting modes modeling of traction electric motors with serial and serial-parallel connection were showed. The feasibility of a series-parallel connection of the electric locomotive traction motors at the start in terms of power consumption was proved. It is shown that this connection method results in lower cost and in engines power loss. The results of calculation of energy loss in electric locomotive engines at different ways of connection and different forms of voltage changes are diven. **Originality**. The laws of optimum voltage change of direct current electric traction motors were adapted to mine electric locomotive operation conditions. **Practical value**. The optimization scheme of functioning modes of the direct current mine locomotive traction electric motor was conceived. **Conclusions.** The series-connected traction engines are accompanied by more (by 17-27 %) energy losses than connected in series-parallel mode. The way of voltage changes of TEM affects the level of energy losses at the motor start. Smooth start results in half of energy loss of the direct start.

Key words: electric motor, electric locomotive, the energy loss, start, optimum parameters.

ЕНЕРГОЕФЕКТИВНІ РЕЖИМИ ПУСКУ ТЯГОВИХ ЕЛЕКТРОТЕХНІЧНИХ КОМПЛЕКСІВ РУДНИЧНИХ КОНТАКТНИХ ЕЛЕКТРОВОЗІВ

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Розглянуто питання зниження втрат електричної енергії в тягових електричних двигунах постійного струму рудничних контактних електровозів у пускових режимах. Проведено порівняльний аналіз способів з’єднання тягових електричних двигунів під час пуску електровоза. Наведено результати моделювання пускових режимів тягових електричних двигунів при послідовному та послідовно-паралельному з’єднанні. Доведено доцільність послідовно-паралельного з’єднання тягових двигунів під час пуску електровоза з точки зору обсягів витрат електричної енергії. Представлені закони оптимальної зміни напруги живлення тягового електричного двигуна постійного струму послідовного збудження рудничного транспортного засобу. Запропоновано схему оптимізації режимів функціонування тягового електричного приводу постійного струму рудничного електровоза.

Ключові слова: електричний двигун, електровоз, енергія, втрати, пуск, оптимальні параметри.

PROBLEM STATEMENT. In modern conditions of rapid technological development in various areas of industrial production an electric motor control system based on semiconductor modules is used. The use of them improves the control quality of technological equipment, reduces power consumption and helps to increase energy efficiency and reliability of technology.

The issue of energy efficiency is particularly relevant for mining enterprises of Ukraine. This is due to the fact that the electricity consumption makes about 25% of the cost of the finished product and has a tendency to increase. Most of the consumed energy accounts for on the traction rolling stock, for traction engines [1].

A characteristic difference of regimes of traction electric motors (TEM) functioning of the mine electric motors is a large number of transients during the working cycle [2]. As is known, these regimes significantly affect the energy consumption in electric machines. That is why minimization of the energy consumption in a starting mode of traction electric motors (TEM) by the development of the optimum ways to manage a traction electric motor of mine electric locomotives is an important task [2, 3].

Therefore, research of the processes of energy consumption by TEM in the starting mode and development of the optimum way of control is a relevant task.

EXPERIMENTAL PART AND RESULTS OBTAINED. Direct current traction electric motors with series excitation are used as biaxial electric mine locomotives. In studies presented in [3, 4] it was found that more than 60% of time TEM work in the unsteady transition processes conditions, and uncontrolled thermal processes are the main cause of their failure [5]. Furthermore, the heating of coils changes their resistance that leads to increase of power losses. The fact that during the start of TEM power loss reaches significant quantities is well-known. In order to minimize energy losses in starting modes different schemes of TEM connection are used. The most effective among the known is a scheme of switching TEM from the serial connection in the first half of start, to the parallel – in the second [6, 7].

Series-parallel start compared with single-stage provides significant energy savings and, in addition, allows to get two economic speeds of locomotive depending on serial or parallel connection of the engine running while driving. So switching the TEM from sequential to parallel connection is an effective way to manage it without any additional energy loss.

The work of direct current traction rolling stock with series connection of TEM is described by the system of equations of the form:

$$\begin{cases} U_r = \omega\left(k\Phi_1 + k\Phi_2\right) + I_r R_\Sigma + L_\Sigma \dfrac{dI_r}{dt} \\ J\dfrac{d\omega}{dt} = k\Phi_1 I_r - M_{r1} \\ J\dfrac{d\omega}{dt} = k\Phi_2 I_r - M_{r2} \\ k\Phi = f(I_r) \end{cases}, \qquad (1)$$

where $R_\Sigma = R_{r1} + R_{e.c.1} + R_{r2} + R_{e.c.2}$ – active resistance of armature winding and excitation of circuit with series-connected TEM; $L_\Sigma = L_{r1} + L_{e.c.1} + L_{r2} + L_{e.c.2}$ – inductance of armature winding and excitement; U_r – supply voltage; I_r – a current of chain of armature engine; $k\Phi_1$, $k\Phi_2$ – flow coefficients of TEM; $M_{r1,}M_{r2}$ – electromagnetic resistance moments of engines; J – the inertia moment of TEM.

Given the fact that TEM work with the hard mechanical connection their rotational speeds are similar and defined according expression:

$$\omega = \frac{U_r - I_{r1}R_1}{k\Phi_1} = \frac{U_r - I_{r2}R_2}{k\Phi_2}.$$

Parallel connection of motors is described by the equation:

$$\begin{cases} U_{r1} = \omega k\Phi_1 + I_{r1}\left(R_{r1} + R_{e.c.1}\right) + \left(L_{r1} + L_{e.c.1}\right)\dfrac{dI_{r1}}{dt} \\ U_{r2} = \omega k\Phi_2 + I_{r2}\left(R_{r2} + R_{e.c.2}\right) + \left(L_{r2} + L_{e.c.2}\right)\dfrac{dI_{r2}}{dt} \\ J\dfrac{d\omega}{dt} = k\Phi_1 I_{r1} - M_{r1} \\ J\dfrac{d\omega}{dt} = k\Phi_2 I_{r2} - M_{r2} \\ k\Phi = f(I_r) \end{cases} .(2)$$

Analyzing the ways to connect TEM, it should be noted that the series connection of engines provides high inductance and, therefore, the better work at low speeds. Reduction of inductance is achieved in parallel connection but at the same time it results in the increase torque at high speeds [6].

For serial connection of engines the expressions are valid [7]:

$$L_\Sigma \frac{dI_r}{dt} = U_r - I_r R_\Sigma - \omega\left(k\Phi_1 + k\Phi_2\right), \qquad (3)$$

$$J_\Sigma \frac{d\omega}{dt} = I_r\left(k\Phi_1 + k\Phi_2\right) - M_r, \qquad (4)$$

where J_Σ – the total inertia moment of the electric drive which includes the inertia moment of trolleys; for parallel:

$$L_1 \frac{dI_{r1}}{dt} = 0{,}5U_r - I_{r1}(R_{r1} + R_{e.c.1}) - \omega k\Phi_1, \qquad (5)$$

$$L_2 \frac{dI_{r2}}{dt} = 0{,}5U_r - I_{r2}(R_{r2} + R_{e.c.2}) - \omega k\Phi_2, \qquad (6)$$

$$J_\Sigma \frac{d\omega}{dt} = I_r\left(k\Phi_1 + k\Phi_2\right) - M_r. \qquad (7)$$

Thus, the series connection of engines in the first half of start, and the parallel in the second are more efficient than just series or parallel that provides lower power losses. The total inertia moment of electric drive given to the motor shaft depends on the electric locomotive load. Based on the requirements of sustainability of kinetic energy the expression for calculating the moment of inertia reduced to the motor shaft of the mine electric locomotive with the trolleys is written as:

$$J_\Sigma = \frac{\left[M_{el} + N \cdot M_e \cdot \alpha \cdot N \cdot M_l\right] \cdot v_n^2}{\omega_n^2}, \qquad (8)$$

where M_{el}, M_e, $M_в$ – weight of empty trolley and load; N – the number of trolleys; ω_n^2 – nominal angular velocity of the shaft of TEM; v_n^2 – linear electric locomotive speed at nominal angular velocity of the motor shaft; α – trolleys load factor.

For mine electric locomotives K14 inertia moment reduced to the motor shaft varies from 12,26 N·м at the empty trolleys, to 44,5 N·м at their maximum load.

Among the known electric circuits of the traction systems the possibility to change the circuit connection in engine in the starting mode is available in circuits of dual electrotechnical complex (Fig. 1). The scheme feature is the minimum number of semiconductor devices that affects the overall energy loss [8]. But despite the high energy efficiency of the scheme compared to other technical solutions schemes the optimization of starting modes remain relevant. Therefore, the study of energy losses during the TEM start was conducted on the basis of the scheme.

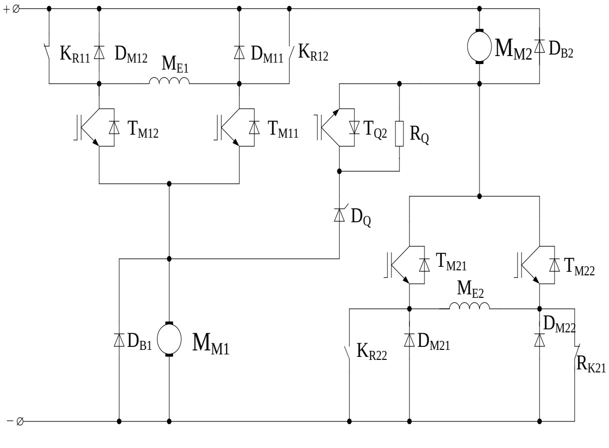

Figure 1 – Diagram of the dual traction electrical complex with the pulse converters

Simulation of starting modes was conducted using application package MatLab. The model is prepared in accordance with equations (1)–(2) and contains two direct current traction motors of series excitation DTN45/27, two IGBT module of MDTKI-200-06 type, two diode of DChL 233-200 type, 250 V power supply which allows to form different shapes of voltage supply (Fig. 2). The switch from sequential to parallel connection of the engines at a time when the rate of acceleration engine reaches half of the nominal was implemented in the model. Determination of power losses at start was realized using the expression:

$$\Delta E=\int_{0}^{t} I_r^{2}\cdot R dt\,. \tag{9}$$

Research was conducted for the conditions of direct (Signal 1, Fig. 2) and the smooth start with the various forms of voltage changes (Signal 2, 3, 4).

The simulation results (Fig. 3-6) showed that the lowest energy losses occurred at a smooth increase of TEM voltage (in the fourth mode), the largest – in direct start. With a smooth start the losses are two times less than in direct start. Comparing the last two modes it should be noted that the rapid increase of TEM voltage leads to greater energy losses compared to the smooth.

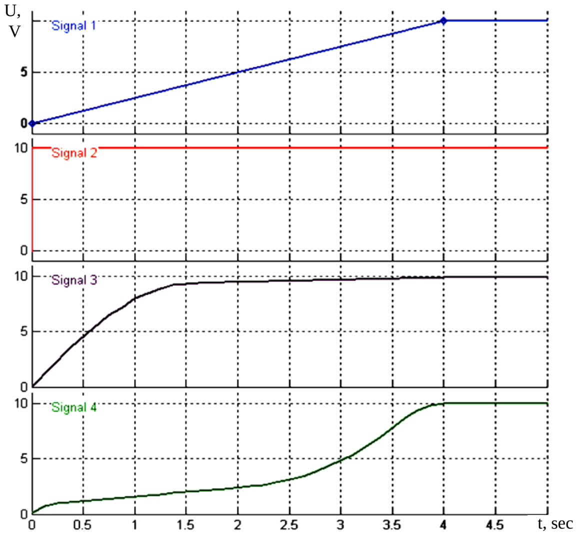

Figure 2 – Input signals that are given to the pulse converter

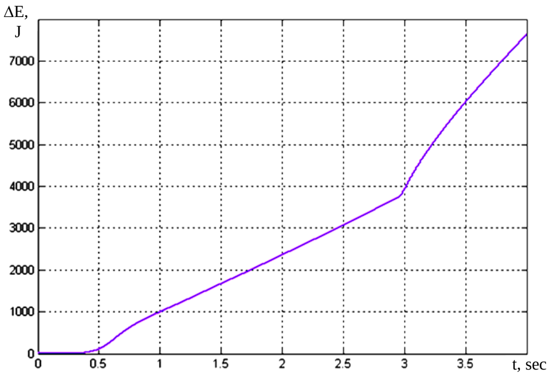

Figure 3 – Loss of electric power during acceleration mode at first start

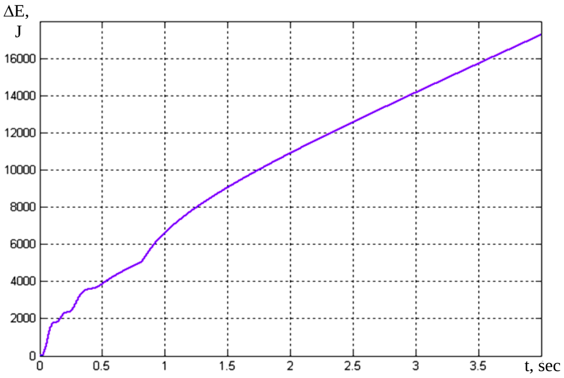

Figure 4 – Loss of electric power during acceleration in the second mode start

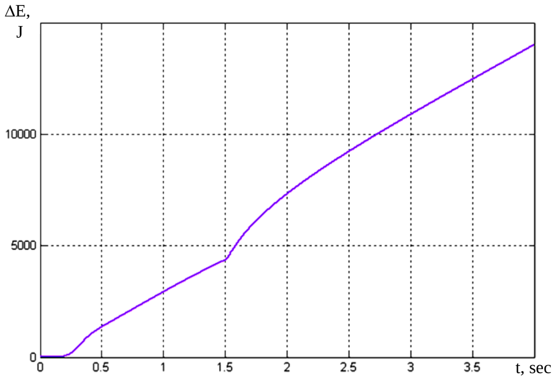

Figure 5 – Loss of electric power during acceleration in the third mode start

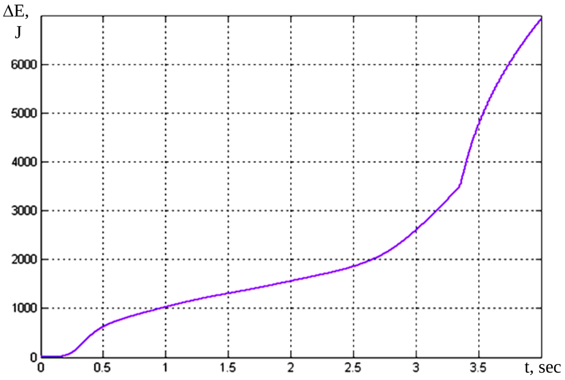

Figure 6 – Loss of electric power during acceleration at the start the fourth mode

The simulation results of TEM work with the different connection schemes and different load showed that the series TEM connection the excessive losses of electrical power were observed at start (Table 1). The table shows that in the economy start mode the difference between energy losses is the most substantial (about 17 % when driving without electric load and about 27 % with loaded trolleys). The study shows that TEM efficiency increases with load increasing with series-parallel connection of TEM.

It appears from foregoing that optimization of the electric drive system operation mode at its start and acceleration should be provided on the criterion of minimum power losses in anchor chains of electric motors.

Table 1 – Comparizon of TEM energy parameters in the starting modes

Start-up mode	The method of connection traction motors	Moment of load, N·m	Energy losses, Vt·g
1	2	3	4
1	series	12,26	2,24
		44,5	4,51
	series-parallel	12,26	2,16
		44,5	3,33
2	series	12,26	4,2
		44,5	7,56
	series-parallel	12,26	4,9
		44,5	7,84
3	series	12,26	3,92
		44,5	7
	series-parallel	12,26	3,61
		44,5	6,16
4	series	12,26	2,35
		44,5	4,23
	series-parallel	12,26	1,96
		44,5	3,08

According with [9] the optimization task of TEM dynamic modes is as follows: to find the laws of changing current and the motor shaft rotation speed that satisfy the condition (9). But in the analysis of opportunities to implement these laws in practice was established that to influence the current value and the electric motor rotational speed directly is impossible [10, 11]. At the same time it is possible to affect on the other engine parameter - the armature voltage. The expression to calculate voltage motor armature is:

$$U = C_e \cdot \Phi \cdot \omega + I_r R_r\,, \qquad (10)$$

where Φ – magnetic flux; C_e – coefficient determined design parameters of electric cars:

$$C_e = \frac{pN}{2\pi a}\,,$$

where p – number of pole pairs motor; N – the number of active conductors rotor winding; a – the number of pairs of parallel branches of the rotor winding [9].

It is known that the engine runs at start on the linear section of the magnetization curve, and that in the steady mode it works on parabolic section [9]. Mathematical model of the magnetization curve of these cases is written as:

$$\Phi(I_r) = a_1 + b_1 I_r \qquad (11)$$

$$\Phi(I) = -a_2^2 I_r + b_2 I_r\,, \qquad (12)$$

where a_1, b_1, a_2, b_2 – coefficients of mathematical model of the magnetization curve of the direct current motor sequential excitation which is represented by the segments of the line and parabola [12].

Considering this the optimum laws of engine anchor voltage change for both cases are as follows:

$$\begin{aligned}
U^{st} &= C_e \cdot \Phi \cdot \omega_n \cdot a_1 \cdot \left(1 + \frac{b_1 \cdot \left(C^{st} \cdot T_M + \lambda_0^{st} \cdot t\right)}{2 \cdot \left(T_M - b_1 \cdot \left(C^{st} \cdot T_M + \lambda_0^{st} \cdot t\right)\right)}\right) \times \\
&\times \left\{ \frac{{a_1}^2}{4\lambda_0^{st} \cdot b_1} \cdot \left[\frac{T_M}{b_1 \cdot \left(T_M - b_1 \cdot \left(C^{st} \cdot T_M + \lambda_0^{st} \cdot t\right)\right)} - \frac{1}{b_1} - \frac{1}{T_M} \cdot \left(C^{st} \cdot T_M + \lambda_0^{st} \cdot t\right) \right] - \frac{M_r}{M_n \cdot T_M} \cdot t + C_1 \right\} + , \qquad (13) \\
&+ \frac{a_1 \cdot I_n \cdot R_\Sigma \cdot \left(C^{st} \cdot T_M + \lambda_0^{st} \cdot t\right)}{2 \cdot \left(T_M - b_1 \cdot \left(C^{st} \cdot T_M + \lambda_0^{st} \cdot t\right)\right)}
\end{aligned}$$

$$\begin{aligned}
U^c &= \frac{2}{3a_2} \left(b_2 - \frac{T_M}{C^c \cdot T_M + \lambda_0^c \cdot t} \right) \times \\
&\left(\frac{C_e \cdot \Phi \cdot \omega_n}{3} \left(b_2 + \frac{2T_M}{C^c \cdot T_M + \lambda_0^c \cdot t} \right) \times \right. \qquad , \quad (14) \\
&\left. \times \left\{ \frac{4}{27a_2^2 \lambda_0^c} \left[\frac{b_2^3}{T_M} (C^c \cdot T_M + \lambda_0^c \cdot t) + \frac{3b_2 T_M}{C^c \cdot T_M + \lambda_0^c \cdot t} - \frac{T_M^2}{(C^c \cdot T_M + \lambda_0^c \cdot t)^2} \right] - \frac{M_r}{M_n T_M} t + C_2 \right\} + I_n R_\Sigma \right)
\end{aligned}$$

where C^{st}, C^{c}– integration constant is determined from initial and boundary conditions; λ_0^{st}, λ_0^{c} – Lagrange fexed; M_n, I_n – electromechanical nominal moment and nominal motor current; $T_м$ – mechanical constant:

$$T_M = \frac{J \cdot \omega_n}{M_n}.$$

Parameters of these models are found according to the rules described in [9].

Described laws of armature voltage changes can be used when creating a system of control the mine electric traction motors in Fig. 2 the proposed functional optimization scheme of the traction electric motor mode is shown.

Using the laws of search the optimum parameters of mine electric locomotive TEM the creating of programmed TEM supply voltage control system is possible which can operate with transistor converters. The functional scheme of mine electric locomotive TEM work modes optimization system displayed in pic. 2 is conceived, the principle of its operation is as follows. The voltage of the power supply (contact network, battery) enters the analog-digital converter, that provides automatic conversion of a continuous variable in the discrete digital form with equivalent values numeric codes in a particular numeric system. Numeric code goes to the controller where logical operations according the laws of search for optimal TEM parameters are performed after which the microcontroller performs pulse modulation, i.e. changing the period, the duration, the duty cycle and the shape of the input voltage. The received signals are given to the IGBT module that controls these signals changing its status (open/close transistor). After all changes are made the voltage is applied to the mine locomotive traction motor.

The obtained values of speed, current and voltage are measured by electronic sensors of digital current, voltage, and speed and displayed on the indicators located on computers. The obtained values are analyzed by the engine operator.

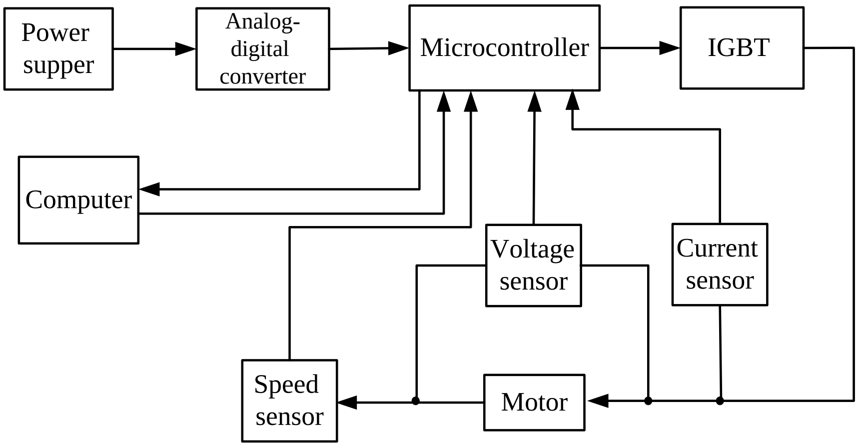

Figure 7 – A simplified block diagram of the traction electric locomotive optimization

Thus, the developed optimization system of mine locomotive TEM modes has the ability to automatically find and select the most economical mode of TEM start.

CONCLUSIONS. 1. The undertaken study of efficiency of TEM starting modes of mine electric locomotives indicate that the series-connected traction engines are accompanied by more (17-27 %) energy losses than in series-parallel connection.

2. The form of TEM voltage changing affects the level of energy losses at start. It follows from the simulation results that losses of energy are two times less with a smooth start than the direct.

3. The laws of optimum TEM voltage change that allow reaching minimum energy losses at motor start are mentioned.

4. The optimization scheme of mine electric locomotive TEM work mode is conceived where the control of impulse converter operation and of the form of TEM supply voltage change is performed by the microcontroller.

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ЭНЕРГОЭФФЕКТИВНЫЕ РЕЖИМЫ ПУСКА ТЯГОВЫХ ЭЛЕКТРОТЕХНИЧЕСКИХ КОМПЛЕКСОВ РУДНИЧНЫХ КОНТАКТНЫХ ЭЛЕКТРОВОЗОВ

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Рассмотрены вопросы снижения потерь электрической энергии в тяговых электрических двигателях постоянного тока рудничных контактных электровозов в пусковых режимах. Проведен сравнительный анализ способов соединения тяговых электродвигателей при пуске электровоза. Приведены результаты моделирования пусковых режимов тяговых электродвигателей при последовательном и последовательно-параллельном соединении. Доказана целесообразность последовательно-параллельного соединения тяговых двигателей при пуске электровоза с точки зрения объемов расходов электроэнергии. Представлены законы оптимального изменения напряжения питания тягового электродвигателя постоянного тока последовательного возбуждения рудничного транспортного средства. Предложена схема оптимизации режимов функционирования тягового электрического привода постоянного тока рудничного электровоза.

Ключевые слова: электрический двигатель, элктровоз, энергия, потери, пуск, оптимальные параметры.

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