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FEATURES OF MODERNIZATION OF A TRUCK WITH A HYBRID POWER TRANSMISSION

Purpose. Substantiation of peculiarities of modernization of a heavy-duty vehicle with a hybrid power transmission by using the formed set of analytical and technological solutions for power transmission under operating conditions.

Methodology. For the developed functional model of a hybrid vehicle operation, the parameters of the functional model and its links are presented, the relationships between the elements are described, and the boundary conditions are formed. A combined series-parallel hybrid drive scheme has been used, as it has a higher efficiency compared to parallel and series ones. When operating in idle mode and low loads, the diesel generator set replenishes the energy reserve in the energy storage device and the vehicle is operated. To recharge the energy storage devices, it is possible to use the traction electric motor as a generator, and during operation it is used in the energy recovery mode during vehicle braking. An optimization mathematical model has been developed to determine the parameters of the power plant and energy storage device, taking into account operating conditions. A procedure has been developed along with, on its basis, a subroutine algorithm for calculating the required energy intensity of the energy storage device and the power of the vehicle's power plant. An assessment of the modernization effectiveness of mining dump trucks by hybrid power transmission was made.

Findings. A functional model of a hybrid vehicle operation under appropriate operating conditions has been developed, and the main parameters limitations of the state have been given. The corresponding procedures and algorithm for calculating the parameters of the energy storage device and the power unit were compiled and then were used in the corresponding computer calculation program. In the study on fuel efficiency, three BelAZ-7547 dump trucks were considered. The values of the kinetic energy configuration were determined with an increase in speed (acceleration) and with a decrease in speed (deceleration). An assessment of the upgrading effectiveness was made for mining trucks with hybrid power transmission. The payback period of the corresponding measures was 1.42 years.

Originality. To determine the power storage and power unit parameters, a functional model of a hybrid vehicle operation and an optimization mathematical model for determining the parameters of the power plant and energy storage, taking into account operating conditions, have been developed. The substantiation of a complex of analytical and technological solutions for the power transmission of a hybrid mining dump truck under operating conditions has been carried out.

Practical value. The results obtained are useful in the implementation of the modernization of heavy mining dump trucks with hybrid power transmission in the operating conditions.

Keywords: *vehicle, modernization, hybrid power transmission, power plant, energy storage device, energy intensity*

Introduction. The global energy crisis, the catalyst of which was the war in Ukraine, will grow and deepen – such disappointing results were published in the report of the UN Development Program. Experts also believe that the continuous increase in the price of fossil fuels with inevitable fluctuations in world prices will expand the economic limits of the use of alternative renewable energy sources and increase their share in the structure of energy consumption. The transformation of the energy sector is inextricably linked and takes place simultaneously with the revolutionary attitude to ecology. The energy sector is taking on noospheric features, which indicates a modern global energy-ecological revolution that will change the face of the planet.

Transport is one of the main and largest consumers of fuel and energy resources, therefore the solution to the problem of energy saving concerns not only transport, but also the economy of the country as a whole. There is a need to develop a systemic approach to the problem, which involves both the optimization of energy consumption and the implementation of scientific and technical measures that stabilize the level of energy consumption and reduce unproductive costs in transport. The greatest cost reduction can be achieved through the introduction of resource-saving technologies, which in turn affect the change in the amount of fuel and energy resources used in the transportation process. Effective energy saving implies not only and not so much the saving of energy resources, but their optimal use. Modern transport presents more and more stringent requirements for the economic, energy and toxicity indicators of the internal combustion piston engine, but their modernization is facing more and more new difficulties. Effective use of fuel and energy resources in transport is possible by increasing the efficiency of the energy system and reducing energy losses.

Literature review. The use of dual-flow transmissions [1, 2] and energy recovery during the operation of traction rolling stock is one of the most rational ways to save energy and increase the environmental performance of rolling stock units [3, 4]. Two-flow stepless hydraulic-mechanical transmissions are mainly used on tractors [1] and mine diesel locomotives [2] with a small engine power. However, for quarry dump trucks [5, 6] the system of storing electrical energy in large-capacity capacitors in braking modes (regenerative braking) with its subsequent use in acceleration and traction modes is quite effective, as well as the storage of electrical energy can be additionally carried out during operation of the diesel generator set in idle mode.

The effectiveness of the use of recuperative systems increases with increasing unevenness of the vehicle's movement during frequent braking and acceleration, or when changing the direction of movement. In road transport, the greatest effect from the use of the electrical energy recovery system can be obtained on quarry dump trucks, where the greatest unevenness of movement is observed [7].

There are many varieties of hybrid vehicle traction drive systems. They are built according to certain principles and use various schemes and elements. Thus, in the study [8, 9], the hybrid system of the traction vehicle was considered, but the models did not take into account the peculiarities of work and operating conditions of quarry dump trucks. This does not make it possible to compare the obtained results, respectively, for the vehicles considered in this paper. The authors [10, 11] do not take into account the mass-dimensional parameters of a vehicle with a hybrid drive, and do not take into account the cost indicators of its elements. This does not allow recommending the application of the obtained results without conducting additional research. In works [12, 13], energy storage devices were chosen based on a comparative evaluation of various options, but the cost indicators of the hybrid drive were not taken into account. The results of the work do not indicate directions for improving the hybrid transmissions of quarry dump trucks. The authors' collectives [14, 15] choose the parameters of hybrid power transmission based on the loading of power plants depending on the operating conditions of the vehicle, but their overall and cost indicators are also not taken into account. Modes of the vehicle operation and indicators of the efficiency of its use are taken into account in [16, 17], but without reference to the dimensions and cost of the element base. We also note that the solution to the problem of energy saving also applies to other types of mining and transport equipment [18, 19].

In many countries of the world, they are trying to implement hybrid power transmission in vehicles [20, 21]. Paper [20] presents an overview of the research for improving lithium-ion battery energy storage density, safety, and renewable energy conversion efficiency. The authors of [21] calculate the supercapacitor capacity and current control for a battery electric hybrid vehicle in real time using an acceleration and braking scheme. However, most vehicles operated and manufactured in Ukraine have a transmission without energy storage. Quarry dump trucks are no exception.

Purpose. The purpose of the work is the modernization of hybrid power transmission with energy storage to increase fuel economy and reduce harmful emissions using the example of quarry dump trucks.

Development of a functional model of the operation of a hybrid vehicle. Based on the analysis of the considered systems, the following generalized functional model of the hybrid vehicle operation is proposed (Fig. 1).

The model allows determining the functional relationships between the elements of power transmission with a hybrid drive. It is based on the most common type of hybrid vehicle, which uses a diesel generator set (DGS) and an energy storage (ES) as a power plant, and the DGS is the main element in this energy set. A combined series-parallel scheme of the hybrid drive is used, as it has a higher efficiency compared to parallel and series.

Below are the parameters of each link of the functional model, the relationships between its elements are described.

For the *"ICE"* link, the internal parameters are as follows: N_{ICE} is the *ICE* power, kW; t_{ICE} is *ICE* temperature, °C; g_e is the specific fuel consumption *DGS*, g/kWh; g_{idl} is the specific fuel consumption of *DGS* in idling mode, g/kWh; η_{ICE} is the *ICE* efficiency; V_{ICE} is the *ICE* capacity, m^3; m_{ICE} is the mass of *ICE*, kg.

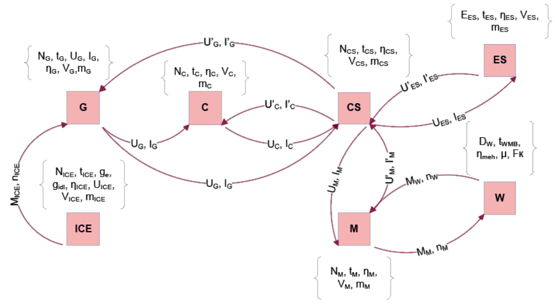

Fig. 1. Functional model of a hybrid vehicle operation:

ICE – internal combustion engine; G – traction generator; C – converter; CS – control system; M – traction electric motor; ES – energy storage; W – wheel

The output parameters of the *"ICE"* link and the input parameters for the *"G"* link are as follows: M_{ICE} is the torque on the shaft *DGS*, kN m; n_{ICE} is the *DGS* speed, rpm.

For the *"G"* link, the internal parameters are: N_G – the traction generator power, kW; t_G – the temperature of the traction generator, °C; U_G – the voltage at the clips of the traction generator, V; I_G – the current of the traction generator, A; η_G – the efficiency of the traction generator; V_G – the capacity of the traction generator, m^3; m_G – the mass of the traction generator, kg.

The input parameters of the *"G"* link from the "*ICE"* (feedback) link are M_{ICE} and n_{ICE}, and from the "*CS"* (feedback) link, these are U_G – the required voltage at the traction generator clips, *V*, and I_G – the required current of the traction generator, A. The initial parameters of the *"G"* link are U_G and I_G, which are included for the *"C"* and *"CS"* links.

The internal parameters of link "*C*" are as follows: N_C is the power of converter (*C*), kW; t_C is the temperature, °C; η_C is the efficiency of *C*; V_C is the capacity of *C*, m^3; m_C is the mass of *C*, kg.

The output parameters of the *"C"* link are voltage and current, *A*, which are input to the link *"CS",* with which the input parameters to the link *"C"* (feedback) is U'_C – the required voltage at the clips *C*, *B*, and I'_C – the required current of *C*, *A*, and from the *"G"* link these are U_G and I_G.

The *ES* link has the following internal parameters: E_{ES} is the energy density of *ES*; t_{ES} is the *ES* temperature, °C; η_{ES} is *ES* the efficiency factor; V_{ES} is the *ES* capacity, m^3; m_{ES} is the mass of *ES*, kg.

The output parameters of the *"ES"* link are U'_C – the voltage on *ES*, *V*, and I'_C – the current of *ES*, A, which are input to the *"CS"* link. From the *"CS"* link, the input parameters to the *"ES"* link (feedback) are U_{ES} – the required voltage on *ES*, *V*, and I_{ES} – the required current *ES*, *A*.

Link *"M"* has the following internal parameters: N_M is the traction electric motor power, kW; t_M s the temperature of *M*, °C; η_M is the efficiency factor of *M*; V_M is the capacity of *M*, m^3; m_M is the mass of *M*, kg.

The output parameters of the *"M"* link are U'_C – the voltage on *M*, *V*, and I'_M – the current of *M*, *A* input to the *"CS"* link, as well as M_M – the torque on the shaft *M*, kN · m, and n_M – the rotational speed *M*, rpm, included in the *"W"* link. The input parameters to the link *"M"* (feedback) with *"CS"* are U_E – the required voltage on *M*, *V,* and I_E – the required current *M*, A; from the link *"W"* these are M_T – the torque on the axle of the vehicle wheel (*W*), kN · m, and n_M – the rotational speed of *W*, rpm.

The internal parameters of the *"W"* link are as follows: D_W is the diameter of *W*, m; t_{WMB} is wheel-engine block (*WMB*) temperature, (*WMB*), °C; η_{meh} is the mechanical transmission efficiency; μ is the gear ratio of the reducer; F_K is the tangential traction force on the rim *W*, kN.

The input parameters of the *"W"* link are M_M and n_M, and the output parameters are M_W and n_W.

The *"CS"* link has the following internal parameters: *NCS* is the power of the control system (*CS*), kW; t_{CS} is the *CS* temperature, °C; η_{CS} is the *CS* efficiency; V_{CS} is the *CS* capacity, m^3; m_{CS} is the mass of *CS*, kg.

The input parameters of the *"CS"* link are U_C, I_C, U'_{ES}, I'_{ES}, U'_M, I'_M. The output parameters are U'_C, I'_C, U_{ES}, I_{ES}, U_M, I_M.

The limit values of the parameters of the functional model are reduced to a set of constraint systems for each of its links

$$\left[\begin{array}{l}
\begin{cases} N_{ICE\max} \ge N_{ICE} \ge N_{ICE\min} \\ t_{ICE\max} \ge t_{ICE} \ge t_{ICE\min}, \quad t_{ICEa\max} \ge t_{ICEa} \ge t_{ICEa\min} \\ \varphi_{ICEa\max} \ge \varphi_{ICEa}, \quad \grave{I}_{ICE\max} \ge \grave{I}_{ICE} \\ V_{ICE\max} \ge V_{ICE}, \quad m_{ICE\max} \ge m_{ICE} \end{cases} \\
\begin{cases} N_{G\max} \ge N_G \ge N_{G\min} \\ t_{G\max} \ge t_G \ge t_{G\min}, \quad t_{Ga\max} \ge t_{Ga} \ge t_{Ga\min} \\ \varphi_{Ga\max} \ge \varphi_{Ga}, \quad U_{G\max} \ge U_G, \quad I_{G\max} \ge I_G \\ n_{ICE\max} \ge n_{ICE}, \quad \grave{I}_{ICE\max} \ge \grave{I}_{ICE} \\ V_{G\max} \ge V_G, \quad m_{G\max} \ge m_G \end{cases} \\
\begin{cases} N_{C\max} \ge N_C \ge N_{C\min}, \quad t_{C\max} \ge t_C \ge t_{C\min} \\ t_{Ca\max} \ge t_{Ca} \ge t_{Ca\min}, \quad \varphi_{Ca\max} \ge \varphi_{Ca} \\ U_{C\max} \ge U_C, \quad I_{C\max} \ge I_C, \quad V_{C\max} \ge V_C, \quad m_{C\max} \ge m_C \end{cases} \\
\begin{cases} N_{CS\max} \ge N_{CS} \ge N_{CS\min}, \quad t_{CS\max} \ge t_{CS} \ge t_{CS\min} \\ t_{CSa\max} \ge t_{CSa} \ge t_{CSa\min}, \quad \varphi_{CSa\max} \ge \varphi_{CSa} \\ U_{CS\max} \ge U_{CS}, \quad I_{CS\max} \ge I_{CS} \\ V_{CS\max} \ge V_{CS}, \quad m_{CS\max} \ge m_{CS} \end{cases} \\
\begin{cases} E_{ES\max} \ge E_{CS} \ge E_{CS\min}, \quad t_{CS\max} \ge t_{CS} \ge t_{CS\min} \\ t_{ESa\max} \ge t_{ESa} \ge t_{ESa\min}, \quad \varphi_{ESa\max} \ge \varphi_{ESa} \\ U_{ES\max} \ge U_{ES} \ge U_{ES\min}, \quad I_{ES\max} \ge I_{ES} \\ V_{ES\max} \ge V_{ES}, \quad m_{ES\max} \ge m_{ES} \end{cases} \\
\begin{cases} N_{M\max} \ge N_M \ge N_{M\min}, \quad t_{M\max} \ge t_M \ge t_{M\min} \\ t_{Ma\max} \ge t_{Ma} \ge t_{Ma\min}, \quad \varphi_{Ma\max} \ge \varphi_{Ma} \\ U_{M\max} \ge U_M, \quad I_{M\max} \ge I_M \\ n_{M\max} \ge n_M, \quad \grave{I}_{M\max} \ge \grave{I}_M \\ V_{M\max} \ge V_M, \quad m_{M\max} \ge m_M \end{cases} \\
\begin{cases} t_{WMB\max} \ge t_{WMB} \ge t_{WMB\min} \\ t_{WMBa\max} \ge t_{WMBa} \ge t_{WMBa\min} \\ \varphi_{WMBa\max} \ge \varphi_{WMBa}, \quad n_{W\max} \ge n_W \\ M_{W\max} \ge M_W, \quad F_{k\max} \ge F_k \end{cases}
\end{array}\right.,$$

where $N_{ICE\max}$, $N_{G\max}$, $N_{C\max}$, $N_{CS\max}$, $N_{M\max}$ are the maximum powers of *ICE, G, C, CS, M* respectively, kW; $N_{ICE\min}$, $N_{G\min}$, $N_{C\min}$, $N_{CS\min}$, $N_{M\min}$ are the minimum powers of *ICE, G, C, CS, M* respectively, kW; $E_{ES\max}$ is the maximum energy capacity of *ES, MJ*; $E_{ES\min}$ is the minimum energy capacity of *ES, MJ*; $t_{ICE\max}$, $t_{G\max}$, $t_{C\max}$, $t_{CS\max}$, $t_{ES\max}$, $t_{M\max}$, $t_{WMB\max}$ are the maximum temperatures of *ICE, G, C, CS, ES, M, WMB* respectively, °C; $t_{ICE\min}$, $t_{G\min}$, $t_{C\min}$, $t_{CS\min}$, $t_{ES\min}$, $t_{Ma\min}$, $t_{WMB\min}$ are the minimum temperatures of *ICE, G, C, CS, ES, M, WMB* respectively, °C; $t_{ICEa\max}$, $t_{Ga\max}$, $t_{Ca\max}$, $t_{CSa\max}$, $t_{ESa\max}$, $t_{Ma\max}$, $t_{WMBa\max}$ are the maximum ambient temperatures for the operation of *ICE, G, C, CS, ES, M, WMB* respectively, °C; $t_{ICEa\min}$, $t_{Ga\min}$, $t_{Ca\min}$, $t_{CSa\min}$, $t_{ESa\min}$, $t_{Ma\min}$, $t_{WMBa\min}$ are the minimum ambient temperatures for the operation of *ICE, G, C, CS, ES, M, WMB* respectively, °C; φ_{ICEa}, φ_{Ga}, φ_{Ca}, φ_{CSa}, φ_{ESa}, φ_{Ma}, φ_{WMBa} are the relative humidity values for the operation of *ICE, G, C, CS, ES, M, WMB* respectively, %; $\varphi_{ICEa\max}$, $\varphi_{Ga\max}$, $\varphi_{Ca\max}$, $\varphi_{CSa\max}$, $\varphi_{ESa\max}$, $\varphi_{Ma\max}$, $\varphi_{WMBa\max}$, are the maximum relative air humidity values, respectively operation of *ICE, G, C, CS, ES, M, WMB* respectively, %; $n_{ICEa\max}$, $n_{M\max}$, $n_{W\max}$ are the maximum rotation speed values of the shaft *DGS, M, W* respectively, rpm; $M_{ICEa\max}$, $M_{M\max}$, $M_{W\max}$ are the maximum torques on the shaft *DGS, M*, on the axis *W* respectively, kN · m; $V_{ICEa\max}$, $V_{G\max}$, $V_{C\max}$, $V_{CS\max}$, $V_{ES\max}$, $V_{M\max}$, $V_{WMB\max}$ are the maximum volumes of *ICE, G, C, CS, ES, M, WMB* respectively, m^3; $m_{ICEa\max}$, $m_{G\max}$, $m_{C\max}$, $m_{CS\max}$, $m_{ES\max}$, $m_{M\max}$, $m_{WMB\max}$ are the maximum mass values of diesel, *G, C, CS, ES, M, WMB* respectively, kg; $U_{G\max}$, $U_{C\max}$, $U_{CS\max}$, $U_{ES\max}$, $U_{M\max}$ are the maximum voltage values of *G, C, CS, ES, M, V*; $U_{ES\min}$ is the minimum voltage value of *ES, V*; $I_{G\max}$, $I_{C\max}$, $I_{CS\max}$, $I_{ES\max}$, $I_{M\max}$ are the maximum current values of *G, C, CS, ES, M*, A; *Fкmax* is the maximum value of the traction force on the wheel rim, kN.

Description of the functional model of the hybrid vehicle. Energy from the diesel engine is transmitted to *G*. From the latter, energy is transmitted to *C*, and from it to CS, which connects ES, M, C and G.

In traction mode, the energy from DGS is transmitted through C, if available, and CS to M, which can also be additionally fed from ES in the event that DGS energy is insufficient.

When operating at idle speed and low loads, the DGS replenishes the energy reserve in the ES and the vehicle is operated.

To recharge ES, it is also possible to use M as a generator, when they work in energy recovery mode during vehicle braking.

Determining of the energy storage device parameters and the power plant parameters of a hybrid vehicle. An optimization mathematical model was developed to determine the parameters of the power plant and ES, taking into account the operating conditions and their mass-dimensional parameters, when placed on a vehicle. The input data for the calculation are a number of values of the power plant power *Nfi*, which is determined during the trip every $\Delta\tau$ minutes of the i^{th} interval. The model is based on the principle that the energy capacity of *ES EES, MJ*, should be minimal for the given power *DGS* N_{eng}, kW, for the given values of *Nf* and $\Delta\tau$, provided that the given operating cycle is ensured. In an implicit form, the model can be presented as

$$E_{ES}(Neng, Nf, \Delta\tau) \to \min. \qquad (1)$$

The system of inequalities of mass-dimensional limitations of model (1) has the form

$$\begin{cases} m_{ne}(E_{ES}) + m_{eng}(Neng) \le m_{\lim} \\ V_{ne}(E_{ES}) + V_{eng}(Neng) \le V_{\lim} \end{cases},$$

where $m_{ne}(E_{ES})$ is the dependence of *ES* mass on its energy consumption, kg; $m_{eng}(Neng)$ is the dependence of DGS mass on its power, kg; $V_{ne}(E_{ES})$ is the dependence of ES capacity on its energy consumption, kg; $V_{eng}(Neng)$ is the dependence of DGS capacity on its power, kg; $m_{\lim}$, $V_{\lim}$ are the limit values, respectively, of the mass and volume of the free space of the vehicle for installation on its DGS and ES, kg.

The procedure for solving this problem is presented in Fig. 2.

The determination of the required energy capacity *ES* and the power of the power plant of the hybrid vehicle is performed as follows.

First, the operation data of existing vehicles is analyzed for a certain area where a hybrid vehicle is expected to be used.

Based on the initial data, the value of the number of recorded data *n*, the duration of the vehicle's operation τ_{zm}, min, as well as the dependence $Nf(\tau)$, the number of steps N_{step} of changing the power of the power plant, which is calculated, is determined. Based on this, vector *j* is constructed, and $j \in (1 - N_{step})$. Then a vector of the coefficient of power change b_j is formed. Next, the average power is calculated according to the operating data N_{cp}, kW, which is taken as the base for calculations N_{pr}, kW

$$N_{pr} = N_{cp}.$$

On the basis of these data, the power vector of the power plant is formed, which is calculated, $Nust_j$, kW.

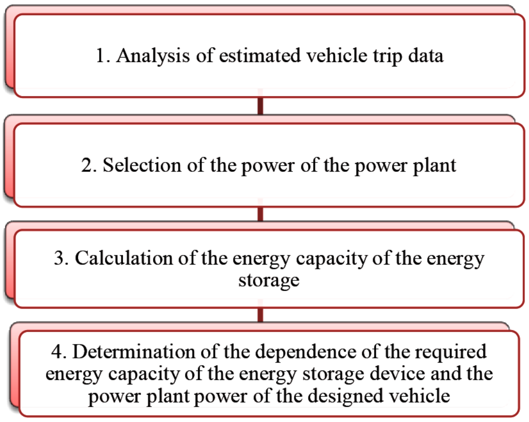

Fig. 2. The procedure for determining the required energy capacity of the energy storage and the power of the power plant of a vehicle with a hybrid power transmission

To calculate the energy capacity of *ES*, it is necessary to form a matrix of the required energy capacity $E_{i,j}$, MJ, where $i \in (1 - n - 1)$, while n is the number of elements of the power plant power series Nf_i. We take the initial energy capacity $Eo = 0$, MJ.

Then we determine the energy capacity *ES* $E_{i,j}$ at each stage of changing the required power of the vehicle.

We will form the matrix $E_{i,j}$ as follows, taking into account the efficiency of charging η_c and discharging η_d of *ES* and taking the initial value of energy capacity of *ES*, MJ. Then

$$E_{i+1,j} = \left[\begin{array}{l} E_{i,j} - (Nf_{i+1} - Nust_j)\Delta\tau/\eta_d, \quad \text{if} \quad Nf_{i+1} > Nust_j, \\ E_{i,j}, \quad \text{if} \quad Nf_{i+1} = Nust_j \\ \left\{\begin{array}{l} E_{i,j} - (Nf_{i+1} - Nust_j)\Delta\tau/\eta_z, \\ \quad \text{if} \quad E_{i,j} - (Nf_{i+1} - Nust_j)\Delta\tau/\eta_c \le Eo \\ Eo, \quad \text{if} \quad E_{i,j} - (Nf_{i+1} - Nust_j)\Delta\tau/\eta_c > Eo, \\ \quad \text{if} \quad Nf_{i+1} < Nust_j \end{array}\right. \end{array}\right. . \qquad (2)$$

For a certain j^{th} power of the designed power plant based on the created matrix (2), the required energy capacity of *ES* is determined by the following formula

$$E_{ESj} = |\min(E^j)|. \qquad (3)$$

At the same time, the vector of the necessary power of the power plant $Neng_j$ is formed, kW,

$$Neng_j = Nust_j. \qquad (4)$$

Then, taking into account (4), the matrix (2) will take the form

$$E_{i,j} = \left[\begin{array}{l} E_{1,j} = 0 \\ E_{i+1,j} = \left[\begin{array}{l} E_{i,j} - (Nf_{i+1} - Neng_j)\Delta\tau/\eta_p, \\ \quad \text{if} \quad Nf_{i+1} > Neng_j \\ E_{i,j}, \quad \text{if} \quad Nf_{i+1} = Neng_j \\ \left[\left\{\begin{array}{l} E_{i,j} - (Nf_{i+1} - Nust_j)\Delta\tau/\eta_z, \\ \quad \text{if} \quad E_{i,j} - (Nf_{i+1} - Neng_j)\Delta\tau/\eta_z \le Eo \\ Eo, \\ \quad \text{if} \quad E_{i,j} - (Nf_{i+1} - Neng_j)\Delta\tau/\eta_z > Eo, \end{array}\right.\right. \\ \quad \text{if} \quad Nf_{i+1} < Neng_j \end{array}\right. \end{array}\right. . \qquad (5)$$

Then, taking into account (3, 4 and 5) for the designed vehicle, taking into account the change in its operating capacity, the dependence of the energy capacity of ES EES on the power of the selected power plant *Neng* with *ES* weight and volume restrictions imposed on it is constructed provided they are placed on the vehicle.

Restrictions imposed on the model are reduced to the system

$$\left\{\begin{array}{l} m_{ne}(E_{ES}) + m_{eng}(Neng) \le m_{\lim} \\ V_{ne}(E_{ES}) + V_{eng}(Neng) \le V_{\lim} \\ Nf_{\min} \le Nf_i \le Nf_{\max} \\ Neng_{\min} \le Neng_j \le Nf_{\max} \\ 0 \le E_{ES} \le Em_{\max} \\ 0 \le E_{ES} \le Ev_{\max} \\ 1 \le i \le n-1 \\ 1 \le j \le Nsteep \end{array}\right. ,$$

where $Nf_{\min}$ is the minimum value of the required power of the vehicle according to the vehicle operation data, kW; $Nf_{\max}$ is the maximum value of the required power of the vehicle according to the vehicle operation data, kW; $Neng_{\min}$ is the minimum power value of DGS, kW; $Em_{\max}$ is the maximum value of ES energy capacity by mass for a certain vehicle; $Ev_{\max}$ is the maximum value of ES energy capacity by volume for a certain vehicle.

On the basis of the above, the subprogram algorithm for calculating the required *ES* energy capacity and power of the vehicle power plant with a hybrid power transmission was compiled. The subprogram algorithm is shown in Fig. 3.

On the basis of the proposed algorithm, a subprogram was developed for calculating the required energy capacity of *ES* and the power of the vehicle power plant with a hybrid transmission.

It is necessary to consider the proposed algorithm in more detail. For the analysis of vehicle operation data, the initial data are: the vector of power of the power plant Nf_i, which was determined during the trip every $\Delta\tau$ minute. As a result, we obtain: the value of the number of recorded data n, the duration of the vehicle operation τ_c, as well as the dependence $Nf(\tau)$.

When choosing the power of the power plant, the output data are: vector i according to the operating data of the vehicle, the number of steps N_{steep} for changing the power of the power plant, which is calculated, and vector *j* based on this. At the same time, the following are calculated: coefficient of power change b_j, average power according to the operating data of the vehicle N_{avr}, power N_{pr}, which is taken as the base for calculations, power of the power plant, which is calculated, N_{ustj}.

The following raw data are used to calculate the energy density of *ES*:

- the initial power E_o of calculation;
- energy capacity of *ES* E_{ESj} at each stage of changing the required power of the vehicle;
- the dependence of the energy $E(\tau)$ required by a vehicle with ES on the operating time τ;
- the minimum necessary energy capacity of *ES* E_{ESj} depending on the selected power of the power plant.

To determine the $EES(N_{eng})$ dependence of the required energy capacity of *ES* and the power of the vehicle power plant being designed, the initial data are:

- vector $Neng_j$ of power values of the projected power plant;
- vector EES_j of values of the minimum energy capacity of *ES* necessary to ensure the initial operation of the vehicle.

In this block, a matrix of *ES* parameters is introduced in the form of a *kne* matrix and restrictions on *DGS* and *ES* according to the mass-dimensional parameters of their placement on the vehicle.

Using this program when designing a vehicle with a hybrid power transmission, it is possible to determine the rational ratio of its power plant and *ES*.

Fuel consumption $G_{i,j}$ by the new *DGS* is determined at each stage of changing the required power of the vehicle, taking into account the specific fuel consumption of the new diesel engines g_e, kg/kW · h.

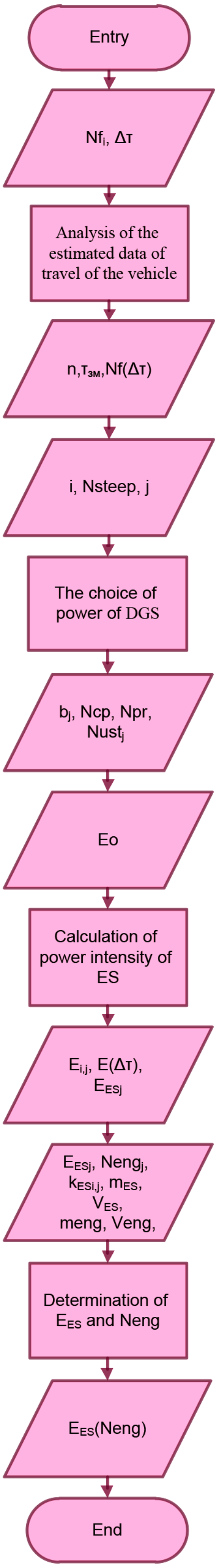

Fig. 3. The subprogram algorithm for calculating the necessary energy capacity of the energy storage and the power of the vehicle power plant with hybrid power transmission

We form the matrix *Gi,j* as follows. For the i^{th} step of power change Nf_i, at a certain j, provided that $Nf_j + 1 > Neng_j$, we have, kg,

$$G_{i+1,j} = Neng_j \cdot gen \cdot \frac{\Delta\tau}{3600}.$$

If at a certain step i, j $Nf_{j+1} = 0$, then $G_{i,j}$, kg

$$G_{i+1,j} = \begin{cases} Neng_j \cdot gen \cdot \dfrac{\Delta\tau}{3600}, \\ \quad \text{if} \quad E_{i,j} - (Nf_{i+1} - Neng_j)\Delta\tau / \eta_z \le Eo \\ 0, \quad \text{if} \quad E_{i,j} - (Nf_{i+1} - Neng_j)\Delta\tau / \eta_z > Eo \end{cases}.$$

If at a certain step i, j $0 < Nf_{i+1} < Neng_j$, then the diesel fuel (*DF*) consumption is determined as follows, kg

$$G_{i+1,j} = \begin{cases} Neng_j \cdot gen \cdot \dfrac{\Delta\tau}{3600}, \\ \quad \text{if} \quad E_{i,j} - (Nf_{i+1} - Neng_j)\Delta\tau / \eta_z \le Eo \\ Nf_{i+1} \cdot gen \cdot \dfrac{\Delta\tau}{3600}, \\ \quad \text{if} \quad E_{i,j} - (Nf_{i+1} - Neng_j)\Delta\tau / \eta_z > Eo \end{cases}.$$

In the next step, the calculation of the *DF* costs with new diesels for the shift $G1_j$ is performed according to the formula, kg

$$G1_j = \sum_{i=1}^{n} G_{i,j}.$$

Also, taking into account the specific fuel consumption of diesel engines *ge*0, kg/kW · h, the *DF* consumption in operation before the vehicle modernization is calculated for the shift of *Gekspl*, kg

$$Gekspl = \sum_{i=1}^{n} \left(Nf_j \cdot ge0 \cdot \frac{\Delta\tau}{3600} \right).$$

Then, it is necessary to determine the reduction of costs *U*3 for the *DF*, in dollars, after modernization, depending on the capacity of the selected *DGS*. This can be calculated by the formula, dollars

$$U3(Neng) = (Gekspl - G1(Neng)) \cdot ct,$$

where *ct* is the cost of *DF*, dollars/kg

The restrictions imposed on the model are reduced to a system of inequalities

$$\begin{cases} m_{ne}(E_{ES}) + m_{eng}(Neng) \le m_{\lim} \\ V_{ne}(E_{ES}) + V_{eng}(Neng) \le V_{\lim} \\ Nf_{\min} \le Nf_i \le Nf_{\max} \\ Neng_{\min} \le Neng_j \le Nf_{\max} \\ 0 \le E_{ES} \le Em_{\max} \\ 0 \le E_{ES} \le Ev_{\max} \\ 1 \le i \le n-1 \\ 1 \le j \le Nsteep \\ 0 < k \le 1 \end{cases}.$$

When choosing the type of *ES,* it is also necessary to take into account its weight and dimensions. Therefore, there is a need to calculate the maximum energy capacity of *ES*, which is limited by the dimensions of the vehicle. For this, it is necessary to know their specific weight and volume.

Table 1 shows the specific mass and volume indicators of various *ES*.

On the basis of the above indicators, as well as under the condition of overall limitations of the vehicle, the maximum energy capacity of various ES is calculated.

Evaluation of the modernization effectiveness of quarry dump trucks with hybrid power transmission. During quarrying, the useful mechanical work performed by the quarry dump truck is spent on overcoming the resistance forces of the vehicle, as well as the change in kinetic and potential energy. To simplify the calculations, we will conditionally assume that the work is performed on a horizontal profile, and therefore the change in potential energy will be zero. The analysis of dump trucks in quar-

Table 1

Specific indicators of ES

Storage type	Specific mass, kg/kJ	Specific volume, l/kJ
Condenser LLC "MNPO Econd"	0.37	0.19
Electrochemical capacitor "Esma"	0.068	0.0465
Flywheel	0.0042	0.0009
Nickel-cadmium battery	0.021	0.012
Lithium-ion battery	0.0003	0.001

ries showed that acceleration and deceleration time is 8–12 seconds. The distance covered by a quarry dump truck from starting to stopping is short, and the dump truck travels about 100 km per shift. The number of stops varies from 60 to 90 in 12 hours. Therefore, the main component of the mechanical work produced by the dump truck during its operation in the quarry will be the work spent on increasing the kinetic energy, i. e. acceleration, which is followed, as a rule, by coasting followed by braking, in which the stored kinetic energy is extinguished by braking devices. By storing the energy dissipated in the environment in energy-intensive capacitors and using it for acceleration, we can get a significant saving in diesel fuel, because in this case the process of acceleration and braking will resemble the oscillating process of a pendulum. During acceleration, the capacitor will be discharged, and during braking, it will be recharged and fuel will be consumed only to overcome the forces of resistance to the movement of the vehicle.

To determine possible fuel savings, three BelAZ 7547 quarry dump trucks were considered. 187 applications of brakes were recorded, fuel consumption was 492.6 kg, the distance covered was 98 km.

The magnitudes of the change in kinetic energy at an increase in speed (acceleration) and at a decrease in speed (braking) were determined.

Then, the amount of mechanical work A_{m1} was determined, which was performed by the dump truck when performing work in the regular way, which consists of work to overcome the forces of resistance to movement A_0 and the change in the kinetic energy of the vehicle A_{k1}. For calculations, the reduced mass was taken equal to 75 tons.

$$A_{m1} = A_0 + A_{k1}. \quad (6)$$

The work, overcoming the running resistance forces of the vehicle, is determined from the expression

$$A_0 = 1000 m \cdot g \cdot \sum_{i=1}^{n} s_i \cdot \omega_{0i}, \quad (7)$$

where m is the mass with load, 75 t; s_i is a distance covered, 98 km; ω_0 is the main resistivity, 80 N/kN.

Then, according to formula (7), we have, MJ

$$A_0 = 1000 \cdot 75 \cdot 9.81 \cdot 98{,}000 \cdot 0.08 = 5768.28.$$

The work on the change in kinetic energy A_{k1} without taking into account recuperation is determined by the formula

$$A_{k1} = 1000 \cdot \frac{m}{2} \cdot \sum_{i=1}^{n} (\nu_{s_f}^2 - \nu_{s_s}^2), \quad (8)$$

where ν_s is the initial speed, m/s; ν_f is the final speed, m/s.

The amount of mechanical work associated with the change in kinetic energy without taking into account recuperation A_{k1} is calculated according to (8) and is equal to, MJ

$$A_{k1} = 93.75.$$

Then, according to formula (6), we have

$$A_{k1} = 5768.28 + 93.75 = 5862.03.$$

Fuel consumption is based on the formula

$$E_1 = \frac{A_{m1}}{Q_H^P \cdot \eta}, \quad (9)$$

where E_1 is fuel consumption excluding recuperation, kg; Q_H^P is lower heat of fuel combustion, 42.5 MJ/kg; η is the efficiency factor of the dump truck, 28 %.

Then it follows from (9) that, kg

$$E_1 = \frac{5862.03}{42.5 \cdot 0.28} = 492.6.$$

We determine fuel consumption E_2 taking into account energy storage in energy-intensive capacitors.

It was found that the mechanical work associated with the change in kinetic energy A_{k2} taking into account energy storage in energy-intensive capacitors is equal to $A_{k2} = 37.5$ MJ, then

$$A_{m2} = 5768.28 + 37.5 = 5805.78.$$

Fuel consumption, taking into account recuperation, is based on the formula

$$E_2 = \frac{A_{m2}}{Q_H^P \cdot \eta}. \quad (10)$$

Then from (10) it follows that, kg

$$E_2 = \frac{5805.78}{42.5 \cdot 0.24} = 487.9.$$

Fuel economy ΔE will be

$$\Delta E = E_1 - E_2. \quad (11)$$

So, from (11) it follows that, kg

$$\Delta E = 492.6 - 487.9 = 4.7.$$

That is, the fuel saving is about 1 % for a simple section with a light profile.

At the next stage, the work of the same quarry dump trucks was considered, but on a more loaded section with a complex profile 151 km long. In this case, the fuel saving ε was about 23 %. Calculations for both options are given in Table 2.

Accumulation of the energy released during braking is possible with the help of high-capacity capacitors 30EK405, which are produced by ESMA Company.

Taking into account the significant economic effect of the quarry dump truck modernization, we consider it expedient to implement it.

Conclusions. The features of the modernization of a heavy-duty vehicle with a hybrid power transmission are substantiated

Table 2

Evaluation of the modernization effectiveness of quarry dump trucks with hybrid power transmission for different travel options

Indicator	Indicator value	
	Option 1	Option 2
A_0, MJ	5768.28	8887.86
A_{k1}, MJ	93.75	3093.75
A_{m1}, MJ	5862.03	11981.61
E_1, kg	492.6	1006.9
A_{k2}, MJ	37.5	309.375
A_{m2}, MJ	5805.78	9197.235
E_2, kg	487.9	772.9
ΔE, kg	4.7	234
ε, %	1	23

by using the formed complex of analytical and technological solutions for power transmission under operating conditions.

A functional model of a hybrid vehicle operation has been developed. For the model, the parameters of each link of the functional model are given, the relationships between its elements are described, and the limiting values of its parameters are formed. A combined series-parallel hybrid drive scheme has been applied. The rationality of its use is confirmed, since it has a higher efficiency compared to parallel and series ones. When idling and at low loads, the diesel generator set replenishes the energy reserve in the energy storage device and the vehicle is operated. To recharge the energy storage device, it is also possible to use the traction motor as a generator when it operates in the energy recovery mode during vehicle braking.

An optimization mathematical model has been developed to determine the parameters of the power plant and energy storage device, taking into account the operating conditions and their weight-and-dimensional characteristics. A procedure has been developed along with, based on it, a subroutine algorithm for calculating the required energy intensity of the energy storage device and the power of the vehicle power plant with hybrid power transmission. As an example, to determine the possible fuel savings, three BelAZ 7547 mining dump trucks were considered that were operated on June 16, 17 and 18, 2018. Their fuel consumption was 493 kg, the distance they traveled was 98 km. In this case, 187 applications of brakes were recorded. The magnitudes of the change in kinetic energy with increasing speed (acceleration) and with decreasing speed (braking) were determined. Using the developed models, an assessment was made of the effectiveness of the modernization of mining dump trucks with hybrid power transmission. It has been established that fuel savings in the sections under consideration reached 23 %, which confirms the feasibility of such an upgrade. At the same time, the payback period of the corresponding measures will be 1.42 years.

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Особливості модернізації великовантажного автомобіля з гібридною силовою трансмісією

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Мета. Обґрунтування особливостей модернізації великовантажного транспортного засобу з гібридною силовою трансмісією шляхом застосування сформованого комплексу аналітико-технологічних рішень передачі потужності в умовах експлуатації.

Методика. Для розробленої функціональної моделі роботи гібридного транспортного засобу наведені параметри ланок функціональної моделі, описані взаємозв'язки між елементами, а також сформовані граничні умови. Застосована комбінована послідовно-паралельна схема гібридного приводу, так як вона має більший ККД у порівнянні з паралельною й послідовною. При роботі в режимі холостого ходу й низьких навантаженнях дизель-генераторна установка поповнює запас енергії в накопичувач енергії та здійснюється робота транспортного засобу. Для зарядження накопичувачів енергії можливе використання тягового електродвигуна в якості генератора, а при роботі – у режимі рекуперації енергії під час гальмування транспортного засобу. Розроблена оптимізаційна математична модель для визначення параметрів силової установки й накопичувача енергії з урахуванням умов експлуатації. Розроблена процедура та на її основі алгоритм підпрограми розрахунку необхідної енергоємності накопичувача енергії й потужності силової установки транспортного засобу. Виконана оцінка ефективності модернізації кар'єрних самоскидів гібридною передачею потужності.

Результати. Розроблена функціональна модель роботи гібридного транспортного засобу у відповідних умовах експлуатації, наведені основні обмеження параметрів стану. Складені відповідні процедури та алгоритм розрахунку параметрів накопичувача електроенергії й силового агрегату, що було покладено у відповідну комп'ютерну програму розрахунку. При дослідженні паливної економічності розглянуті три кар'єрних самоскидів БелАЗ-7547. Були визначені величини зміни кінетичної енергії при збільшенні швидкості (прискорення) та при зменшенні швидкості (гальмування). Була проведена оцінка ефективності модернізації кар'єрних самоскидів гібридною передачею потужності й термін окупності відповідних заходів, що склав 1,42 років.

Наукова новизна. Для визначення параметрів накопичувачів електроенергії й силового агрегату були розроблені функціональна модель роботи гібридного транспортного засобу та оптимізаційна математична модель для визначення параметрів силової установки й накопичувача енергії з урахуванням умов експлуатації. Виконане обґрунтування комплексу аналітико-технологічних рішень передачі потужності гібридного кар'єрного самоскиду в умовах експлуатації.

Практична значимість. Отримані результати є корисними при здійсненні модернізації великовантажних кар'єрних самоскидів із гібридною передачею потужності в умовах експлуатації.

Ключові слова: *транспортний засіб, модернізація, гібридна передача потужності, силова установка, накопичувач енергії, енергоємність*

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