Determining the parameters of a shunting locomotive taking into account the environmental component

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Abstract. The article considers the issues of determining the main technical and economic indicators of the shunting locomotive during its modernization by a hybrid power plant. The analysis of scientific and practical works on the impact of railway transport on the environment and increase the efficiency of shunting locomotives due to design changes, which are aimed at reducing emissions. A model has been developed to determine the rational ecological and energy characteristics of a shunting locomotive, which has been modernized by technical means for energy saving taking into account the ecological component. A procedure, algorithm and program for calculating locomotive parameters have been developed. The main parameters of the shunting locomotive of the ChME3 type at modernization by its hybrid power plant taking into account an ecological component are defined and the estimation of expediency of such modernization is given.

1 Introduction

With the growing trend of human mobility and increasing freight traffic, vehicles face the problem of shortage of primary energy resources. To date, the analysis of the locomotive fleet of Ukraine has shown the urgent need to update it, which can be done in two ways: the purchase of new locomotives, the price of which is very high, or the modernization of the existing rolling stock.

In recent years, active work has been carried out to modernize locomotives on railways and industrial enterprises of Ukraine. The need to increase the efficiency of rolling stock operation motivates the search for innovative solutions during the modernization process. Diesel locomotives need to be more efficient and better adapted to alternative energy sources, the use of which solves the issue of shortage of primary energy resources and increases the environmental performance of diesel traction.

2 Literature review and problem statement

The issue of ecology in transport is given much attention in the works of scientists [1-7]. Thus, in [3] an analysis of various aspects of the impact of rail transport on the environment was conducted, in addition, examples of the negative impact of rail transport on the environment and human health are given.

Studies [4] on reducing the environmental load have shown the need to create a new comprehensive scheme for the treatment of waste oils and technological sludge of railways, the implementation of which will increase the efficiency of recovery and resource conservation, increase the environmental friendliness of oil circulation.

The authors in [5] considered the impact of rail transport on the environment. Ways to reduce the eco-destructive load of transport on the environment are given, the necessity of transition of railway transport to electric traction is also conditioned. As a result, the procedure for calculating the economic damage from the impact of railway transport on the environment is proposed, thus necessitating the introduction of an indicator that takes into account the mode of operation of locomotives at different power, which affects the mass of emissions.

The analysis conducted in [6] showed the relevance of improving the environment and improving the efficiency of natural resources. Thus, the preconditions for the development of "green" logistics in railway transport are identified, in addition, environmental issues in Ukraine are considered, which are the most relevant at present in the existence of problems that hinder the development of "green" logistics.

In [7] the results of researches of determination of bacteria of group of Escherichia coli in ballast of a railway track are published. As a result of which, conclusions were made about the level of pollution of railway ballast and described ways to radically solve this problem.

The issues of modernization of shunting locomotives with hybrid power plants were considered by scientists of the Ukrainian State University of Railway Transport in [8-10]. They provide methods for determining the main characteristics of a locomotive with a hybrid power plant,

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but the environmental component is not sufficiently taken into account.

According to research by scientists and transport workers, shunting locomotives run idle for more than 50% of the time. The specific emissions of pollutants are the largest. Therefore, the introduction of modern power plants, especially those that have the technical means to save energy, in the modernization of locomotives, is a topical issue in terms of ecology.

But, unfortunately, some scientific issues of the use of hybrid transmissions in the modernization of locomotives, taking into account the environmental component, the choice of energy storage and the region of operation of these scientists or not considered at all, or were not fully considered. Therefore, based on the analysis, the purpose of the study was formulated and tasks were set to achieve it.

3. Objective and tasks

The purpose of the work is to increase the efficiency of modernized shunting locomotives by improving their design with modern technical means and technologies for energy saving and improving environmental performance. To achieve the goal of the work it is necessary to solve the following tasks:

- - to analyze scientific and practical works on the impact of railway transport on the environment and increase the efficiency of shunting locomotives due to design changes that are aimed at reducing emissions;
- - to develop a model for determining the rational ecological and energy characteristics of the shunting locomotive, which is modernized by technical means for energy saving
- - to determine the main parameters of the shunting locomotive type ChME3 during the modernization of its hybrid power plant taking into account the environmental component and to assess the feasibility of such modernization.

4 Equations and mathematics

As a result of the analysis of different types of schemes of hybrid power plants taking into account features of shunting locomotives and conditions of their operation for shunting work the scheme which power chain is presented in figure 1 was chosen.

In General, the power of the hybrid power plant *Nгey* is presented as follows,

$$Nгey = f(Ndg, Nne, Ene, limi,j, Mpred, Vpred, Kzav, Uzag\ I, Kvzr) \quad (1)$$

where *Ndg* - diesel power, kW; *Nne* - energy storage capacity, kW; *Ene* - energy consumption of the energy storage, kJ; *limi* - restrictions on the length of the energy storage, m; *j* - the number of elements of energy storage; *Kzav* - locomotive load factor.

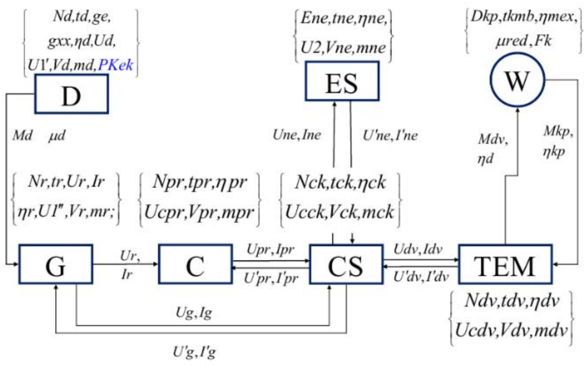

Fig. 1. Functional diagram of the power circuit of a shunting locomotive with a hybrid transmission.

Based on the European experience of environmental taxation, the target function for determining the technical and economic indicators of the locomotive included compensation for environmental losses, in addition to those previously taken into account, the cost of energy storage and maintenance and repair costs. It should also be borne in mind that the parameters of the energy storage can be affected by its limitations in terms of mass and size parameters. In General, the objective function is described as follows:

$$\begin{cases} Czag=f(C0,\ C1,\ C2,\ C3,\ C4,\ C5) \rightarrow min, \\ \Delta Vlim= f(Ene,\ l_{ne},\ b_{ne},\ h_{ne},\ j) \rightarrow min. \end{cases} \quad (2)$$

where C0 – the cost of an old diesel generator, UAH.; *C1* – cost of a diesel generator, UAH.; *C2* – cost of energy storage devices, UAH; *C3* – fuel costs after modernization, UAH.; *C4* – maintenance and repair costs, UAH; *C5* – costs of environmental penalties, UAH; $\Delta Vlim$ – underutilized free space of the locomotive to be engaged in energy storage, m^3; - respectively the length, width and height of one element of the energy storage, m. The costs of environmental penalties are determined by the formula, UAH:

$$C5 = \sum(C5i \cdot \sum gik \cdot \tau k \cdot T10pm \cdot Kf \cdot KT), \quad (3)$$

where $T^{10}_{рт}$ – total operating time of the locomotive for 10 years, hours.

The target function, taking into account the constraints on energy storage, power plant and environmental emissions, will be explicitly presented as follows,

$$\begin{cases} Czag = C0 + A{\cdot}N\partial 2 + B{\cdot}N\partial + C + \\ +\left[\sum_{i=1}^{n}\left(Nf_i \cdot ge0 \cdot \Delta\tau/3600\right) - \sum_{i=1}^{n} G_{i,j}\right] \cdot \text{ct}- \\ -(1-k(Neng_j))Cб + \\ + \sum(C_{5i} \cdot \sum g_{ik} \cdot \tau_k \cdot T^{10}{}_{pm} \cdot Kf \cdot K_T) \rightarrow min, \\ \Delta Vlim = kv{\cdot}Ene \rightarrow min \end{cases} \quad (4)$$

where *A, B, C* – coefficients that characterize the diesel power plant; Nд – power of a diesel power plant, kW;

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u2 – specific cost of energy storage, UAH / kWh; *ct* – fuel cost, UAH / kg; *ge0* – specific fuel consumption by diesel of the base locomotive, kg / kW·h; *Gi,j* – fuel consumption by hybrid locomotive, kg; where *Cб* – costs for maintenance and repair of the base locomotive, UAH.; *k(Nengj)* – the ratio of expenditure on maintenance and repair of the hybrid locomotive to the base, depending on the selected power diesel generator set; k_v – coefficient of underutilization of free space of the locomotive to be engaged in energy storage, m^3 / MWh. The coefficient is chosen depending on the type of locomotive, the overall dimensions of the elements of the energy storage and its required energy consumption.

Parameter limits were set for the model: $Nf_j \in [0\ldots Nf_{max}]$, $Neng_j \in [0\ldots Nf_{max}]$, $Nust_j \in [0\ldots Nf_{max}]$, $E_{1,j}=Eo=0$, $Ene \in [0\ldots Em_{max}]$, $Ene \in [0\ldots Ev_{max}]$, де Em_{max}, Ev_{max} – maximum values of energy consumption by mass and volume for a certain shunting locomotive.

To determine the technical and economic characteristics of the shunting locomotive with a hybrid power plant, an appropriate procedure was developed (Figure 2), which consists of seven stages.

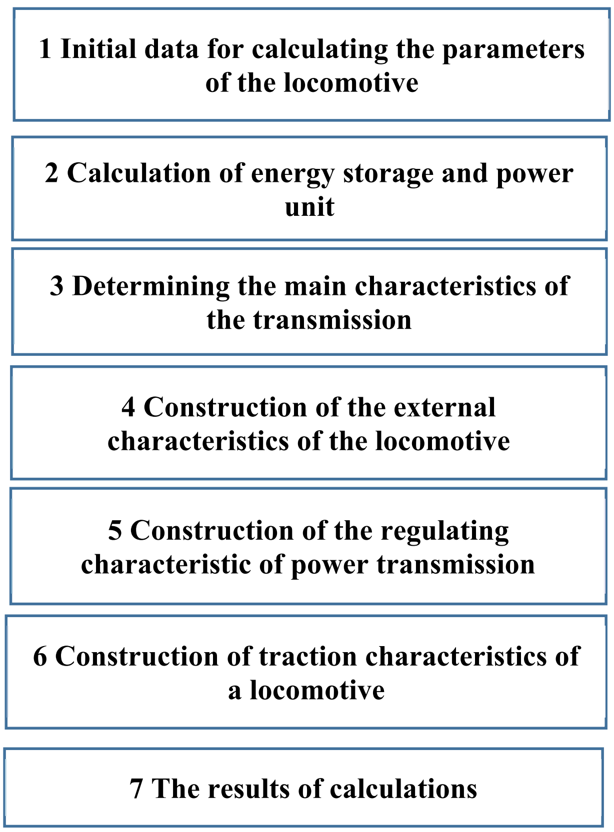

Fig. 2. Procedure for determining the technical and economic performance of shunting locomotive with hybrid power transmission.

At the first stage the values of necessary parameters for calculation are defined. Then the calculation of the energy storage is performed. In the third stage, the main parameters of the hybrid transmission are determined. After that, the construction of the external characteristics of the traction generator, the characteristics of the electric transmission and the traction characteristics are performed.

On the basis of the developed procedure the algorithm of the program of calculation of technical and economic indicators of the shunting locomotive with hybrid transfer of power was made.

To determine the main parameters of power transmission of a shunting locomotive with a hybrid power plant for operation in shunting motion, the model described in [11] was improved.

The initial data for determining the parameters of the energy storage and power plant of the locomotive, taking into account the works [12-14] are: power of the power plant Nf_i, кВт, which is determined during the time interval $\Delta\tau$, c, and a matrix of energy storage parameters is introduced in the form of a matrix *kne* and mass storage limits *Mpred*, kg; and volume *Vpred*, m^3, provided they are placed on the locomotive.

The proposed model differs from the existing ones in that when using an energy storage device, its power *Nne* is used for traction of engines to 3 the position of the driver's controller. Charging it is performed, if necessary, at 6 the position of the driver's controller. When using a power of more than 4 the position of the driver's controller, the shunting locomotive begins to operate according to the usual scheme. If necessary, the power of the energy storage *Nne* added to the power of the diesel generator *Ndg* and total power *Ntey* supplied to traction engines, kW,

$$Ntey = Nne + Ndg. \qquad (5)$$

As a result of calculation of this block we receive: dependence *Ene(Neng)* the required energy consumption of the energy storage, MWh, and the power of the locomotive power plant, kW, as well as the limit parameters of the energy consumption of these storage in the form of a matrix *Enelim*, MJ, and the optimal power values of the diesel generator *Nopt*, kW and energy consumption of the energy storage *Eopt*, MWh.

As a result of the analysis of works [2; 15-20] the initial data for definition of the basic parameters of electric transfer of the locomotive are expressed through an array *Mpoch*:

$$Mpoch = \{Ne\ , kdod, \eta g, Ps, \psi kr, \eta vu, \eta ed, \eta sl, c\}, \qquad (6)$$

where *Ne* – locomotive power, kW;
kdod – percentage of costs for ancillary needs, %;
ηg – efficiency of the generator;
Ps – coupling weight of the locomotive, kN;
ψkr – thrust coefficient on the calculated lift;
ηvu – efficiency of the rectifier;
ηed – efficiency of the electric motor;
ηsl – efficiency, taking into account losses in the power circuit;
c – number of traction motors, pcs.

The result of the calculation of this block is the mass *Mrzr*:

$$Mrzr = \{\Delta N, Nd, Pg, \eta en, Fkr, vp, Ped, Pde\}, \qquad (7)$$

where *ΔN* – power auxiliary needs, kW;

Nd – потужність дизеля, яка віддається на тягу, кВт;
Pg – diesel power, which is given to traction, kW;
ηen – efficiency of power transmission;
Fkr – the calculated thrust force determined from the condition of realization of the thrust coefficient on the calculated lift, kN;
vp – speed on the calculated rise, km / h;
Ped – power at the terminals of the traction motor, kW;
Pde – power on the shaft of the traction motor beforehand, kW.
An array of parameters was used to construct the external characteristics of the traction generator:

$$M_{TT} = \{Ugmax,\ Cgu,\ CgI\}, \qquad (8)$$

where *Ugmax* – maximum voltage of the traction generator, kW;
Cgu – voltage control factor of the traction generator;
CgI – current control coefficient of the traction generator.
The result of the construction of this unit is the construction of the external characteristics of the traction generator *U(I)* with all restrictions.

To build the control characteristic of the power transmission is also added *vmax* – maximum speed of the locomotive, km / h. The result of the calculation of this block is the construction of graphs and dependence *Ig(v)* and *Ug(v)* generator current and voltage from the speed of movement.

To construct the traction characteristics of the locomotive, the dependence of the efficiency of the electric transmission on the current is introduced. As a result, dependence is built *F(v)* with limitation on current and coupling.

Based on the proposed algorithm, a program for calculating the technical and economic characteristics of a shunting locomotive with a hybrid power transmission using a software package was developed Mathcad,

The verification of the developed model for adequacy was performed on the basis of the choice of parameters of the locomotive ChME3.

The parameters of the locomotive were calculated and its characteristics were constructed. In Figure 3.5. shows the traction characteristics of the locomotive ChME3: real and built on the model. Current and clutch restrictions are also applied to the characteristics.

Figure 3 shows that the characteristics are almost identical. But there is a need to determine the difference between them. For this purpose, the absolute error of the traction characteristic according to the formula was determined:

$$\Delta(v) = \left|Fp(v) - F(v)\right|, \qquad (9)$$

where *Fp(v)* – traction characteristics of the locomotive ChME3, built on the model;
F(v) – real traction characteristic of the ChME3 locomotive.

From the analysis of which it turns out that the maximum error is about 6.3%, which is satisfactory for calculations.

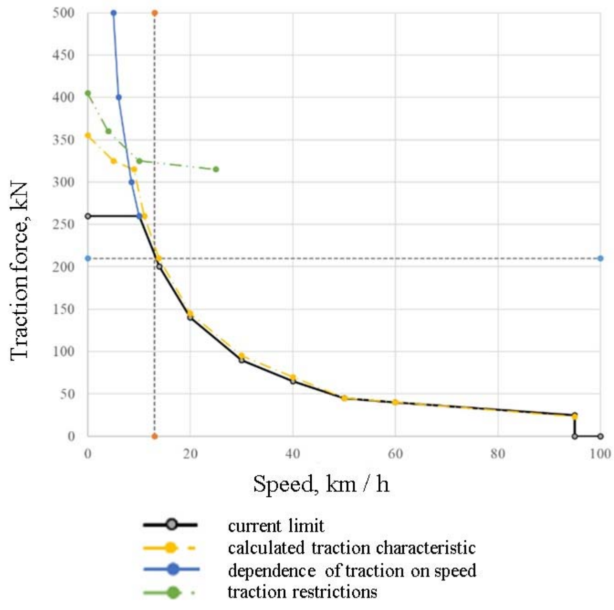

Fig. 3. Traction characteristics of the locomotive ChME3 basic and calculated and its limitations.

Based on the absolute error, the relative error of the traction characteristic is calculated by the formula,

$$\delta(v) = \frac{\Delta(v)}{F(v)} \cdot 100\%. \qquad (10)$$

Figure 4 shows the change in the absolute and relative errors of traction from velocity in the construction of the traction characteristics of the locomotive ChME3.

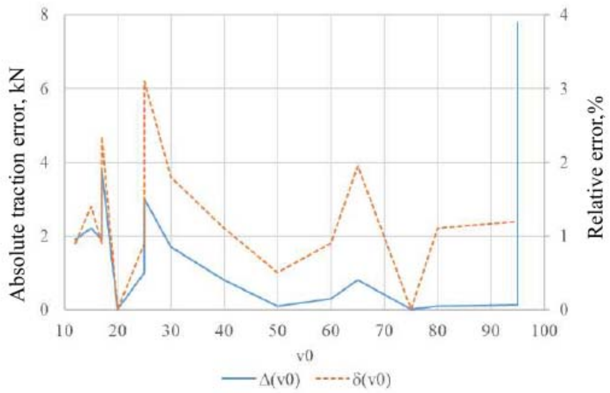

Fig. 4. Dependences of absolute and relative error in determining the thrust force as a function of speed

Based on the developed model, the main technical and economic parameters for a six-axle shunting locomotive are determined, taking into account the selected modern energy-saving technologies.

According to scientific research and operation of serial six-axle shunting locomotives, taking into account the limitations (mass and dimensions and provided that the free space of the locomotive is limited), the maximum energy consumption of various energy storage devices was calculated. The capacity of the energy storage is selected so that it is sufficient for the operation of the locomotive, which is equivalent to its operation at 1 to 3 positions of the driver's controller. The power dependences of the hybrid locomotive power plant for each position of the locomotive driver's controller are constructed.

The total costs associated with the upgrade are calculated *Czag*, UAN. It is determined that taking into account the restrictions imposed on the energy storage device, the minimum modernization costs are observed for the power of the diesel generator of 360 kW and the energy consumption of the energy storage device of about 600 kWh. Calculations of parameters of the modernized shunting locomotive with the hybrid power plant for performance of shunting works by the locomotive are executed.

The calculations of life cycle costs of modernized locomotives by a hybrid power plant (two options) and the base locomotive ChME3 showed the following. The costs of emission fines in the base locomotive ChME3 are more than 40% higher than in the locomotive with the base engine and energy storage and almost 75% higher than in the modernized locomotive with a new power plant and energy storage.

Similarly, the life cycle costs for modernized locomotives have shown that it is advisable to perform a deep modernization of the shunting locomotive with a new diesel and energy storage. But at lower costs, ie the installation of only energy storage and repair of the base diesel, there will also be a positive effect, the costs will be lower by 12%.

According to the results of calculations, the appropriate parameters of the modernized shunting locomotives at the energy capacity of the energy storage of 600 kWh are selected, the optimal power of the diesel generator will be within: for shunting operation 250 kW; for export - 800 kW; for work on a hill - 300 kW. According to the results of traction calculations for export work, fuel consumption of the hybrid locomotive was reduced to 30% compared to the base.

The life cycle of a hybrid locomotive based on ChME3 and a basic locomotive for a period of 20 years - the time from modernization (or overhaul) of the locomotive to its complete decommissioning. Thus, when using a hybrid locomotive based on ChME3, during operation the total economic effect of one locomotive will be UAH 3.5 million.

The efficiency of the shunting locomotive is proposed to be determined taking into account the technical, economic and environmental components according to the formula

$$K_{ef} = K_1 \cdot \sum_{i=1}^{i=s} k_n \varphi(i) \Big/ \sum_{i=1}^{i=s} \varphi(i) + K_2 \cdot LLC_{TB} / LLC_{TG} + \\ + K_3 \cdot \sum_{z=1}^{n} A'_z m_{бz} \Big/ \sum_{z=1}^{n} A'_z m_{гz} \qquad (11)$$

where *kn* – the ratio of numerical parameters of the new development to the parameters of existing objects for rational categories and irrational categories; *φ(i)* – function that normalizes the weight of the parameters in the ranked sequence; *i* – shunting locomotive parameter number; LLC_{TB}, LLC_{TG} – life cycle cost of the basic *locomotive* and the modernized, respectively, UAH.; *A'z* – indicator of the relative activity of impurities of the *z*-th type; $m_{бz}$, $m_{гz}$ – average annual masses of pollutant of the *z*-th type, which enter the atmosphere in year t during operation, respectively, of the basic locomotive and modernized, kg / h per section; K_1, K_2, K_3 – weights of efficiency components. At the same time $\sum_{i=1}^{3} Ki = 1$. The weights of the components of efficiency are determined by the expert method depending on the presented tasks. This factor when using a locomotive in shunting operation for the base locomotive is equal to K_e=1, for an upgraded diesel locomotive with a basic diesel engine and an energy storage capacity of 600 kWh equal to K_e=1,13, and for the upgraded new diesel with a capacity of 250 kW and this energy storage equal to K_e=1,4. This confirms the efficiency of modernization of six-axle shunting locomotives with a hybrid power plant of the proposed type.

Conclusions

Based on the results of theoretical and experimental studies, the following conclusions were made.

1. Analysis of the directions of work of scientific organizations, rolling stock manufacturers and works of scientists shows that to solve the problem of determining the technical and economic indicators of locomotives with hybrid power plant requires a comprehensive approach that should link the technical parameters of the locomotive, performance and cost indicators taking into account the environmental component. To substantiate the choice of technical and economic indicators of locomotives with hybrid transmission, an approach based on mathematical modeling was taken. He allowed to justify the choice of the main technical and economic indicators of the modernized locomotive at the lowest cost of the life cycle when using it in shunting work.
2. The functional scheme of the power circuit of a shunting locomotive with a hybrid power plant is proposed, which allowed to determine the functional connections between the elements of power transmission with a hybrid drive.
3. A model has been developed to determine the rational design and energy characteristics of an upgraded shunting locomotive with a hybrid power plant. The functional dependences of the power of the diesel generator set on the energy consumption of the energy storage for shunting operation of the locomotive are obtained.
4. It is proposed to determine the efficiency of shunting locomotive modernization by an appropriate coefficient, which takes into account the technical level of the locomotive, life cycle costs and environmental component with the appropriate weights. This factor when using a locomotive in shunting operation for the base locomotive is equal to K_e=1, for an upgraded diesel locomotive with a basic diesel engine and an energy storage capacity of 600 kWh equal to K_e=1,13, and for the upgraded new diesel with a capacity of 250 kW and this energy storage equal to K_e=1,4. This confirms the efficiency of modernization of six-axle shunting

locomotives with a hybrid power plant of the proposed type.

5. The procedure for the designation of technical and environmental indicators of locomotives for a specific core structure can be used for similar applications in other types of transport.

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