Generalized Method of Calculation of the Joint Characteristics of the Internal Combustion Engine and the Tractor Transmission

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Abstract: ***The article is devoted to the development of a generalized methodology for calculating the joint characteristics of an internal combustion engine and transmission of a mobile unit. The technique allows considering transmissions of various physical nature: electric, hydraulic. The peculiarity of the technique is that the power transmission of any physical nature can be represented by a generalized model, a four-terminal device, the input of which is affected by the values of Min, nin, and the output is Mout, nout. As a result of the calculations, graphical dependencies of the joint characteristics of the internal combustion engine and transmission, the efficiency of the generator and the electric motor, and the mechanical and electromechanical characteristics of the electric motor are obtained.***

Keywords: ***generalized technique, electric transmission, motor-transmission installation, power transmission, generator, electric motor, coefficient of performance, joint characteristics, pump, hydraulic motor, hydrostatic transmission, torque.***

I. INTRODUCTION

Currently, serious attention is paid to reducing the time required to complete the work throughout the chain - from the birth of an idea to mass production of a product. There are frequent cases when they are extremely stretched, and the machines being created are morally obsolete at the development stage. In the process of creating a tractor, experimental studies occupy the maximum share of the total time spent [1,2]. They require attracting significant capital investments. Reducing the timing of the development of new equipment, reducing the reduced costs can be achieved by applying effective theoretical research methods, improving design methods and substantiating a rational version of the designed product.

A feature of the theoretical methods of researching technical means is that they allow the widespread use of modern computer technology, to implement a generalized approach to the issue of choosing an effective product. Thus, on the basis of the foregoing, important aspects can be distinguished, which is currently fundamental in the technical policy of agricultural engineering in Russia:

- Reducing the development time of technical means and reducing the cost of research.
- The world tractor industry is characterized by ever wider use of hydrostatic, hydrodynamic, electric transmissions.
- Generalized theoretical techniques will allow for comparative studies of power transmissions of various physical nature.

The essence of the generalized methods developed by the authors is that the power transmission in the study of loading properties is considered as a four-terminal device. This aspect involves the study of transmission as a regulated system. An assessment must be made of the stability of the angular velocity of the crankshaft of the engine under the influence of a low-frequency load.

In this work, serious attention is paid to the issues of developing an algorithm for calculating these parameters. The aim of this work is to develop a generalized methodology for the study of the protective properties of stepless power transmissions of agricultural tractors.

In this case, on the basis of research methods of the loading properties of power transmissions, a comparative assessment of the latter can be carried out taking into account the real regulation law [3-6].

A. Study of the properties of hydrostatic gears

A hydrostatic machine is a device that converts a rotational mechanical energy flow into a translational hydrostatic flow, or, conversely, a translational hydrostatic flow into a rotational mechanical flow. The first type of machine is called a pump, the second one is called a hydraulic motor [7,8].

A hydrostatic machine consists of the following main parts of a rotating rotor, a fixed stator. The stator closes the space around the rotor filled with the working fluid, and inlet and outlet pipelines are connected to it. With the help of distributors, the volumes of liquid under high pressure are connected to the high-pressure pipe (discharge line), and the volumes of liquid under low pressure are connected to the low-pressure pipe (suction line).

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As a review of literary sources shows, research methods for the joint operation of a hydrostatic transmission and an internal combustion engine do not exist [7, 8, 9, 10]. This is due to the fact that the hydrostatic gears used in the manufactured tractors are designed primarily for manual control. In such cases, the determination of the loading properties of the transmissions makes no sense. However, it should be noted that work is currently underway to develop effective automatic control systems for hydrostatic transmissions of tractors and machine-tractor units [11, 12 ... 15].

Therefore, to solve the problem of selecting and justifying power transmissions of promising tractors, it is necessary to have methods for studying the loading properties of hydrostatic transmissions. These methods should allow you to determine the desired law of regulation of transmission parameters at the design stage. According to the data obtained, it will be possible to select the appropriate type of hydraulic machine regulator from the reference books [8]. The latter include not only types of regulators and hydraulic machines, but also their characteristics. They are a set of curves of efficiency, flow, pressure for hydraulic machines. The directories provide theoretical and real laws of regulation of automatic systems used in hydrostatic transmissions.

B. Study of the collaboration of a hydrodynamic transmission and an internal combustion engine

In the torque converter, two main processes take place: first, the mechanical energy supplied from the engine to the drive shaft of the torque converter is converted into the kinetic and potential energy of the working fluid, then this energy is converted into mechanical energy on the driven shaft [16, 17, 18]. In the simplest case, the torque converter consists of three coaxial impeller type wheels - pump, turbine, and reactor.

The main feature of hydrodynamic transmission is its automaticity. It lies in the fact that in a certain range of loads and frequency of rotation of the turbine wheel, the desired speed and power modes are provided on the shaft of the pump wheel. It depends on the degree of transparency of the torque converter. So, for example, with an opaque torque converter, a torque and speed constancy mode are established on the pump wheel shaft, and changes in the moment and speed on the turbine wheel shaft do not affect the engine. With partial or full transparency of the torque converter, external changes in speed and load will affect the operation of the heat engine, causing a deviation in the crankshaft speed.

To assess the loading properties of the hydrodynamic transmission, input torque characteristics are constructed [19], which are the dependencies of the torque on the input shaft on the rotation frequency [2]. Based on these dependencies, the amplitude of the moment and speed fluctuations on the drive transmission shaft is determined at the limiting values of the change of similar parameters on the driven shaft [17, 18, 19, 20]. This method of studying the loading properties of hydrodynamic gears is called graph-analytical. The main advantage of these methods is simplicity and clarity. It allows with sufficient accuracy to evaluate the loading properties of hydrodynamic gears. In addition, on its basis, it is possible to determine ways to improve the quality of combining the characteristics of a heat engine and transmission.

The disadvantages include the fact that their capabilities are limited from the point of view of the application in determining the loading properties of other types of gears - electric, hydrostatic. These methods do not allow to take into account the work of special additional automatic devices (control systems), which mainly determine the loading properties of electric and hydrostatic transmissions.

C. A study of the collaboration of an electric transmission and an internal combustion engine

Research methods for the loading properties of electric power transmissions are detailed in [21,22]. In them, loading properties are understood to mean the possibility of achieving, through the transfer of a degree of stabilization of the engine loading mode. The authors propose two methods for the study of loading properties: analytical and graph-analytical.

The only generalized method for evaluating the properties of power transmission is the experimental method, i.e. based on the test results of a prototype tractor. Thus, the search for a rational version of power transmission and determination of the parameters of the latter is carried out to a greater extent empirically. This leads to a long time to create a model of the tractor and high material costs.

There is an urgent need to assess the loading properties of power transmissions at the design stage: tractors, and based on their comparison, determine the rational type of power transmission.

For this, generalized methods are needed that allow analytically using a computer to determine the properties of transmissions of various physical nature. The objective of this article was formed on the basis of the following scientific hypothesis: an increase in the efficiency of a machine-tractor unit can be achieved by selecting the parameters of the tractor's engine-transmission system that determine its loading properties.

The scientific task is to develop a generalized theoretical methodology for studying the loading properties of stepless power transmissions of agricultural tractors, with the help of which at the design stage of the tractor it would be possible to select and justify the power transmission effective in terms of productivity, fuel economy, reliability.

When solving this problem, the following position was accepted as a working hypothesis: the commonality of the functional purpose of power transmission and the similarity of their structural display suggest the possibility of developing generalized methods for studying the loading properties of power transmission.

D. Paper Submission Criteria

Any one author cannot submit more than 05 papers for the same volume/issue. The authors of the accepted manuscripts will be given a copyright form and the form should accompany your final submission. It is noted that:

- Each author profile along with photo (min 100 word) has been included in the final paper.
- Final paper is prepared as per journal the template.

- Contents of the paper are fine and satisfactory. Author (s) can make rectification in the final paper but after the final submission to the journal, rectification is not possible.

II. STATEMENT OF THE PROBLEM

The loading properties of power transmission characterize the power transmission as an object equipped with an automatic control system and give an idea of the power transmission's ability to protect the energy source - the internal combustion engine - from low-frequency load fluctuations.

A feature of the considered task of analyzing the loading properties of a power train is that the object of the study is power gears of various physical nature, for which there are special methods. Private methods are based on taking into account the features of physical processes that occur in each of the specific options []. Therefore, they cannot be used to analyze the loading properties of the transmission of various physical nature. The problem that is solved in this section is to find a generalized approach, on the basis of which a generalized technique can be formed.

In order to show the effectiveness of the applied method, specific examples of the analysis of loading properties should be considered.

The power transmission of any physical nature can be represented by a generalized model, a four-terminal network, the input of which is influenced by the values of Min, nin, and the output are Mout, nout.

The task of constructing a methodology based on the theory of the four-terminal network is to determine the ways of calculating the constant of the four-terminal network, taking into account the physical features of a particular version of the power transmission. The sequence of solving the problem for each specific type of transmission is given.

III. RESEARCH METHOD

Power train as a quadrupole. From the theory of quadrupoles, it is known that the relationship between the input and output parameters can be described by the equations [21]

$$M_{in}=A_1\,\omega_{in}+B_1\,\omega_{out} \qquad (1)$$
$$M_{out}=A_2\,\omega_{in}+B_2\,\omega_{out}$$

The A_1, A_2, B_1, B_2 coefficients in the general case are variable and are determined to take into account the specifics of the power train under study.

generator $\quad U_g=E_1-IR_{ag} \qquad (2)$

engine $\quad U_e=E_2+IR_{ae}.$

For a single-flow hydrostatic transmission, consisting of a pump and a hydraulic motor, these equations have the form:

pump $\quad Q_p=Q_1-py_p \qquad (3)$

hydraulic motor $\quad Q_m=Q_2+py_m.$

Consider the moment equations for electric and hydrostatic machines:

$$M_{in.e}=c_{mh}\,\Phi_{\text{г}}\,I\eta_{mh}^{-1} \qquad (4)$$
$$M_{in.g}=q_p\,p\,\eta_{mp}^{-1} \qquad (5)$$
$$M_{out.e}=c_{me}\,\Phi_e\,I\eta_{me}$$
$$M_{out.g}=q_m\,p\,\eta_{mm}$$

From equations (2) and (3) we find the current and pressure:

$$I=(E_1-E_2)/R=(c_{mg}\Phi_g\omega_g-c_{me}\Phi_e\omega_e)/R; \qquad (6)$$
$$p=(Q_1-Q_2)/y=(q_p\omega_p-q_m\omega_m)/y. \qquad (7)$$

We make the substitution (6) and (7) in (4) and (5), then we obtain for electric transmission:

$$M_{in.e}=\frac{c_{eg}^2\,\Phi_g^2\,\eta_{mg}^{-1}}{R}\,\omega_{in}-\frac{c_{mg}\,c_{me}\,\Phi_g\,\Phi_e\,\eta_{mg}^{-1}}{R}\,\omega_{out}; \qquad (8)$$
$$M_{out.e}=\frac{c_{mg}\,c_{me}\,\Phi_g\,\Phi_e\,\eta_{me}}{R}\,\omega_{in}-\frac{c_{me}^2\,\Phi_e^2\,\eta_{me}}{R}\,\omega_{out}.$$

For hydrostatic transmission:

$$M_{in.g}=\frac{q_p^2\,\eta_{mp}^{-1}}{y}\,\omega_{in}-\frac{q_p\,q_m\,\eta_{mp}^{-1}}{y}\,\omega_{out}; \qquad (9)$$
$$M_{out.g}=\frac{q_p\,q_m\,\eta_{mp}}{y}\,\omega_{in}-\frac{q_m^2\,\eta_{mm}}{y}\,\omega_{out}.$$

where ω_{in} and ω_{out} are angular speeds of input and output shafts power transmission.

Comparing the equations of electric and hydraulic machines, we find that they are identical in structure. It can be seen from them that some parameters in electric and hydrostatic machines are similar: U_g, U_e voltages respectively; Q_p, Q_m consumptions; $c_{mg}\Phi_g$, $c_{me}\Phi_e$ magnetic fluxes respectively; q_p, q_m working volumes; armature current I and pressure of the hydraulic line p, resistance of the armature windings Rad, Rad, and hydraulic conductivity yp, ym.

From a comparison of the obtained expressions with the equations of the four-terminal network (1), it follows that for electric transmission, the coefficients:

$$A_1=\frac{c_{mg}^2\,\Phi_g^2\,\eta_{mg}^{-1}}{R},$$
$$B_1=\frac{c_{mg}\,c_{me}\,\Phi_g\,\Phi_e\,\eta_{me}^{-1}}{R}, \qquad (10)$$
$$A_2=\frac{c_{mg}\,c_{me}\,\Phi_g\,\Phi_e\,\eta_{me}}{R},$$
$$B_2=\frac{c_{me}^2\,\Phi_e^2\,\eta_{me}}{R}$$

similar to the coefficients of the equations describing the hydrostatic transmission:

$$A_1=\frac{q_p^2\,\eta_{mp}^{-1}}{y},$$
$$B_1=\frac{q_m\,q_p\,\eta_{mm}^{-1}}{y}, \qquad (11)$$
$$A_2=\frac{q_m\,q_p\,\eta_{mm}}{y},$$
$$B_2=\frac{q_m^2\,\eta_{mm}}{y},$$

where c_{mg}, c_{me} are the constants of electric machines; Φ_g, Φ_e are magnetic fluxes of the excitation of the generator, engine; R is the impedance of the anchor chain; η_{mg}, η_{mm} are the efficiency of the generator and engine, mechanical and magnetic losses; q_p, q_m are working volumes of a hydraulic pump and a hydraulic motor; y is full hydraulic conductivity; η_{mp}, η_{mm} are the efficiencies of the pump and the motor for hydraulic and mechanical losses.

Equations (1) can be transformed into another form [25]:

$$M_{out}=AM_{in}+B\omega_{in}, \qquad (12)$$
$$\omega_{out}=CM_{in}+D\omega_{in}$$

The coefficients A, B, C, D will be equal to:

- for electric transmissions:

$$A=B_2/B_1=-(A_2/A_1)\,\eta_{mg}\,\eta_{me}=\left(\frac{c_{me}\,\Phi_e}{c_{mg}\,\Phi_g}\right)\eta_{mg}\,\eta_{me}; \qquad (13)$$
$$B=0; \quad C=1/B_1=\frac{R\eta_{mg}}{c_{mg}\,c_{me}\,\Phi_g\,\Phi_e}; \quad D=A_1/B_1.$$

- for hydrostatic transmissions:

$$A=\left(\frac{q_{м}}{q_p}\right)\eta_{mp}\,\eta_{mm}; \quad B=0; \quad C=\frac{y\,\eta_{mp}}{q_p\,q_m}; \quad D=\frac{q_p}{q_m}. \qquad (14)$$

The obtained dependencies allow us to propose a generalized methodology for calculating the external characteristics of continuously variable power transmissions, described below.

IV. THE RESULTS OF THE STUDY

A. Methodology for determining the joint characteristics of an internal combustion engine and hydrostatic transmission

Stage 1. Initial data: heat engine power and parameters of its regulatory characteristic; single-circuit hydrostatic transmission with an adjustable pump; parameters of hydraulic machines - range of variation of the pump displacement qp (0…qmax); hydraulic displacement qm, maximum pressure pmax, nominal speed of the pump shaft np nom, maximum speed of the motor shaft nмmax.

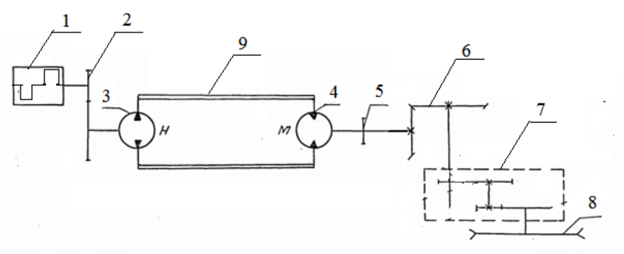

Fig. 1.Simplified kinematic diagram of the motor-transmission installation of the DT-75M tractor with hydrostatic transmission 1- internal combustion engine A-41; 2 – matching gear; 3 – pump; 4 – hydraulic motor; 5 – coupling; 6 – bevel gear; 7 – final drive; 8 – drive wheel; 9 – hydrostatic transmission.

Stage 2. We determine the desired (ideal) law of change in the pump displacement. We use the flow equations of the pump and the hydraulic motor (3). By converting these equations based on the fact that Qp and Qm are equal, we obtain

$$q_p = (N_{pm} + p^2 y_p + p^2 y_m)/(\omega_p\, p) = (N_{pm} + y p^2)/(\omega_p\, p). \quad (15)$$

Since in the general case $y_p = \varphi(q_p)$, then, transforming the right-hand side of expression (15), we obtain the general equation of the required law for changing the pump displacement in the form

$$q_p = ((N_{pm} + p y_m) q_m)/(p(\omega_p q_m - y_m p)). \quad (16)$$

In the expressions (15) and (16), y_p, y_m are the conductivity caused by a leak in the pump and hydraulic motor systems is determined by the formulas [40]:

$$y_p = (k_l q_p)/\pi\mu,$$
$$y_m = (k_l q_m)/\pi\mu, \quad (17)$$

where $k_y = 0{,}15\ 10^{-7}$ is leak rate; μ is dynamic fluid viscosity coefficient.

Note that expression (16) gives more accurate results compared to (15). But since in practice, when the pump displacement changes, its leakage conductivity changes insignificantly, we can use the simplified expression (15) for calculations. The calculation result of the theoretical law of regulating the displacement of the transmission pump of an experimental tractor DT-75M is presented in the figure 22.

Stage 3. We determine the law of change in the pump displacement, taking into account the properties of real regulators.

An analysis of the well-known systems for automatic control of hydrostatic gears shows that the most common types of controllers use pressure feedback.

In this case, the liquid of the power circuit acts on the piston, which overcomes the resistance of springs having different characteristics. As a result of the movement of the piston, the inclination of the cylinder block or washer changes.

The characteristics of the springs and their number are selected so that they approximate the required accuracy of the law of variation of the pump displacement q_p as a function of the load.

Therefore, the real function $q_p = f(p)$ is not a monotone curve, but a broken line, in our case, dependence (15) is approximated by three segments of a straight line (Figure 21) and can be described by the equation:

$$q_н = a_1\, \omega_н - b_1 p - b_1'(p - p_k') - b_1''(p - p_k''), \quad (18)$$

where a_1 is proportionality coefficient between pump shaft speed and displacement

$$a_1 = q_{pmax}/\omega_{max}; \quad (19)$$

b_1, b_1', b_1'' are linear proportionality coefficients characterizing the elasticity of the regulator springs

$$b_i = (\Delta q_i)/(\Delta p_i). \quad (20)$$

In the case under consideration, as was noted in the initial data, the speed of the output of the power transmission is regulated by changing the working volume of the pump. Therefore, the equation of engine displacement will have the form

$$a_2 = q_m - \text{const}. \quad (21)$$

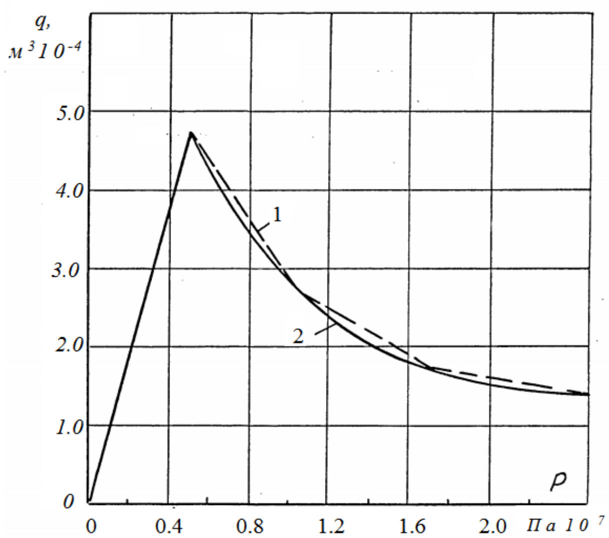

Fig. 2.The law of changing the working volume of the hydrostatic transmission hydraulic pump of the experimental tractor DT-75M as a function of pressure.1 - real, 2 - theoretical.

In the event that the gears provide for regulation by changing the displacement of the motor, it is necessary to establish the required law of change at stage 2. Then expression (21) will have a different form, structurally similar to expression (18).

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Stage 3. We find the equations of the family of input moment characteristics.

In general, the input and output gearboxes with gear ratios are used to coordinate the rotational speeds of the shafts of the heat engine and pump, as well as the hydraulic motor and the working body (for example, propulsion) i_{in}, i_{out} . Thus, between the rotation speed of the motor shafts ω_{in} working body ω_{out} and pump shafts ω_p and hydraulic motor ω_m, the following relationships hold:

$$\omega_p = i_{in}\ \omega_{in};$$

$$\omega_{out} = i_{out}\ \omega_m.$$

The equation of the family of input moment characteristics in this case can be represented

$$M_{in} = q_p\, p = [a_1\, \omega_{in} - b_1\, p - b_1' (p - p_k') - b_1'' (p - p_k'')]p . \quad (22)$$

The pressure in the hydraulic system of the power transmission is determined from the system of equations (3)

$$p = (q_p\ \omega_{in} - q_m\, \omega_{out})/(y_p + y_m). \quad (23)$$

Substituting (18) and (21) into (23), we obtain

$$p = (a_1\, \omega_{in}^2 + b_1' p_k' \omega_{in} + b_1'' p_k'' \omega_{in} - a_2\, \omega_{out})/(y + (b_1 + b_1' + b_1'')\, \omega_{out}). \quad (24)$$

For every ω_{out}=const using expressions (22) and (24), we construct a family of input moment characteristics (Figure 3).

Stage 5. We find the equations of the family of output torque characteristics $M_{out} = \varphi(\omega_{out})$. This equation can be obtained using the equations of the four-terminal network of the form (12), i.e.

$$M_{out} = AM_{in} + B\omega_{in},$$

substituting the values of the coefficients, we obtain

$$M_{out} = M_{in}\ (q_м\, \eta_{mp}\, \eta_{mm})/q_p.$$

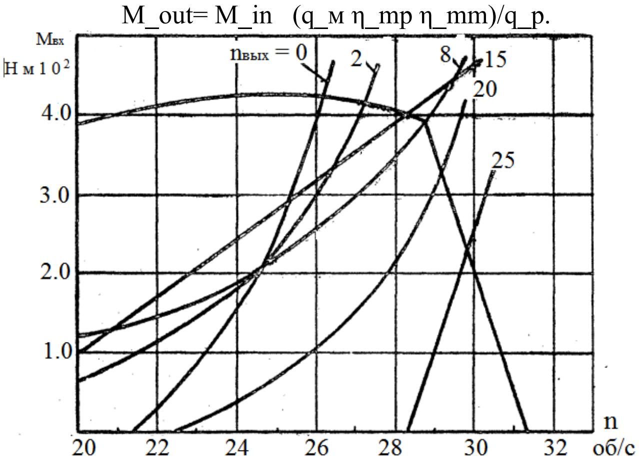

Fig. 3.External characteristic of the A-4I engine and family input torque characteristics of hydrostatic transmissions of an experimental tractor DT-75M.

After that, taking into account (18,19,20,21) and (24), the desired equation can be written

$$M_{out} = M_{in}\ (a_2\,(y + c\,\omega_{in}))/((a_1\, \omega_{in} + c_1' + c_1'')y + a_2\, c\omega_{out}), \quad (25)$$

here:

$$c = b_1 + b_1' + b_1''\ ; \quad c_1' = b_1' p_k'\ ; \quad c_1'' = b_1'' p_k''.$$

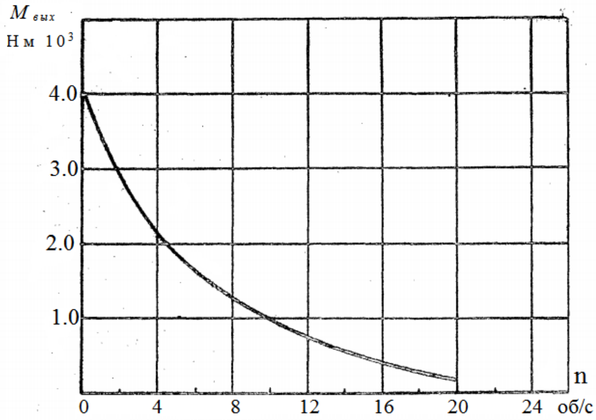

Fig. 4.The output torque characteristic of the hydrostatic transmission of an experimental DT-75M tractor

When constructing the output torque characteristic (Figure 4) by (25), the values M_{in} and ω_{in} take as the coordinates of the points of intersection of the curves of the family of moment characteristics and the regulatory characteristics of the heat engine (Figure 3).

Stage 6. Based on the constructed external characteristics (Figures 3 and 4), we will evaluate the quality of the joint operation of the engine and transmission of the DT-75M tractor.

V. METHODOLOGY FOR CALCULATING THE JOINT CHARACTERISTICS OF AN INTERNAL COMBUSTION ENGINE AND ELECTRIC TRANSMISSION OF A TRACTOR

Initial data

N_{rtm} is rated power of traction motor, W;

R_a is total resistance of the chain of the armature of the generator and traction motor, Ohm;

Ω_{gn} is nominal angular velocity of the generator shaft, rad/s;

η_{mmm} is the efficiency of the traction motor for magnetic and mechanical losses;

$U_{(max\ g)}$ is maximum voltage at the terminals of the generator, V;

ω_{maxg} is maximum angular velocity of the generator shaft, rad/s;

U_{ming} is minimum voltage at the terminals of the generator, V;

I_{max} is maximum current of the armature of electric machines, A;

Ω_{maxm} is maximum angular speed of the shaft of the traction motor, rad/s;

Ω_{minm} is minimum angular speed of the shaft of the traction motor, rad/s;

I_{12} is current strength of the armature circuit, at which switching from the first control range to the second, A;

$〚(c\Phi)〛_i$ is intermediate value of the magnetic flux within the second regulation range, V s/rad.;

I_{max1} is intermediate value of the armature current within the second regulation range, A;

R_{ag} is generator circuit resistance, Ohm;

R_{am} is traction motor armature circuit resistance, Ohm;

$\Omega_{rm}$is rated rotation speed of the traction motor shaft, rad/s;

ΔN_{mechg} is generator idle losses, W;

$\Delta N_{mechm}$is idle loss of the traction motor, W;

$U_{mmin}$is minimum voltage at the clamps of the armature of the traction motor, V;

m_1, k_1 are coefficients of a linear equation approximating the corrector branch of the ICE characteristic;

m_2, k_2 are coefficients of a linear equation approximating the regulatory branch of the ICE characteristic.

Resulting data

M_e~ engine crankshaft torque of ICE, N m;

I_a is armature circuit current, A;

η_{mmg} is coefficient of magnetic and mechanical losses of the generator;

Ω_e is angular rotation speed of the crankshaft of an internal combustion engine, rad/s;

$\Omega_{tm}$is traction motor shaft rotation speed, rad./s;

M_{tm} is torque on the shaft of the traction motor, N m;

η_{mmm} is coefficient of magnetic and mechanical losses of the traction motor;

$\eta_{мд}$ is coefficient of performance for losses in the winding of the armature of the traction motor.

A. Calculation of the theoretical law of regulation magnetic current generator

By transforming the equations describing the electric circuits of the generator and the traction motor, we obtain for a parameter proportional to the value of the magnetic flux [26]:

$$c_g\Phi_g=\left(\frac{N_{rtm}}{\eta_{rmmm}}+I_a^2 R_a\right)/(\Omega_{rg} I_a), \quad (26)$$

where:

$N_{rtm}$is rated power of traction motor, W;

η_{rmmm} is rated efficiency of the traction motor;

$R_a = R_{ag} + R_{am} + R_{pg} + R_{bg} + R_{bm}$ is total electrical resistance of the chain of the armature of the generator and traction motor, Ohm;

R_{ag} is generator circuit resistance, Ohm;

R_{am} is same of the electric motor ohm;

R_{sg} is same of sequential field winding of the generator, Ohm;

R_{bg} is same of brush contact generator, Ohm;

R_{bm} is same of brush contact of the electric motor, Ohm;

I_a is armature circuit current, A;

$\Omega_{rg}$is rated angular speed of the generator shaft, rad/s.

B. The mathematical description of the real laws of regulation magnetic flux generator and traction motor

An analysis of the principles underlying the formation of the laws of change in magnetic fluxes suggests that they (laws) can be described by dependencies:

Generator

$$c_g\Phi_g= a_1\Omega_g- b_1 I_a , \quad (27)$$

$$a_1= U_{maxg}/(\Omega_{maxg}^2),$$

$$b_1=((c_g\Phi_g)_0-(c_g\Phi_g))/I_{max},$$

U_{maxg} is maximum voltage of the generator, V;

Ω_{maxg} is maximum angular velocity of the generator shaft, rad. /s.

1st subband. The magnetic flux of the electric motor here remains unchanged and is equal to

$$c_m\Phi_m= U_{maxg}/(\Omega_{maxm}), \quad (28)$$

where: Ω_{maxm} is maximum angular speed of the motor shaft, rad./s.

II. subrange.

$$c_m\Phi_m= (c_m\Phi_m)_0+ b_2 (I_a-I_0), \quad (29)$$

$$(c_m\Phi_m)_0 = a_2$$

is magnetic flux of the traction motor at the starting point of the second subband;

I_0 is current strength of the armature circuit at the same point, A;

$$b_2=((c_m\Phi_m)_k-(c_\Phi_m)_0)/(I_{max}- I_0),$$

$$(c_m\Phi_m)_k$$

is magnetic flux of the electric motor at the end point of the second control sub-range.

Note: the law of variation of the magnetic fluxes of the generator and the electric motor can take the form of a broken line.

C. Calculation of the current strength of the armature circuit

I. subband

$$I_a= (a_1\Omega_g^2- a_2\Omega_m)/(R_a+b_1\Omega_g), \quad (30)$$

II. subband

$$I_a= (a_1\Omega_g^2+(b_2 I_0- a_2)\Omega_m)/(R_a+ b_1\Omega_g+ b_2\Omega_m). \quad (31)$$

D. Calculation of the generator efficiency by magnetic and mechanical losses

$$\eta_{мнг}= (E_g I_я)/(E_g I_я \Delta N_{nmechr} (\Omega_п/\Omega_{гн})^2+ k_1 E_g^{\alpha_1}), \quad (32)$$

k_1, α_1 are smallest coefficients squares based on dependency $\Delta N_{mg}=f(E_r)$ (Figure 5);

ΔN_{mg} is magnetic power loss, W;

ΔN_{nmechg} is mechanical losses in the generator, W.

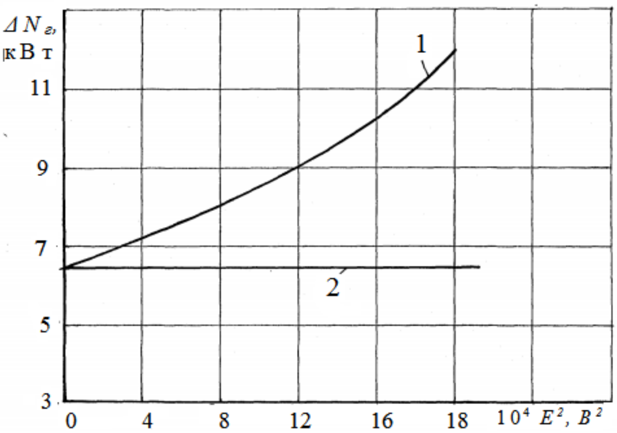

Fig. 5.Magnetic (1) and mechanical (2) losses in the ГПА-220М generator

E. Calculation of torque on the generator shaft

$$M_g= \eta_{mmg}^{-1} (a_1\Omega_g- b_1 I_a) I_a. \quad (33)$$

Calculation of the efficiency of the traction motor for magnetic and mechanical losses

$$\eta_{mmm}=(E_m I_a-\Delta N_{nmechm} (\Omega_m/\Omega_{mn})^2-k_2 E_m^{\alpha_2})/(E_m/I_a), \quad (34)$$

$E_m = E_g - I_a (R_{ag} + R_{am})$,

k_2, α_2 are least squares coefficients based on the relationship

$\Delta N_{mm} = f(E_д)$ (Figure 6);

ΔN_{mm} is magnetic power loss, W;

ΔN_{nmechm} is mechanical losses in the electric motor, W.

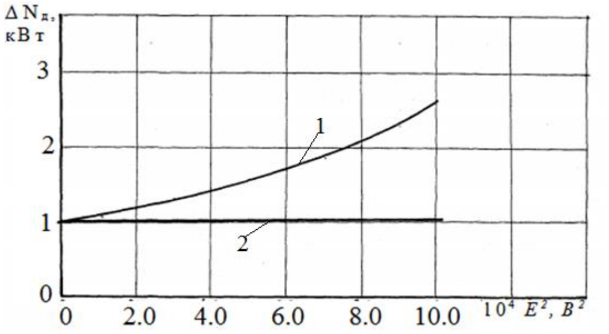

Fig. 6.Magnetic (1) and mechanical (2) traction losses of the ЭДП-200M electric motor.

F. Calculation of the efficiency of electrical machines for losses in the armature winding

Generator $\eta_{mg} = U_g/(U_g + I_a R_a)$. (35)

Electric motor $\eta_{mm} = (U_g - I_a R_a)/U_g$. (36)

G. Calculation of torque on the traction shaft

I. subband

$M_{tm} = (M_g a_2 \eta_{mmg} \eta_{mmm})/(a_1 \Omega_g - b_1 I_a)$. (37)

II. subband

$M_{tm} = M_g ([b]_2 I_a - (b_2 I_0 - a_2)] \eta_{mmg} \eta_{mmm})/(a_1 \Omega_r - b_1 I_a)$, (38)

M_g and Ω_g are torque and angular velocity on the generator shaft are defined as the coordinates of the intersection points of the combined characteristics of the engine and transmission.

H. An example of calculating the joint characteristics of an internal combustion engine and an electric transmission of the DET-250M2 tractor

Initial data:

Diesel engine	B-3I;
Rated power	$N_{ен}$= 242880 W;
Rated speed	$n_{(ен)}$= 1400 rpm;
Maximum moment	M_{max}= I960 Nm;
Minimum speed	n_{min} = 900 rpm;
GShh-220M generator	
Rated power	N_{nr} = 220000 W;
Rated voltage	U_{nr}=310 V;
Maximum voltage	U_{gmax}= 500 v;
Rated current	I_{gr} = 710 A;
Maximum current	I_{gmax}= II00 A;
Rated speed	n_{rg} = 2120 rpm;
Armature winding resistance	R_{ag} = 0,00763 Ohm;
Series field resistance	$R_{по}$=0,0034 Ohm;
Generator efficiency	η = 0,91;
EDP-220M electric motor	
Rated power	$N_{тдн}$= 220000 W;
Rated voltage	$U_{тдн}$=300 V;
Maximum voltage	U_{mmax}= 500 V;
Rated speed	n_{mr}= 430 rpm;
Maximum speed	n_{mmax} = 2000 rpm;
Armature winding resistance	R_{am}= 0,013 Ohm.

I. Calculation of the theoretical law of regulation magnetic flux generator

Table- I: The theoretical law of regulation of the magnetic flux of a generator

$I_я$, A	100	200	300	400	500	600	700	800	900	1000	1100
$c_r\Phi_r$, Bc	8.95	4.5	3.02	2.31	1.88	1.6	1.41	1.27	1.16	1.08	1.02

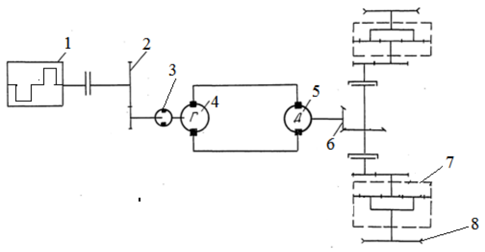

Fig. 7.Simplified kinematic diagram of a DET-250M2 tractor engine-transmission installation.

J. Calculation of the real laws of regulation of magnetic fluxes

a_1= 500/2312 = 9.37·10-3 (V/s^(-2));

$(c_g \Phi_g)0$ = 500/231 = 2.16 (V/s-1);

$(c_g \Phi_g)k$ = (220000 + 11002 · 0.1958)/(IIOO • 222,1) = 0,997(V/s-1);

b_1 = (2,16-0,997)/IIOO = 1,06 10-3 (V·s/A);

$[(c_m \Phi_m)]_0$= 500/209,44 = 2,39 (V/s-1);

$(c_m \Phi_m)k$ = (199,93-1100 · 0.0221)/30 = 60 (V/s-1);

b_2= (5.5-2,39)/(600-370) = 1,37 · 10-2 (V·s/A);

b_3= (6,0-5,5)/500 = 1,0 ·10-3(V·s/A);

$c_m \Phi_m$ = 2,39 4- 1,37· 10-2 (I_a- 370) (V·s);

$c_m \Phi_m$= 5,5 + 1,0 ·10-3 (I_a - 600) (V·s);

The graphs constructed on the basis of the obtained dependencies are presented in Figures 8 and 9.

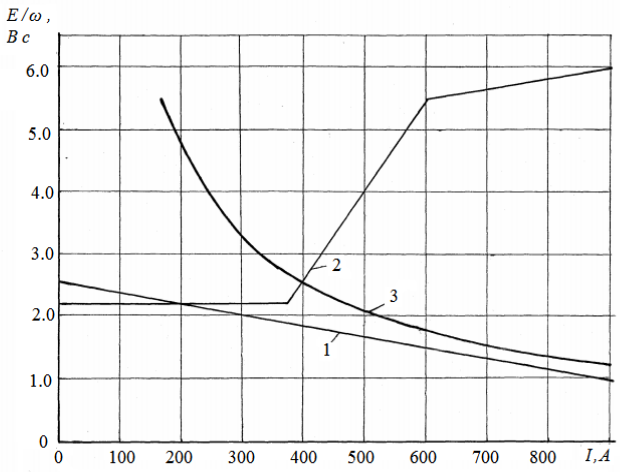

Fig. 8.The laws of regulation of magnetic flux: 1 - generator (real); 2 - traction electric motor (real); 3 - generator (theoretical)

K. Calculation of the current strength of the armature

I. subband

$$I_a = (9.37\cdot 10^{-3}\,\Omega_g^2 - 2.39\Omega_m)/(0.04167 + 10^{-3}\,\Omega_g),\ \text{when } I_a \leqslant 370\ A;$$

II. subband

$$a = (9.37\cdot 10^{-3}\,\Omega_g^2 - 2.39\Omega_g)/(0.04167 + 〚1.06\cdot 10〛^{-3}\,\Omega_г + 1.37\cdot 10^{-2}\,\Omega_д),\ \text{when } (370 < I_a \leqslant 600)\ A;$$

$$I_я = (9.37\cdot 10^{-3}\,\Omega_g^2 - 4.9\cdot\Omega_m)/(0.04167 + 〚1.06\cdot 10〛^{-3}\,\Omega_g + 1.0\cdot 10^{-3}\,\Omega_m),\ \text{when } (600 < I_a \leqslant 1100)$$

The electromechanical characteristic of the electric motor is shown in Figure 11.

Simplified kinematic diagram of a DET-250M2 tractor engine-transmission installation.

L. Calculation of the generator efficiency by magnetic and mechanical losses

$$\eta_{ммг} = (E_g I_a)/(E_г I_я + 0.1313\,〚\Omega〛_г^2 + 6.59\cdot 10^{-4}\,E_Г^{2.6}),$$

$$E_g = 3.37\cdot 10^{-3}\,\Omega_g - 1.16\cdot 10^{-3}\,I_a.$$

Here, an expression approximating the dependence of magnetic and mechanical losses is obtained by the least-squares method based on Figure 6. The dependence of the generator efficiency on magnetic and mechanical losses is shown in Figure 10.

M. Calculation of torque on the shaft of the generator and internal combustion engine

$$M_g = \eta_{mmm}(9.37\cdot 10^{-3}\,\Omega_г - 1.06\cdot 10^{-3}\,I_a)\,I_a,$$

on the shaft of an internal combustion engine

$$M_e = M_g\cdot i,$$

where i = 1.414 is the drive ratio of matching gear.

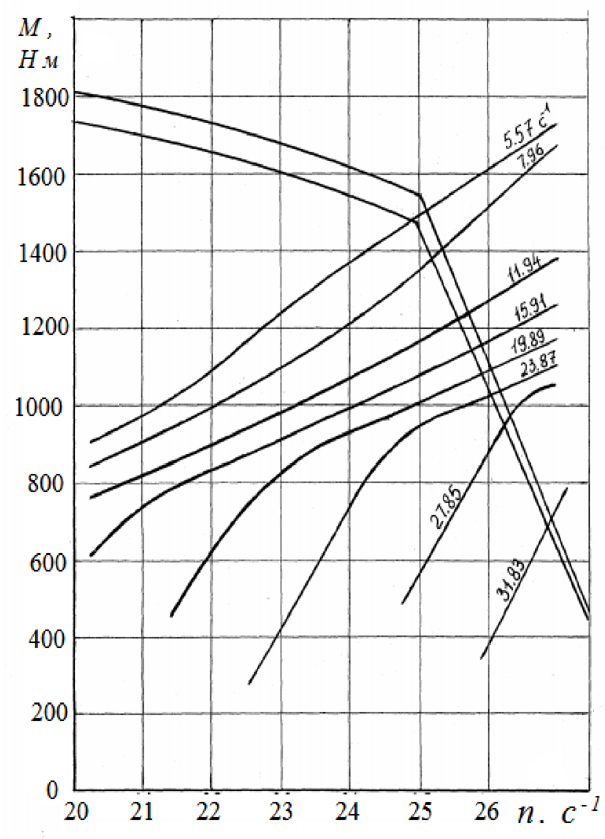

Fig. 9.Combining the characteristics of the B-3I engine and GPA-220M generator of DET-250M2 tractor

N. Calculation of the efficiency of the electric motor by magnetic and mechanical losses

$$\eta_{mmm} = (E_m I_a - 0.499\,\Omega_{тд}^2 - 4.67\cdot 10^{-4}\,E_m^{2.6})/(E_д I_я),$$

$$E_m = E_g - 0.04167\cdot I_a.$$

The dependence of the efficiency of the electric motor on magnetic and mechanical losses is presented in Figure 10.

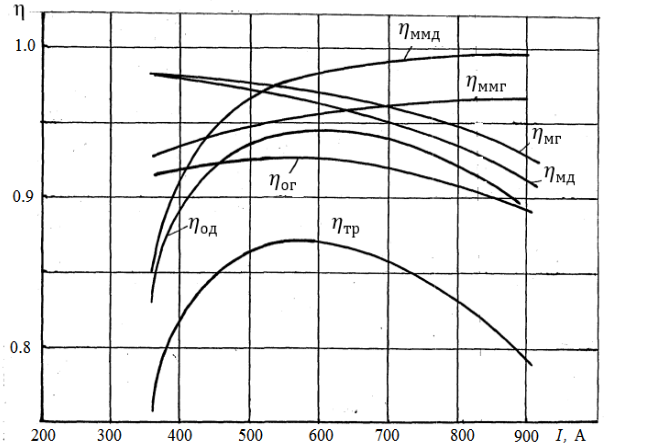

Fig. 10. The calculated values of the efficiency of electric transmission machines of DET-250M2 tractor

O. Calculation of torque on the motor shaft

$$M_{тд} = M_g\,(2.35\,\eta_{mmg}\,\eta_{mmm})/(9.37\cdot 10^{-3}\,\Omega_g - 1.06\cdot 10^{-3}\,I_a),\ \text{when } I_a \leqslant 370\ A;$$

$$M_{тд} = M_g\,((1.37\cdot 10^{-2}\,I_a - 2.72)\eta_{mmg}\,\eta_{mmm})/(9.37\cdot 10^{-3}\,\Omega_g - 1.06\cdot 10^{-3}\,I_a),\ \text{when } (370 < I_a \leqslant 600)\ A;$$

$$M_{тд} = M_{(g)}\,((1.0\cdot 10^{-3}\,I_a - 4.9)\eta_{mmg}\,\eta_{mmm})/(9.37\cdot 10^{-3}\,\Omega_g - 1.06\cdot 10^{-3}\,I_a),\ \text{when } (600 < I_a \leqslant 1100)\ A;$$

The dependences reflecting the relationship between the torque on the motor shaft and the armature current are shown in Figure 11.

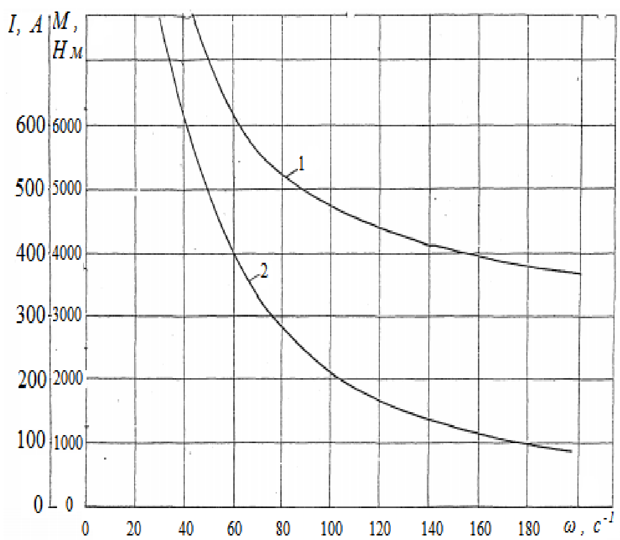

Fig. 11. Electromechanical (I) and mechanical (2) characteristics of the EDP-20 traction motor.

VI. DISCUSSION

The results obtained indicate that the proposed methodology is generalized. It allows you to carry out calculations of both the joint characteristics of the internal combustion engine and transmissions of various physical nature and energy indicators. Therefore, make an informed choice of a particular power train at the design stage of a mobile unit.

An analysis of the calculated joint characteristics of the engine and transmission makes it possible to recommend rational operating modes of the mobile unit at the design stage, taking into account the features of the relief and soil.

VII. CONCLUSIONS

1. Based on the analysis of information sources, it was found that in the theory of power transmission of mobile units there are no generalized methods for comparative studies of power transmission of various physical nature (electrical, hydraulic).

2. Stepless gears, regardless of the physical nature of the machines used in them, can be described by generalized equations in the form of quadrupole equations. This makes it possible to develop a generalized methodology for calculating characteristics that reflect the loading properties of the transmission.

3. The article shows that, based on a generalized methodology for studying the loading properties of power transmissions, at the tractor design stage, it is possible to determine the combined characteristics of an internal combustion engine and transmission, the desired laws of magnetic flux control in electric and displacement in hydrostatic power transmissions. In addition, the technical requirements for electric and hydrostatic machines can be determined from the point of view of the maximum and minimum values of magnetic flux, armature current, voltage, displacement, pressure in the hydraulic system, flow rate of the working fluid, and shaft rotation speed.

4. One of the main advantages of the developed generalized methodology is the possibility of its use at the design stage of a machine-tractor unit. Moreover, it is useful from the point of view of the choice and justification of effective power transmission of various physical nature.

REFERENCES

1. Yakovenko F.I., Bednyakov P.V., Nosov A.A. Acceleration of scientific and technological progress in tractor engineering and its economic evaluation. - // Tractors and agricultural machinery. - 1983. - 11. - C.1-3.
2. Anokhin V.I. The use of torque converters on high-speed tracked agricultural tractors. - M.: Mechanical Engineering, 1972. - 304 p.
3. Balandin V.M. Volgograd Tractor Plant named after F.E. Dzerzhinsky // Tractors and agricultural machinery. - 1982. - 12 - S. 3-6.
4. Epishkov N.E. The study of electromechanical gears and the rationale for their rational use in agricultural tractors: Abstract. dis. ... cand. tech. sciences. - Chelyabinsk, CHIMZSH. - 1974. - 25 p.
5. Novozhilov F.A. Justification and study of rational schemes of electromechanical gears of self-propelled machines: Abstract. dis ... cand. tech. sciences. - Chelyabinsk, CHIMESKH. - 1969. - 22 s,
6. Noskov V.A. The study of electromechanical gears for self-propelled machines with power take-off from a heat engine: Abstract. dis ... cand. tech. sciences. - Chelyabinsk, CHIMESKH. - 1975. - 25 p.
7. Antonov A.E., Zapryagaev M.M., Hydro-volume gears of transport and traction machines. - L .: Engineering, 1968. - 212 p.
8. Vasilenko V.A., Hydraulic equipment of mobile machines. Directory. - M.: Mechanical Engineering, 1983. - 301 p.
9. Bashta T.L., Zayachenko I.Z., etc. Volumetric hydraulic drives, - M.: Mechanical Engineering, 1969. - 628 p.
10. Dokukin A.V., Rogov A.Ya., Feifep L.S. Multiple action radial piston motors. - M.: Mechanical Engineering, 1980. - 288 p.
11. Kurmaev R.Kh., Petrov S.E. The use of hydrostatic transmissions in the construction of vehicles // News of MSTU "MAMI". - No. 2 (8). - 2009 .-- S. 108-113.
12. Sergeev V.P. Justification of the main parameters of the hydromechanical transmission of forestry tractors: Abstract. dis ... cand. tech. sciences. - L .: LTA, 1990 -19 p.
13. Krumbolt L.N., Golovashkin F.P., Strelkov A.G. Hydrostatic transmissions in transmissions of special self-propelled machines // News of MSTU "MAMI". - No. 1 (15). –V.1. - 2013 .-- S. 96-103.
14. Lebedev A.T. Regulators of operating modes of tractors with hydrostatic transmission. - M.: 1967. - 64 p.
15. Wu Hai Kuan. Improving the efficiency of skidders by substantiating rational gear ratios of promising transmissions: Abstract. dis ... cand. tech. sciences. - St. Petersburg, 2015 .-- 19 p.
16. Ageev L.E., Shkrabak B.C., Margulis-Yakushev V.Yu. Heavy duty agricultural tractors. - L .: Agropromizdat, 1986 .-- 415 p.
17. Narbut A.N. Hydromechanical transmission cars. At 3 hours. Part 3. Management systems. - M .: MADI, 1999 .-- 44 p.
18. Narbut A.N. Torque converters. - M.: Mechanical Engineering, 1966, - 215 s,
19. Laptev Yu.N. Autotractor torque converters. - M.: Mechanical Engineering, 1973. - 280 p.
20. Aleksapolsky D.Ya. Hydrodynamic transmission. - M .: Mashgiz, 1963 .-- 271 p.
21. Bondar V.N., Kondakov S.V., Novoselsky A.E. A rational combination of the characteristics of an internal combustion engine and an electric DC drive of an industrial tractor // Vestnik SUSU. - No. 11. - 2006. - S.85-90.
22. Kondakov S.V., Novoselsky A.E. Combining the characteristics of an internal combustion engine and electric transmission of an industrial tractor // Vestnik SUSU. - No. 23.- 2008. - P.40-45.
23. Voldek A.I. Electric cars. - L .: Energy, 1974.- 839 p.
24. Berdnikov V.V. Applied theory of hydraulic circuits. - M.: Mechanical Engineering, 1980 .-- 192 s,
25. Andreev Yu.M., Isaakyan K.G., Prolygin A.P. and others. Electric machines in traction autonomous electric drive. - M .: Energy, 1979.- 240 s,
26. Yusupov R.Kh. Increasing the efficiency of the functioning of the machine-tractor unit by improving the static and dynamic characteristics of its energy part. “Dis ... doctor.” tech. sciences. - St. Petersburg, 1993 .-- 497 p.