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Concept of A Low-Cost Hybrid Car

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Abstract: Fuel economy and emissions reduction are the vital tasks, which are currently being solved by dismissing cars with only internal combustion engines to the benefit of electric and hybrid electric vehicles (HEV). HEVs have a significant advantage over electric vehicles, namely a bigger drive range and independence from the charging stations at hand. However, high cost and big weight of HEVs discourage their wider use. To minimize the cost and weight of HEV, the algorithm of its power plant operation is changed. This paper presents a method for calculating the electric drive mode of a hybrid vehicle in accordance with the proposed algorithm for the power plant operation. The results of calculation of the main characteristics are presented and analyzed. The experimental studies were carried out with the hybrid vehicle developed on the base on the Lanos pickup vehicle. The research results showed good agreement between the experimental and the calculated results. The proposed technical solution is presented as practical and effective. The results of this work can be used in the automotive industry. The development helps to reduce the cost and weight of hybrid vehicles, maintaining their operational characteristics and good economic and environmental indicators.

Keywords: Hybrid vehicle, hybrid vehicle calculation, valve electric motor, electric vehicle, traction electric drive

1. Introduction

Fuel economy and emissions reduction are topical for both manufacturers and owners of various vehicles [1]–[4]. One of the effective ways to solve these problems is transition to electric vehicles [5]. But electric vehicles have their own rather significant drawbacks that do not allow them to completely replace the cars with internal combustion engines. The main disadvantages are as follows: low mileage without recharging the traction battery, long charging time and an undeveloped infrastructure of charging stations [6], [7]. To charge a large number of electric vehicles, it is required to significantly increase the capacity of power plants and electric grids, develop a charging infrastructure and introduce alternative energy sources everywhere [8], [9]. In addition, current electric vehicles are costly and heavy as they need to use traction batteries of large capacity [10].

At this stage of technological development, a more acceptable partial solution to the problem of efficiency and environmental friendliness of road transport is the use of hybrid vehicles, which do not possess the main disadvantages of electric vehicles [11].

Hybrid cars have a higher cost and greater weight than the cars with only internal combustion engine, since, in addition to internal combustion engines, they must have both an electric traction drive and a traction accumulator battery (TAB), although the TAB has a much smaller capacity (and therefore smaller dimensions and cost) than the one in electric vehicles [12]–[14]. Therefore, reducing the cost and weight of hybrid cars and their energy consumption while maintaining their main positive characteristics is a priority.

Problems of fuel economy and environment are already partially solved in hybrid electric vehicles called Mild Hybrid Electric Vehicles (MHEV) [15]. MHEVs combine the best qualities of electric and internal combustion engine (ICE) vehicles [16].

MHEVs use mostly a 48 V electrical system as it is easily integrated into a vehicle being modular, compact, safe, lightweight and inexpensive [17].

There are 5 main powertrain architectures for MHEV [17]:

• P0 – electric motor (EM) is connected to the internal combustion engine by a belt on the front-wheel drive of auxiliary units

• P1 – EM is directly connected to the crankshaft of the internal combustion engine

• P2 – EM is attached on the side (through a belt) or is built-in between the internal combustion engine and the transmission; it is separated from the ICE and has the same speed as the ICE (or a multiple of it)

• P3 – EM is connected to the transmission through a gearing, it is separated from the internal combustion engine, and its speed is a multiple of the wheels' rotation speed

• P4 – EM is connected via a gear train on the rear axle of the vehicle; it is separated from the internal combustion engine and located in the rear axle drive or the wheel hub

But apart from these basic configurations, there are many different P-configurations, and it is also possible to combine two or more P-configurations, each having its advantages and disadvantages. The choice of configuration depends on many factors: technical and material capabilities, vehicle configuration (manual or automatic transmission), vehicle purpose, operating conditions, etc.

Plug-in Hybrid Electric Vehicles (PHEV) have larger traction batteries than conventional hybrid vehicles. Therefore, they are more expensive and heavier not only than the cars with ICE but also than the not plug-in hybrid cars.

Scientists and engineers from all over the world are engaged in eliminating the disadvantages of hybrid vehicles [18]. For example, [19] proposes a power management strategy for a 48 V MHEV using a battery with a lower capacity and lower voltage than a fully hybrid electric vehicle.

Special attention is paid to the temperature control of the traction battery. For example, in paper [20] temperature control is developed to warm up a 48 V MHEV battery to quickly restore hybrid functions in cold climates.

Paper [21] presents a strategy for adaptive power control of MHEV with a belt starter-generator. The purpose of this development is to minimize fuel consumption. The simulation results show that the proposed strategy is effective in various driving cycles.

The authors of article [22] developed a strategy for controlling regenerative braking with a spatial distribution of the energy of state. This development is based on the Q-learning algorithm. The developers insist that the proposed strategy maintains battery power balance better than the traditional strategy.

Considering the abovesaid, we believe that reducing the cost and weight of a hybrid car while maintaining its main positive characteristics is a priority. The paper proposes an algorithm for operation of hybrid vehicles engines, including plug-in hybrid vehicles, which allows reducing their cost and weight while maintaining quite good economic and environmental performance of the vehicle.

2. Problem Statement

An obvious way to cut down the cost, as well as the weight and dimensions of the traction drive elements, is to reduce the power of the electric motor, which in turn will decrease the current consumed by the traction electric drive, and, therefore, diminish the energy capacity and weight of the TAB. Then, due to the decrease in the weight of the TAB and the electric drive, the consumption of fuel and electricity will lower. However, this solution in traditional hybrid vehicles leads to unacceptably long acceleration time, which makes the vehicle a hindrance in the urban traffic today. There are modern, so-called MHEVs with a TAB voltage of 48 V, which enable slow driving on electric traction in premises, yards, parking lots [23]–[25]. But such traffic is unacceptable on public roads, it is possible only as an exception, for example, in traffic jams.

Consequently, a significant decrease in the power of the traction electric motor and the capacity of the TAB requires a new algorithm for the operation of the hybrid car engines, since all traditional hybrid cars have a start-stop system and accelerate in an electric mode, which requires a powerful electric drive. In addition, to reduce the power of the electric drive, not only a new algorithm is required or a theoretical substantiation for the choice of traction motor power for this algorithm, but also the correct choice of the energy capacity for the TAB [23]. An experimental verification of the proposed algorithm and the obtained calculated values is also required.

We use the fact that, as will be shown below, for steady motion at relatively low speeds, a relatively low power of the electric motor is necessary. Therefore, to ensure the possibility of reducing the power of the traction electric drive, it is necessary to develop an algorithm describing the driving conditions for using the internal combustion engine and the conditions for using the electric drive. Such an algorithm would be different from the algorithm commonly used in hybrid vehicles. It will also differ from the algorithm used in MHEV, including MHEVs where the electric motor (EM) is connected directly with the transmission (P3, P4).

2.1 Description Of The Proposed Algorithm

Before moving on to the algorithm in question, we will consider how we are going to reduce energy consumption and, consequently, the cost of a kilometer of mileage, and lessen harmful emissions. For this, we will use two sources of energy. The first source is the hydrocarbon fuel, and the second source is the maximum utilization of the kinetic and potential energy of a moving vehicle, notably not only in the form of regeneration, but also directly for the movement of the car, with minimal losses, without converting kinetic and potential energy into other types of energy. Also, as an auxiliary source, we can use the AC power grid (plug-in hybrid) [5]. Such an auxiliary source is not necessary and can only be used when the car can be parked overnight near a power source. This auxiliary source is expedient because a kilometer of travel on energy from the electric network is several times cheaper than a kilometer of travel on the hydrocarbon fuel.

In order to minimize the power of the traction electric drive in the hybrid mode in the proposed vehicle the operating modes of the ICE with low load but with high specific fuel consumption are replaced by movement with an electric drive. It is a mainly steady motion at a relatively low speed (50-60 km/h) on an asphalt road without a noticeable rise. Also in some cases, when large accelerations are not required, it is a slow movement with ICE working in low gears (for example, in traffic jams, premises, yards, parking lots), when both speed and acceleration are low. The idling mode of the internal combustion engine using the start-stop system is excluded.

If the engines of modern cars, both ICEs and electric ones, are used to gain speed, they must be powerful enough so that the car does not fall out of the traffic flow. Consequently, traction motors, as well as TABs of modern hybrid vehicles, have a relatively high power, because in all hybrid vehicles driving starts with an electric motor. In the proposed MHEV operation algorithm, an energetic gain of speed is performed on an internal combustion engine with manual or automatic gear shifting. In cases where large accelerations are not required, and no noticeable rise can be seen, it is possible to start moving with a low-power electric drive (for example, in traffic jams). When driving in urban conditions, where the maximum speed is limited to 50-60 km/h, the movement of the proposed car with a manual transmission begins with the automatic start of the internal combustion engine by the "start-stop" system. Then, using the internal combustion engine, with gear shifting, we pick up a speed of 30-50 km/h, the gearbox is set to the neutral position, and then, automatically, using the start-stop system, the internal combustion engine stops and an automatic transition to the electric drive takes place. This happens due to the fact that the start-stop system reacts to the opening of the transmission, i.e. either the clutch pedal is depressed or the gear is not engaged (transmission neutral position). On the electric drive, a further set of speed is made up to 50-60 km/h and then the steady motion continues. This steady motion occurs in an active acceleration-coasting mode. With such a movement, either coasting occurs when the accelerator pedal is released and the speed drops, or electrical acceleration takes place, which compensates for a certain drop in speed and is made by connecting the power to the traction motor by pressing the accelerator pedal. The small absolute values of positive or negative acceleration required in this mode can be fully provided by the electric motor, which is controlled by the driver using the accelerator pedal and, if necessary, regenerative braking by retracting brake pedal from the pedal stop. The gear ratio of the electric drive gear is optimized for this speed range, and therefore the car does not accelerate above the speed of 60 km/h on the electric motor, even when the accelerator pedal is fully depressed. It is convenient in the urban conditions to comply with the speed limit. If it is necessary to pick up a speed exceeding 50-60 km/h, the driver, having pressed the clutch, turns on the appropriate gear and then, after engaging the clutch, the internal combustion engine is automatically started without a starter from the kinetic energy of the moving car. At this speed, there are no noticeable jolts when starting the ICE [18]. Next, the electric drive is turned off due to the fact that the transmission is closed, i.e. when the clutch pedal is released, the gear is engaged (there is no neutral position of the gearbox), and further movement occurs with the help of the ICE.

Before stopping, for example at a traffic light, a service regenerative electric braking is made. To do this, the driver presses the brake pedal a little (only moves it away from the stop), the brake light is triggered, and, together with it, the service braking begins. In this case, the brake pads do not yet touch the discs, but when it is necessary to finally stop the car, the driver increases the pressure on the brake pedal and the standard brake system stops the car. This algorithm is especially effective when driving with frequent stops, which is typical for urban driving.

The proposed algorithm improves the balance of electrical energy in the TAB, since during acceleration, hydrocarbon fuel is consumed, and during regenerative braking the TAB is recharged. This energy of the TAB after acceleration is immediately consumed with further active acceleration-coasting, freeing up some TAB capacity for charging. Therefore, the TAB may be of small capacity. The relatively small capacity of the TAB of such a hybrid vehicle in a rechargeable version allows you to quickly charge the TAB from a convenience network with a relatively low power consumption. This power does not exceed the permissible power of almost any convenience socket.

Since the car is capable of running not only in hybrid mode, but also on gasoline, there is no problem with the range. This is also facilitated by the fact that a relatively light TAB and an electric motor are used, therefore, the mass of the car does not increase significantly compared to a conventional car. Respectively, this fact also contributes to a relatively low fuel consumption in the driving mode on the ICE and low energy consumption in the driving mode on the electric drive. In contrast to a traditional plug-in hybrid car, the internal combustion engine of the car in question is

more likely to work when accelerating, so it has a better thermal regime and better heating of the interior. In other words, fewer ICE starts are required due to the need of raising the coolant temperature.

Fig. 1 shows a functional diagram of the proposed algorithm. In this diagram, immediately after turning on the ignition, there is a branch instruction (conditional jump instruction) "Was the ICE launched?" In the case of the option (state) "No", control is transferred to the other branch instructions described below. In the case of "Yes" option, the readings of the speed sensor are checked, they are processed by the branch instruction "Is the speed over 40 km/h?". If "No", the processing is repeated, if "Yes", then the next branch instruction works – "Is the ICE spinning?" If "Yes", then the driver continues to drive as in a normal car with the electric motor off. If the driver puts the gearshift lever in the neutral position, the start-stop system will shut off the internal combustion engine and the branch instruction will go into the "No" state. Control then passes to the next two branch instructions. This is also where control comes after the first branch instruction, if there is the state "No" in it. These two branch instructions are "Is the accelerator pedal depressed?" and "Is the brake pedal out of the stop?" For the branch instruction "Is the accelerator pedal depressed?" the "Yes" state leads to the power supply of the traction motor with its current regulation by the accelerator pedal, "No" – to the shutdown of the electric motor. For the branch instruction "Is the brake pedal out of the stop?" the "Yes" state leads to the transfer of the traction motor to the regeneration mode, "No" leads to the shutdown of the electric motor. These two branch commands operate alternately as the driver presses the accelerator and brake pedals alternately with the right foot. In order not to clutter up the algorithm diagram, it does not show all the paths of organizing the cycles available in the program of the process microcontroller after any states of all branch instructions, as well as the elements of the start-stop system involved in the work.
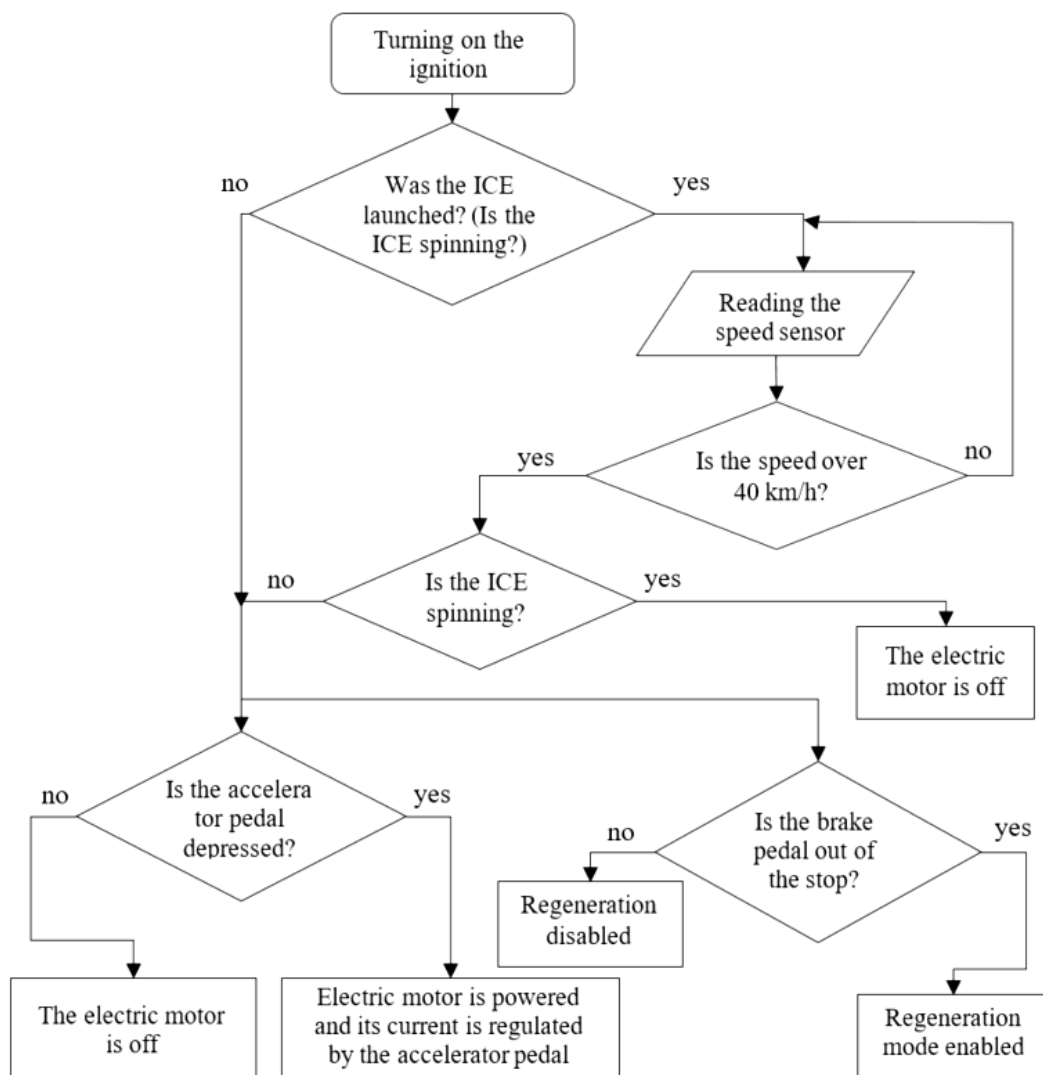

Fig. 1 - Algorithm of operation of a hybrid car with a manual transmission and an integrated start-stop system at speeds up to 50-60 km/h

In order to confirm the merits of the proposed algorithm, we will calculate the Lanos pickup car, converted at Kharkiv National Automobile and Highway University into a hybrid car with the above mode of operation of the main

ICE and auxiliary valve electric motor (VEM) [18]. This electric motor is kinematically connected via a poly-V belt drive to the output shaft of the vehicle's manual transmission. The kinematic diagram of a hybrid vehicle is shown in Fig. 2, and the exterior view of the car and the belt drive between the VEM and the secondary shaft of the gearbox are presented in Fig. 3 [18].
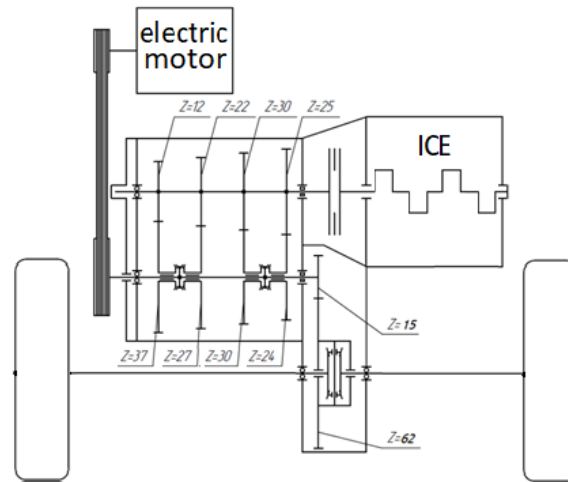

Fig. 2 - Kinematic diagram of the hybrid vehicle "Lanos pickup"
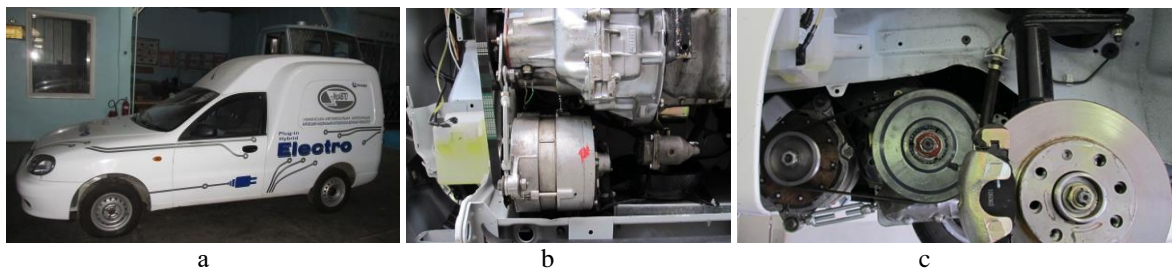

a   b   c

Fig. 3 - Plug-in hybrid car based on the Lanos pickup car (a) an exterior view; (b, c) an electric motor connected through a poly-V belt drive with a secondary shaft of a mechanical transmission

The valve electric motor is made on the basis of a synchronous electric machine G-290 with electromagnetic excitation. Electromagnetic excitation of a synchronous electric machine enables to achieve better coasting than excitation with permanent magnets. The reverse diodes of the power control switch of the three-phase controlled bridge of the valve inverter based on MOSFET transistors operate as a rectifier in the generator mode. Such mode is used for regenerative braking. We will make the calculations according to the methodology developed in paper [11].

2.2 Calculating The Main Characteristics Of The Plug-In Hybrid Car

2.2.1 Calculating The Power Of The Electric Drive For The Main Steady Motion

We will choose the speed range from 0 to 60 km/h for driving on an electric drive. With that, the main steady motion will be executed in the speed range of 40-60 km/h. For this, as is shown below, a relatively small electric motor power is required. At the same time, in this interval of speeds, as the experiment shows, the kinetic energy of a moving car is large enough for the part of it to be used unnoticed by the driver and passengers to start the ICE, which is required when using the algorithm described above.

We calculate the power of the electric drive as it is done in paper [26] on the basis of the power balance, which, after multiplying by the speed of the car, results in the power balance equation. After taking into account the transmission efficiency η_{tr} from the power balance equation, we have the expression for the required power of the electric motor N_e [26].

$$N_e = \frac{1}{\eta_{tr}}(\psi G V + \frac{1}{2}C_s A \rho_a V^3 + \frac{1}{g}G\delta a V) \qquad (1)$$

where G is the weight of the car, N, α is the slope of the road, f_k is the rolling resistance coefficient, $\psi = f_k cos\alpha + sin\alpha$ is the total coefficient of the road resistance, δ is the coefficient of accounting for rotating masses, for a passenger car δ can be 1.05, a is the acceleration of the car, V is the speed of the car, ρ_a is the air density, C_s is the streamlining coefficient, A is the frontal area of the car, g is the acceleration of gravity.

From expression (1), it is possible to obtain the mechanical power of the electric motor required for the Lanos pickup hybrid conversion vehicle to gain the speed up to 60 km/h on an asphalt road. On the horizontal section, we get 6.4 kW, on the rise of 2 % it is possible to reach a speed of 60 km/h with an electric motor power of 10 kW. We will choose the power of the traction motor close to 10 kW.

As will be shown below, on a flat road in the speed range of 40-60 km/h the power reserve will provide sufficient vehicle dynamics when driving on an electric drive, because such a hybrid vehicle fully retains the capabilities of a conventional vehicle. Steep rise or high road resistance can be overcome by using the internal combustion engine in the appropriate gears.

2.2.2 Calculating The Transmission Ratio Between The Axle Of The Electric Motor And The Driving Wheels Of The Car

We equate the resistance force of the road in the sum with the air resistance force to the speed-dependent traction force of an electric car, expressed in terms of the moment on the electric motor shaft.

$$P_c = \psi G + \frac{1}{2} C_s A \rho_a V^2 = \frac{M_e(V) i_{mt} i_{eg} \eta_{tr}}{r_{wh}} \qquad (2)$$

where $M_e(V)$ is the speed-dependent torque of the electric motor, η_{tr} is the transmission efficiency, i_{mt} is the main transmission ratio, i_{eg} is the transmission ratio between the electric motor and the secondary shaft of the gearbox, r_{wh} is the dynamic wheel radius. For a valve motor based on a synchronous electric machine, the dependence $M_e(V)$ is obtained from the equation of the mechanical characteristic [23].

$$M_e(V) = \frac{k\Phi}{R_a}(U - \frac{Vk\Phi i_{mt} i_{eg}}{r_{wh}} \qquad (3)$$

On one graph we construct the family of dependences on speed for the left side of equality (2) and the family of dependences on speed for the right side of equality (2). We use the following notation for the curves obtained from the left side of (4): curve P_{c1} corresponds to a horizontal road, P_{c2} – to 1% rise, P_{c3} – to 2% rise, P_{c4} – to 3% rise P_{c5} – to 4% rise, P_{c6} – to 5% rise. We calculate the dependence of the value of the moment on the motor shaft on the speed $M_e(V)$ in the right-hand side of equation (2) by the method of constructing the external mechanical characteristics of the electric motor, suggested in paper [26]. We take the data for the synchronous electric machine G290 for which the total active resistance of the armature circuit R_a is 0.03 Ohm and select the TAB voltage in a hybrid car based on the Lanos pickup car equal to 89.6 V. We use the following notation for the curves obtained from the right side of (2): curve P_{T1} corresponds to gear ratio $i_{mt} i_{eg} = 8.88$, curve P_{T2} to 7.88, curve P_{T3} to 6.88, curve P_{T4} to 5.88, curve P_{T5} to 4.88. The coordinate along the horizontal axis of the intersection point of dependences P_T and P_c is the maximum attainable speed of a car with the corresponding gear ratio on a road with a corresponding slope. At speeds lower than the maximum achievable, the difference between the ordinates of the corresponding curves P_T and P_c is the force that provides the acceleration of the vehicle. To select the optimal gear ratio between the electric motor and the driving wheels of the car, we note that according to the graph in Fig. 4 with slopes of up to 1%, a speed of 60 km/h can be reached with all the indicated gear ratios.
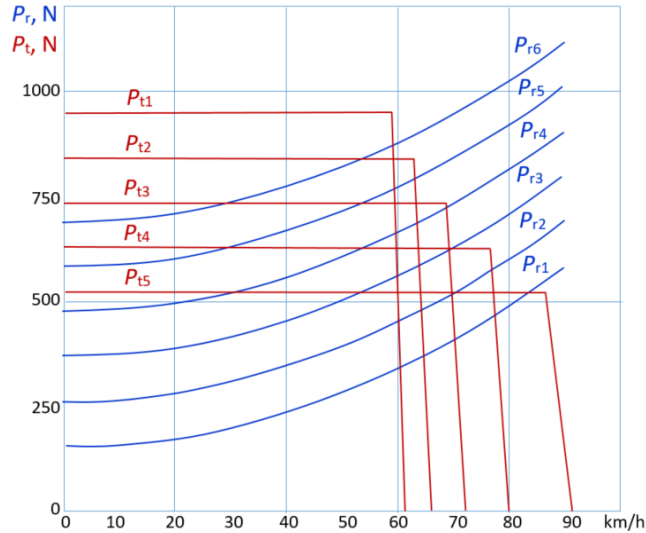
Fig. 4 - The dependence of the traction force of the electric drive for different gear ratios and the force of resistance to motion for different slopes on the speed of the conversion hybrid car

We choose a gear ratio of 6.88 (curve P_{T3}) to improve acceleration. For the Lanos pickup car with a main gear ratio of 4.133, a gear ratio of 6.88 is obtained with a gear ratio between the electric motor and the secondary shaft of the gearbox equal to 1.66 (belt drive pulley diameters, respectively, 120 and 200 mm). Of course, we can improve the acceleration dynamics and the ability to overcome steep rises, if we use higher gear ratios and limit the maximum speed on an electric drive to 30-40 km/h, as is done in traditional hybrid cars. However, in this case, we will get neither a gain in weight and cost, nor fuel economy, as we do with the proposed algorithm.

2.2.3 Calculating Acceleration Dynamics

As paper [23] shows, the acceleration time t_a on an electric drive from speed V_1 to speed V_2 can be calculated by the formula.

$$t_a = \int_{V_2}^{V_1} \frac{\delta G}{g\left(\frac{M_e(V)i_{mt}i_{eg}\eta_{tr}}{r_{wh}} - \frac{1}{2}C_s A\rho_a V^2 - \psi G\right)} dV = \frac{\delta G}{gb}\int_{V_2}^{V_1} \frac{1}{\frac{d}{b}-V^2} dV = \frac{\delta G}{gb}\left\{\frac{1}{2\sqrt{d/b}}\ln\left|\frac{\sqrt{d/b}+V}{\sqrt{d/b}-V}\right|\right\}_{V_2}^{V_1} \quad (4)$$

where the following notations are introduced: $d = P_T - \psi G = (1/r_{wh})\, M_e i_{mt} i_{eg} \eta_{tr} - \psi G$; $b = 0.5 C_x \rho_a A$,

The calculation of the acceleration time using expression (4) is made for an electric drive based on a synchronous electric machine (generator) G290. Such an electric drive has a torque of about $M_{emax} = 30$ N·m at an armature current of 150 A, which can last for a long time or we have a torque of about $M_{emax} = 40$ N·m at an armature current of 230 A, (such a current can be short-term, up to 1 min). During the calculation the following numerical parameters are used: $G=11000$ N, $\alpha = 0$, $\delta = 1.05$, $\psi = 0.014$, $C_x = 0.38$, $r_{wh} = 0.284$ m, $i_{mt}i_{eg} = 6.88$, $\eta_{tr} = 0.92$, $\rho_a = 1.29$ kg/m³, $A = 2.6$ m², $V_1 = 16.66$ m/s. For acceleration from 0 to 60 km/h at $M_{e\,max} = 30$ N·m, the calculated time is 44.1 s. For $M_{e\,max} = 40$ N·m, the calculated time is 29 s. Such acceleration time is unacceptable in modern urban traffic; therefore, such acceleration is performed using an internal combustion engine.

The basic mode of the electric drive of the proposed hybrid car is to maintain steady motion in the speed range of 40-60 km/h or 40-50 km/h. To assess the dynamics in this mode, a calculation is made using formula (4) for acceleration from 40 to 60 km/h. Such a calculation gives a calculated time of 17.4 s for $M_{e\,max} = 30$ N·m, and a calculated time of 10.7 s for $M_{e\,max} = 40$ N·m. For the steady traffic in urban conditions such dynamics is quite acceptable.

2.2.4 Calculating Electric Energy Consumption And The Starting Length Of Electric Traction Drive

We calculate the amount of electrical energy W consumed by the Lanos pickup hybrid vehicle with the above algorithm of controlling the power plant for the fastest acceleration using an electric drive from 40 to 60 km/h. The energy spent during such acceleration can be represented in the form of two components: the energy spent on

acceleration, taking into account the transmission efficiency η_{tr} and the efficiency of the pulse stabilizer (limiter) of the armature current η_{cl} and the energy spent on heating due to the active resistance of the motor armature circuit R_a.

$$W = S\frac{k\Phi I_{a\,max}\,i_{mt}\,i_{eg}}{r_{wh}\eta_{cl}\eta_{tr}} + R_a I^2_{a\,max}\,t_{acc} \tag{5}$$

where S is the distance traveled from the reference point (speed 40 km/h) to gaining the speed of 60 km/h, I_{a_max} is the maximum current of the armature circuit of the electric motor, t_{acc} is the acceleration time, Φ is the magnetic flux of the field winding. There is still energy spent in valve motor (VM) on bearing losses, ventilation losses and magnetic losses. Considering the smallness of this energy, we neglect it. To find the distance traveled from the reference point (speed 40 km/h) to the moment the speed reaches 60 km/h, we use the integral expression.

$$S = \int_{t_1}^{t_2} V(t)\,dt = \int_{t_1}^{t_2} a(t)\,t\,dt \tag{6}$$

where: t_1 is the acceleration time to a speed of 40 km/h, t_2 is the acceleration time to a speed of 60 km/h. We calculate the vehicle acceleration a similarly to the manner it was done when deriving expression (4), however, using the fact that in this interval of speeds a relatively small part of energy is spent on overcoming air resistance, we apply a linear approximation of the dependence of the air resistance force on time [23]. This approximation introduces an insignificant error, but simplifies the calculation. In this case, we have the following acceleration of the car:

$$a = \frac{g\left(\dfrac{k\Phi I_{a\,max}\,i_{mt}\,i_{eg}\eta_{tr}}{r_{wh}} - P_{в} - \psi G\right)}{\delta G} = \frac{g\left(\dfrac{k\Phi I_{a\,max}\,i_{mt}\,i_{eg}\eta_{tr}}{r_{wh}} - \dfrac{P_{a60}}{t_1}t - \psi G\right)}{\delta G} \tag{7}$$

where: P_{a60} is the force of air resistance at the speed of 60 km/h, $g = 9.8$ m/s^2.

$$S = \left(\frac{g}{\delta G}\cdot\frac{k\Phi}{r_{wh}}I_{a\,max}\,i_{mt}\,i_{eg}\eta_{tr} - \frac{g\psi}{\delta}\right)\int_{t_1}^{t_2} t\,dt - \frac{g}{\delta G}\frac{P_{a60}}{t_1}\int_{t_1}^{t_2} t^2\,dt \tag{8}$$

After integrating and substituting the numerical values for the experimental Lanos pickup car, we have the acceleration distance from 40 km/h to 60 km/h for $M_{a\_max} = 30$ N·m equal to 240.5 m.

Substituting in expression (7) the obtained path and traction force, which is developed by the electric drive, and which, as can be seen from Fig. 4, is constant on the way of acceleration from 40 km/h to 60 km/h, we have (9).

$$W = S\frac{M_{e\,max}\,i_{mt}\,i_{eg}}{r_{wh}\eta_{cl}\eta_{tr}} + R_a I^2_{a\,max}\,t_{acc} \tag{9}$$

Calculation of the amount of electrical energy consumed by the experimental vehicle Lanos pickup for acceleration from 40 km/h to 60 km/h using formula (9) with the substitution of the corresponding numerical values gives for $M_{e\,max} = 30$ Nm·194,352.2 J or 0,053987 kW·h. The comparison of these calculated values with the results obtained on the on-board watt-hour meter during experimental runs shows a good agreement between the calculation results and the experiment.

2.2.5 Calculating The Maximum Speed On The Electric Drive And The Specific Electricity Consumption At The Maximum Speed

To calculate the maximum speed of the proposed hybrid electric vehicle, we use the power balance (4). This balance occurs because the pulling force is equal to the resistance to motion. It should be noted that this balance is stable to arbitrary small perturbations at maximum speed, since the point of intersection of the curves in Figure 4 is in the falling section of the mechanical characteristic. Therefore, any change in speed caused by a change in the drag force causes a change in the thrust force, compensating for the change in the drag force.

We also use the mechanical characteristic of the electric motor (5) from which we obtain the expression for the torque.

$$M_e = \frac{(k\Phi)^2}{R_a}\left(\frac{U}{k\Phi} - \frac{Vi_{mt}i_{eg}}{r_{wh}}\right)$$

(10)

We substitute this expression for the moment on the right side of (4), after which we have a quadratic equation for the speed *V*.

$$\frac{1}{2}C_s A\rho_a V^2 + \frac{(k\Phi)^2 (i_{mt}i_{eg})^2 \eta_{tr}}{R_a r_{wh}^2}V + \psi G - \frac{k\Phi U i_{mt}i_{eg}\eta_{tr}}{R_a r_{wh}} = 0$$

(11)

In the resulting equation, we substitute the numerical values for the experimental car: $G = 11{,}000$ N, $R_a = 0.03$ Ohm, $\psi = 0.014$, $C_s = 0.38$, $r_{wh} = 0.284$ m, $i_{mt}i_{eg} = 6.88$, $\eta_{tr} = 0.92$, $\rho_a = 1.29$ kg/m³, $A = 2.6$м², $U = 89.6$В, $k\Phi = 0.192$ and find the roots of this equation, one of which will be the maximum achievable speed on the electric drive. A positive root is chosen, which gives a speed of 18.6 m/s or 67.0 km/h. The experimentally achieved maximum speed of an electric car is 64 km/h.

To find the valve motor (VM) current at a uniform speed of 60 km/h on an electric drive, we will use the power balance equation for a car movement with zero acceleration.

$$\eta_{vm}\eta_{tr}UI_{vm} = \psi GV + \frac{1}{2}C_s A\rho_a V^3$$

(12)

where η_{vm} is the efficiency of VM without taking into account the current of the excitation winding, I_{vm} is the current of VM, from which we obtain the expression for the current.

$$I_{vm} = \frac{\psi GV + \frac{1}{2}C_s A\rho_a V^3}{\eta_{vm}\eta_{tr}U}$$

(13)

which for an experimental hybrid car gives a current of $I_{vm} = 74.3$ A. Since VM has electromagnetic excitation, we have a total current of about 76 A and the total electrical power $N_{vm} = 6.810$ W consumed from TAB.

To calculate the consumption of electrical energy per kilometer of run Q_a in the electric drive mode at a speed of 60 km/h and taking into account that $V = S/t$ we have (14).

$$Q_a = \frac{W}{S} = \frac{N_{vm}t}{S} = \frac{N_{vm}}{V}$$

(14)

where *W* is the consumed electrical energy, *S* is the path on which this energy was consumed, N_{vm} is the average electric power consumed by VM on this distance, *t* is the travel time of this distance.

For an experimental hybrid car, the specific power consumption at a speed of 60 km/h is 0.1135 kWh/km or 11.35 kWh/100km. In this case, the consumed current will be about 80 A, which will give a weak heating of valve motor, since the limiting current in the long-term mode for VM based on the G290 synchronous electric machine is 150 A.

The calculations show that due to the gear ratio optimized for a speed of 60 km/h, the acceleration on the internal combustion engine must be made to a speed of at least 40-50 km/h and then there must be a switch to an electric traction drive. At speeds above 30-50 km/h, the gear ratio from the electric motor shaft to the wheels becomes sufficient so that the hybrid vehicle does not fall out of the traffic stream. However, in the event of a traffic jam or when driving in yards, warehouses or workshops, i.e., when high speeds and accelerations are not needed, electric driving becomes not only convenient for the driver (you can only use the gas and brake pedals), but also economical, since at such speeds the specific power consumption will be small, in contrast to the specific fuel consumption for the internal combustion engine. In addition, there is no pollution of the environment with exhaust gases, which is especially important when driving indoors.

The comparison of the calculated values with the results obtained during the experimental runs showed good agreement between the calculation results and the experiment.

Comparison of the calculation with the experiment for some parameters of the considered Lanos-pickup hybrid car is shown in Table 1.

Table 1 - Comparison of calculation with experiment for some parameters of the considered hybrid car Lanos-pickup

Parameter	Calculation	Experiment
The maximum speed on the electric drive	67 km/h	64 km/h
Current consumed at a speed of 60 km/h	76 A	80 A
Electric energy consumption for acceleration from 40 km/h to 60 km/h	0.054 kWh	0,059 kWh
Electric acceleration from 40 km/h to 60 km/h at M_{max}=30 N/m	17.4 s	19.0 s

3. Discussion

Fuel economy occurs with city traffic, so the experimental estimate of fuel economy and reduction of harmful emissions has a large error, because. it is difficult to repeat the same traffic conditions in the city.

Fuel economy occurs:

– by reducing the operating time of the ICE with fuel supply during traffic;
– by increasing the efficiency of recuperation, since the ICE does not rotate without fuel supply;
– by increasing the convenience and efficiency of using the acceleration-coasting mode, i.e. direct use for the movement of the kinetic and potential energy of the car. Efficiency during coasting is increased by disconnecting a stopped ICE from the transmission;
– additionally by connecting the car to the electrical network at night (if possible). Fuel economy will be due to recharging the traction and 12 V batteries, electric heating of the coolant and the car interior before leaving.

It is possible to obtain experimentally numerical results on reducing fuel consumption and reducing harmful emissions using statistics. We currently estimate a 15-25% reduction in fuel consumption and CO_2 emissions compared to a conventional petrol car.

It is possible to theoretically estimate the fuel savings and the corresponding reduction in CO_2 emissions by using the New European Driving Cycle (NEDC ECE R101). If we use the urban part of this cycle (ECE R15) for the movement of a converted Lanos-pickup hybrid passenger car for one hour, we have 19 min stops, i.e. ICE operation at idle. If we exclude this operation of the internal combustion engine, then the fuel economy at an average gasoline consumption of 0.7 l/h at idle we have a saving of 0.22 liters. In this case, 12 starts of the internal combustion engine from the starter will be required, for which 15840 J (0.0044 kWh) will be spent. This energy with a large margin can be replenished by recuperation. The kinetic energy from which electrical energy will be generated during one hour during regenerative braking is 2,667,174 J or 0.74 kWh. If we take a recovery factor of 0.5, then about 0.37 kWh will enter the battery. When driving in urban mode of the European driving cycle in one hour, smooth traffic sections will take approximately 15 min, the distance traveled will be about 9 km at an average speed of about 36 km/h. A Lanos pickup car in a gasoline version consumes about 0.05 l/km at this speed, so it will use 0.45 liters for uniform movement. If the uniform movement is on an electric motor, then this will require about 0.63 kWh, since a Lanos pickup car at this speed requires a power of 2.52 kW [26], therefore, 0.63 kWh will be required in 15 min. We take into account the efficiency of the electric drive 0.9, then 0.7 kWh is needed. The energy supplied to the battery from recuperation is about 53% of this value, which means that the savings in gasoline will be approximately 0.53·0.45 =0.24 l. The total savings for one hour of urban traffic will be 0.22 + 0.24 = 0.46 l.

The distance of one urban cycle ECE R15 is 4,052 m, the cycle time is 13 minutes, there will be 4.615 cycles in one hour, the path will be 18.7 km. A Lanos pickup in the city has a consumption of about 10 liters per 100 km, so it will use 1.87 l of gasoline for 18.7 km, so the relative savings will be 0.46 / 1.87 = 0.24 or 24%.

4. Conclusion

This article presents a new algorithm for the operation of the engines of the power plant, which allows the use of a traction motor of lower power. To minimize the power of the traction electric drive, the ICE operation modes with a low load, but with a high specific fuel consumption, were replaced with electric drive. In addition, the idle mode of the internal combustion engine was excluded. The paper presents a method for calculating the electric drive mode of a hybrid car in accordance with the proposed algorithm for the operation of the power plant. The results of the calculation of the main characteristics of the proposed hybrid car are presented and analyzed.

The main idea of the new concept lies in the possibility of a hybrid car with a low-power traction electric drive to spend without long-term storage of the electricity received from regeneration for the movement of the car, without creating problems for other road users. At the same time, fuel consumption and emissions can be reduced. This result was obtained without a network connection. But if it is possible to connect such a car to an AC outlet in the parking lot, the level of efficiency and environmental friendliness becomes even higher. This is due to the possibility, at the start of movement after parking, to dump the electricity received from regeneration to accelerate the heating of the coolant until

space in the TAB is freed up for charging. This technique allows you to save fuel spent on heating the coolant in the internal combustion engine.

Calculations have shown that the steady movement of a hybrid car in electric drive mode is possible up to a speed of 60 km/h. However, starting off and picking up speed is relatively slow and does not meet modern requirements for dynamics when driving a car in relatively free road conditions. So, acceleration on an internal combustion engine should be carried out up to a speed of 30-50 km / h and then a transition to a traction electric drive should be made. At speeds above 30-50 km/h, the gear ratio from the electric motor shaft to the wheels becomes sufficient to prevent the hybrid vehicle from falling out of the traffic flow. However, in the case of traffic jams, when driving in yards, warehouses or workshops, when high speed and acceleration are not needed, electric driving becomes not only convenient for the driver, but also economical, since in such conditions the specific power consumption is low, in contrast to the specific fuel consumption for an internal combustion engine. In addition, there is no pollution of the environment by exhaust gases, which is especially important when driving indoors.

Experimental studies were carried out on a hybrid car developed on the basis of a Lanos pickup truck. Studies have shown good agreement between experimental and calculated results. The results of this work can be used in the automotive industry. This development allows to significantly reduce the cost and weight of hybrid vehicles, while maintaining their performance and good economic and environmental performance.

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