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CONVERSION OF ENERGY IN ELECTRIC DRIVE SUPPORTED BY THE HYDROSTATIC DRIVE

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Abstract

In the article, a study of conversion of energy in a hybrid (electro-hydrostatic) drive of a utility van intended for city traffic is described. In this hybrid drive, the electric drive is periodically accompanied by hydrostatic drive, especially during acceleration and regenerative braking of the vehicle. We present a mathematical model of the hybrid drive as a set of dynamics and regulation equations of the van traveling at a given speed. On this basis, we construct a computer program, which we use to simulate the processes of energy conversion in electro-hydrostatic hybrid drive. The main goal of the numerical simulation is to assess the possibility of reducing energy intensity of the electric drive through such a support of the hydrostatic drive. Our results indicate that it is possible to significantly increase the efficiency of energy conversion in the electric drive by support of the hydrostatic drive. In the article, chosen results of simulation studies for multiple starting and braking the car are given, and they show a 30% decrease for energy drawn by the hybrid drive, compared to solely electric drive.

Keywords: *numerical simulations, hybrid drive, electric drive, hydrostatic drive, energy conversion, city traffic*

1. Introduction

An electric drive with hydrostatic support, intended for a utility van characterized by cyclic movement is considered. The aim of the studies was the energy flow in power transmission system and evaluation of the influence of hydrostatic support on electric drive relief. It was assumed that in such a drive, the overall energy intake from the electric battery will decrease and its durability will increase. The object of the study is a hybrid electric-hydrostatic drive for vehicles and construction machinery, the load of which changes cyclically. In this article, a delivery van for city traffic is considered.

Electric cars, despite their ecological advantages mainly visible in urban areas, are mainly questioned in terms of the effectiveness of a cumulated energy conversion process [4, 6, 10, 13], involving: processing energy in power plants and during its transmission, processes related to charging and discharging of a traction battery and shifting the propulsion from an engine to wheels of a vehicle [6, 10, 11, 12]. The effectiveness of the last three processes of energy conversion is directly connected with a vehicle use and influences its energy intensity. Hence, it is economic significance for a user.

The issue of the article refers to energy flow in power transmission system, in order to improve the efficiency if its conversion. It is possible by applying the electric drive with hydrostatic support. In such a solution, it is possible to retrieve energy from braking in the hydrostatic system. In the article, a mathematical description of processes of energy conversion in electric and hydrostatic drives is given.

In order to solve this problem, software for computer calculations used for simulation studies of energy conversion processes in the considered power transmission system has been developed.

Simulation studies were performed using a mathematical model and based on these studies a laboratory station for experimental studies described in [4] was developed.

2. Model of hybrid electric-hydrostatic drive

A structural scheme of the drive is shown in Fig. 1. In the presented system, a process of energy flow occurs among three storage reservoirs, in which energy is accumulated in there forms electric and mechanical kinetic, as well as potential. While powering the vehicle, the energy is drawn from the electric battery, and partly from hydro-pneumatic accumulator, and then is converted into the kinetic energy of a vehicle. As the vehicle brakes, the kinetic energy, after being converted, returns to the hydro-pneumatic accumulator, and partly to the electric battery. The above-mentioned energy flow and conversion processes are accompanied by a process of energy dissipation. Conversion of forms of energy occurs in an electric machine operating as an engine or a generator and in a hydrostatic machine operating as an engine or a pump. The operation of both machines is controlled by an adjusting system. A mathematical description of the hybrid drive has been developed because of combining descriptions of energy conversion processes in electric and hydrostatic drive, presented in papers [2] and [3].

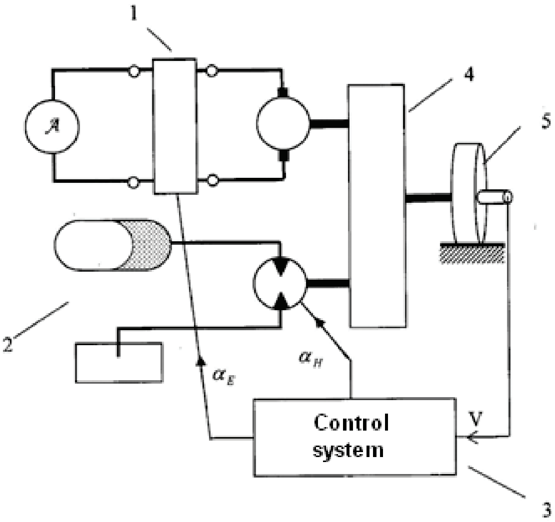

Fig. 1. Scheme of a hybrid electric-hydrostatic drive: 1 – electric drive; 2 hydrostatic drive; 3 – control system 4 – power transmission; 5 – a vehicle

A mathematical description of energy conversion processes in a hybrid system is presented. The set of equations (1) describes thermodynamic processes occurring in a gas bubble:

$$m_G v = \dot{\alpha}_H q_0 \omega_H, \quad \alpha_H \in [-1, +1], \tag{1a}$$

$$\dot{s} = \frac{c_v}{\tau}\frac{T_{zew} - T}{T}, \tag{1b}$$

$$p = p_0 \left(\frac{v_0}{v}\right)^{\varkappa} e^{\frac{s - s_0}{c_v}}, \tag{1c}$$

$$T = T_0 \left(\frac{v_0}{v}\right)^{\varkappa - 1} e^{\frac{s - s_0}{c_v}}, \tag{1d}$$

$$p_1 = p - \Delta p_0 \, sign\, \dot{v}, \tag{1e}$$

where:

v – specific volume of gas,
s – specific entropy of gas,
p – pressure of gas in a bubble,
T – temperature of gas,

p_1 – oil pressure on the pump-engine output from the accumulator side,
ω_H – angular velocity of a pump-engine shaft,
α_H – signal from the control system,
m_G – mass of the gas in the bubble,
q_0 – constant characterizing the pump-engine capacity,
τ – constant characterizing the process of heat exchange between the gas and the environment,
T_0 – ambient temperature,
Δp_0 – constant characterizing oil flow resistances between the accumulator and the pump-engine,
c_v – specific heat of the gas,
$\varkappa$ – adiabatic index.

The set of equations (2) describes of energy conversion in the electric drive system with a direct current engine powered by a battery:

$$L\frac{di_2}{dt} + R_2 i_2 + c\Phi\omega_E = U_2, \tag{2a}$$

$$E_{AK}(q) - R_1 i_1 = U_1, \tag{2b}$$

$$\dot{q} = -i_1\,, \tag{2c}$$

$$U_2 = \alpha_E U_1, \quad i_1 = \alpha_E i_2, \quad \alpha_E \in [0,1], \tag{2d}$$

where:
i_1 – current flowing through the battery,
i_2 – current flowing through the engine,
q – electric charge accumulated in the battery,
U_1 – voltage on battery clamps,
U_2 – voltage on engine clamps,
ω_E – angular velocity of the engine shaft,
α_E – signal from the adjusting system controlling the voltage converter,
L – engine winding inductance,
R_1 – effective resistance of the battery,
R_2 – effective resistance of the engine,
$c\Phi$ – constant characterizing the magnetic flux activating the engine,
E_{AK} – function describing the electromotive force of the battery depending on the amount of the accumulated load.

Set of formulae (3) describes the movement of the vehicle, i.e. its velocity V_{poj}:

$$m\dot{V}_{poj} + f_{opr}^{wyp}(V_{poj}) = \frac{1}{r}(j_E M_E + j_H M_H), \tag{3a}$$

$$M_E = c\Phi i_2, \quad M_H = \alpha_H q_0 (p_1 - p_2), \tag{3b}$$

$$\omega_E = j_E \frac{V_{poj}}{r}, \quad \omega_H = j_H \frac{V_{poj}}{r}, \tag{3c}$$

where:
m – mass of the vehicle,
r – radius of the wheel,
j_E – transmission ratio for the electric engine,
j_H – transmission ratio for the pump-engine,
f_{opr}^{wyp} – function describing resistance of vehicle movement as well as pump-engine movement resistances reduced to the wheels of the vehicle.

Solving the problem of the dynamics of a vehicle with a hybrid drive presented above is described by the courses in time of the above-mentioned variables. The solution depends on initial conditions and on the course of operating signals α_H, α_E occurring among set equations (1) and (2). The courses of these signals are determined in the control system.

The values of some variables of the dynamics problem are limited; in the adjusting system, the signals α_H, α_E are designated in such a way, that the values of the above-mentioned variables are acceptable. Thus, a situation where the power transmission system is not capable of performing a movement at a given speed may occur at times. The major component of the control system is PID speed controller, analysis was presented in the article [8] and [9], which receives at the input V_{poj} and generates the output signal determining the resultant thrust torque M_n.

3. Numerical investigation

Below are shown the assumed parameter values of the model of a vehicle with a hybrid drive, the mathematical model of which was presented in point 2.

The object of the study is a delivery van with an unloaded mass $m = 1900$ kg and the load with the mass $\Delta m = 500$ kg. The following parameters of the vehicle have been assumed: radius of the wheel $r = 0.32$ m, transmission ratio between wheels and engine shafts $j_H = j_E = 8$, the resistance of the movement as well as pump-engine movement resistances have been described using the formula $f_{opr}^{wyp} = 0.013mg + \frac{\Delta M_H j_H}{r}$ where ΔM_H is the moment of forces defining the moment of resistances of the pump-motor movement. It was assumed that $\Delta M_H = 2$ Nm.

Function E_{AK} describing the electromotive force of the battery is as follows: $E_{AK}(q) = E_0 + {q}/{C}$ if $E_0 = 260$ V, $C = 104$ kF, and the internal resistance of the battery is $r_1 = 0.1\ \Omega$. It has been assumed, that when fully charged, the electric charge equals $q = 114$ Ah and the energy of the fully charged battery amounts to 30 kWh. The values of engine parameters are as follows $L = 0.76$ mH, $R_2 = 0.04\ \Omega$, $c\Phi = 0.5$ Nm/A, $I_{max} = 550$ A. The assumed values have been chosen based on the initial analysis presented in the article [1].

The hydrostatic drive is characterized by the following parameter values: in the hydro-pneumatic accumulator bubble there is nitrogen, the mass of which in an initial condition $p_0 = 300$ bar, $V_0 = 14$ dm^3, $T_0 = 293.15$ K, $s_0 = 0$ J/kgK equals $m_G = 4.827$ kg. it has also been assumed that the time constant determining the process of heat exchange equals $\tau = 200$ s and the ambient temperature $T_{zew} = T_0 = 293.15$ K. The hydrostatic system is powered by two hydro-pneumatic accumulators described above. The values of the parameters of the pump-engine model and the hydraulic system amount to: $q_0 = 0.036$ dm^3/rev, $\Delta p_0 = 2$ bar, $p_2 = 2$ bar. The parameters of the accumulator have been chosen based on experimental studies presented in article [7].

The considered simulations referred to a passage on the route of 2860 m lasting 390 s at a given speed V_z, the course of which is illustrated by the graph in Fig. 2. The average speed of the passage is 26.3 km/h.

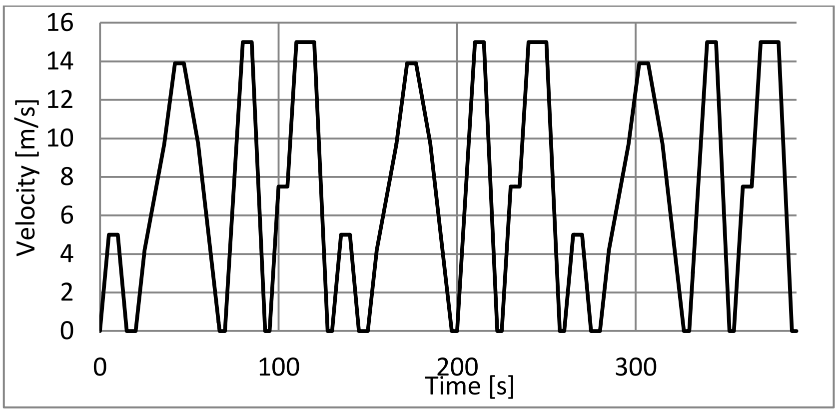

Fig. 2. Vehicle speed

As mentioned earlier, signal λ, determining the involvement of particular drives in thrust torque or braking of the vehicle, plays an important role in controlling hybrid drive. Based on initial simulation studies it has been assumed: $\lambda = 0.7$ – when the vehicle is powered, $\lambda = 0.9$ – when the vehicle brakes, $\lambda = 0.3$ – when the vehicle moves at a given speed. The above-mentioned values are corrected when the load of hydrostatic drive assumes a border value.

Apart from the vehicle with the hybrid drive, a model of an electric drive has been considered as well. It has been assumed that the vehicles have the same electric drives, and the mass of the electric vehicle is smaller by 100 kg. The obtained simulation results have been analysed in terms of the influence of the hydrostatic support on the effectiveness of energy conversion, and as a ratio of this effectiveness, the amount of energy that has been drawn from the electric battery until the moment of the end of the passage, has been assumed.

Graph in Fig. 3 illustrates vehicle acceleration. The maximum value of acceleration amounted to 1.5 m/s^2, whereas the maximum vehicle delay during braking amounted to 2 m/s^2. Based on the course of accelerations it may be concluded that the vehicle power transmission system was heavily loaded, in order to present energy conversion.

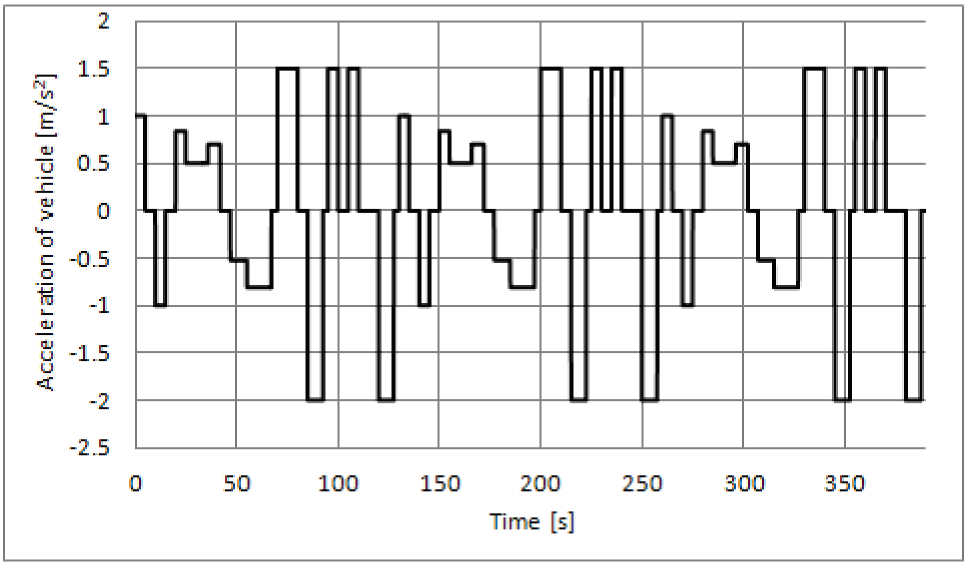

Fig. 3. Acceleration of vehicle

Apart from the vehicle with the hybrid drive, a model of an electric drive has been considered as well. It has been assumed that the vehicles have the same electric drives, and the mass of the electric vehicle is smaller by 100 kg. The obtained simulation results have been analysed in terms of the influence of the hydrostatic support on the effectiveness of energy conversion, and as a ratio of this effectiveness, the amount of energy that has been drawn from the electric battery until the moment of the end of the passage, has been assumed.

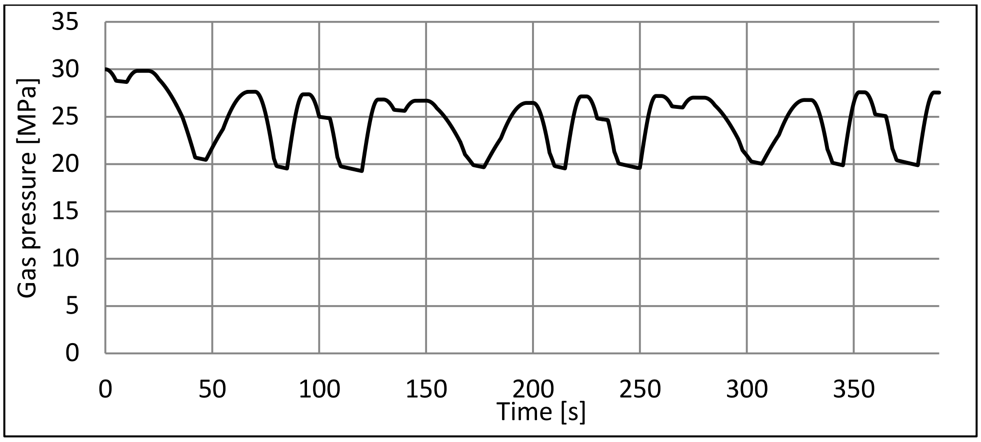

Fig. 4. Gas pressure in the hydro-pneumatic accumulator

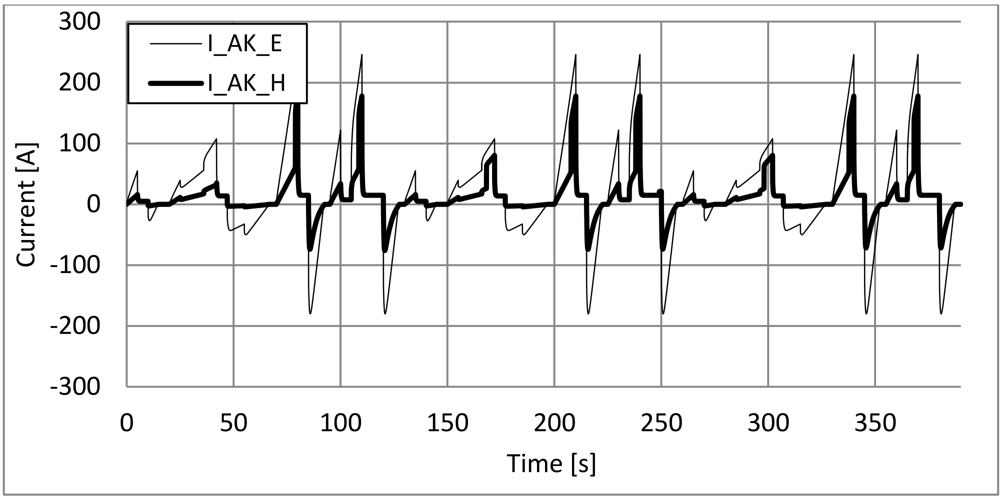

Fig. 5. Comparison of the course of the current intensity of the battery in the hybrid drive (I_AK_H) with the current intensity in the electric drive (I_AK_E)

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The changes in pressure in gas bubble are illustrated in Fig. 4. At the Fig. 5. is illustrated comparison of the course of the current intensity of the battery in the hybrid drive and in the electric drive.

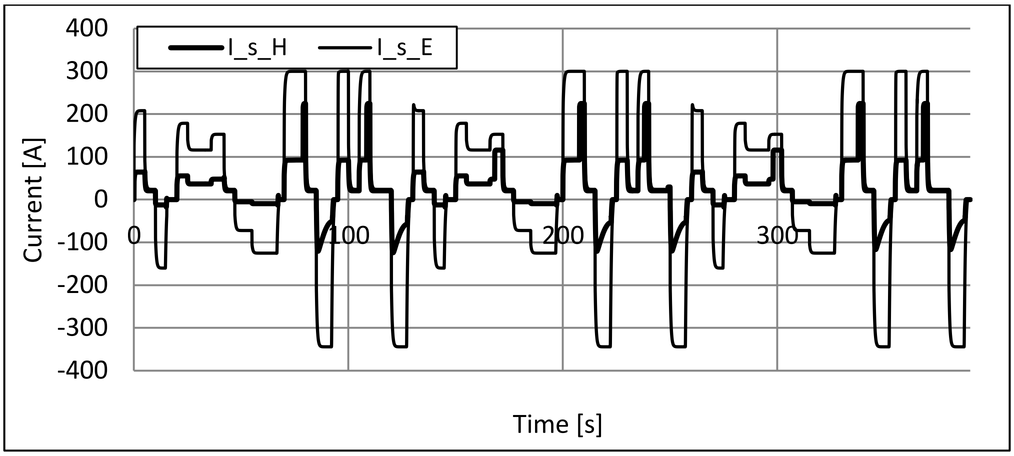

Fig. 6. Comparison of the course of the current intensity of the electric engine in the hybrid drive (I_s_H) with the current intensity in the electric drive (I_s_E)

In order to compare the efficiency of energy conversion in the electric drive and hybrid electro-hydrostatic system, a simulation of vehicle movement with electric drive and with hybrid drive was performed. To evaluate the efficiency two indices were assumed. The value of the former E_{AK}^{E} equals the energy drawn from the electric battery during the course of a passage of the vehicle at the speed defined by the graph (Fig. 2) whereas the value of the latter I_S equals the effective value of the current flowing through the engine.

The value of energy index is calculated according to the formula:

$$E_{AK}^{E}(t) := E_{AK}^{0} - \mathcal{E}\big(q(t)\big) \qquad for \quad t = t_{end} = 390\ [s], \tag{4}$$

where:

$\mathcal{E}$ – the amount of energy collected from the electric battery during the entire passage.

Effective value of intensity of current flowing through the electric engine during the entire passage:

$$I_s^E = \sqrt{\frac{1}{t_{end}} \int_0^{t_{end}} i_2^2(t) dt}. \quad (5)$$

Fig. 6 compiles the graphs of the current intensity of the engine for the vehicle with the hybrid and electric drive, whereas the positive values refer to powering and the negative values to regenerative braking. The sharp increases in current values visible in the graph occur at times when $|\alpha_H| = 1$ which signifies that the pump-engine operates at border efficiency and thus, the strain of the electric drive occurs. By comparing two graphs, it appears that in the hybrid drive the values of current intensity amount to $I_H = 64$ A for the hybrid drive, and $I_E = 184$ A for the electric one. Based on the results of calculations the graphs, illustrating the energy draw from the electric battery during the passage, have been established.

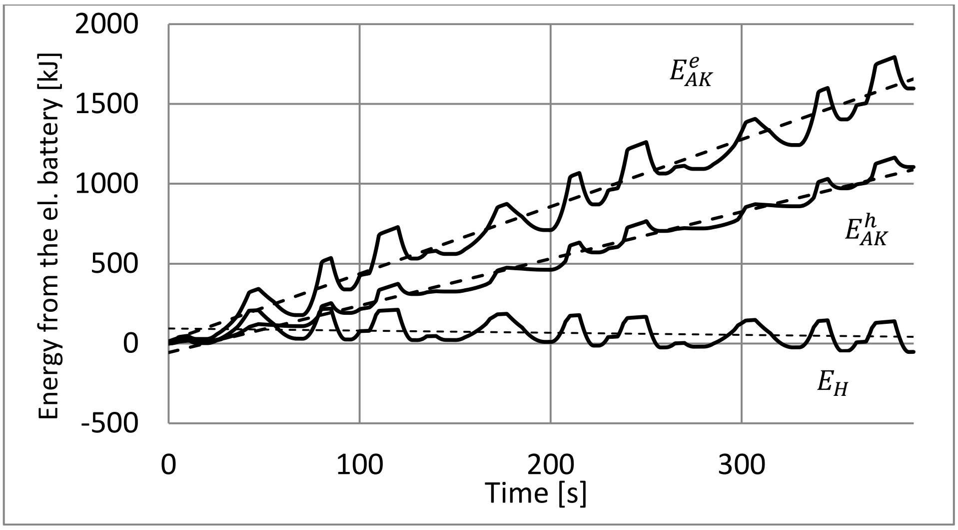

Fig. 7. Energy drawn from the batteries; electric drive (EAKe) hybrid drive: electric battery (EAKh), hydraulic drive (EH)

The comparison of graphs for both drives is presented in Fig. 7. From the comparative analysis of these graphs it appears, that the amount of the energy drawn from the electric battery is smaller in the hybrid vehicle. Having driven the considered route using the hybrid drive, 1105 kJ energy was drawn, whereas with the electric drive, it amounted to 1597 kJ.

The integral average of the power of the energy draw from the electric battery in hybrid drive amounted to 2.68 kW while in the electric drive 4.31 kW that constitutes 62% of the power of the electric drive. An oscillating course of energy collection from the hydro-pneumatic battery, with the amplitude of 100 kJ is worth noting (cf. Fig. 7). It means, that the average amount of energy in the battery does not change.

The analysis of the results of the calculations presented above, shows the possibility to increase the effectiveness of the electric energy conversion process, due to the application of the hydrostatic support. This conclusion refers to the electric drive with a cyclic load.

2. Conclusions

The obtained results of simulation studies of the hybrid electric-hydrostatic drive confirm the thesis stating the possibility of increasing the effectiveness of energy conversion process in the electric drive of an urban vehicle, by means of hydrostatic support. The support consists in drawing energy from the hydro-pneumatic accumulator while a vehicle accelerates and returning it during regenerative braking.

The presented mathematical model of the hybrid drive despite considering the basic phenomena connected with energy conversion process, does not include some aspects of this process – such as power electronic properties of voltage converter or leaks in the hydraulic system.

Thus, it is advisable to improve the developed models of hybrid drive, as well as to perform simulation studies in a broader range, in order to show the possibility of improving the effectiveness of energy conversion during the different conditions of the vehicle use.

The aim of the numerical studies was experimentally show the possibilities of decreasing the vehicle energy intensity thanks to hydrostatic drive support. The results of studies presented in the article indicate that a significant electric drive relief has occurred. In the article, chosen results of simulation studies for multiple starting and braking the car are given, and they show a 30% decrease in the amount of energy drawn by the hybrid drive, compared to solely electric drive. Additionally, a similar decrease in effective currents values has been observed e.g. from 184 A for the electric drive to 64 A for the hybrid drive. The result suggests that there is a possibility of increasing the effectiveness of energy conversion in the vehicle electric drive by means of hydrostatic support.

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