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STUDIES OF ELECTRIC DRIVE WITH HYDROSTATIC SUPPORT

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Abstract

In this article, results of experimental studies concerning the relief of a city car electric drive by means of hydrostatic drive support are presented. Experimental studies were performed using a laboratory station built for this particular purpose. Studies of basic properties of elements of hydraulic system and resistances in the mechanical system were performed. The results of experimental studies of a chosen sub-assembly of hydrostatic drive (i.e. hydro-pneumatic battery) are given. The resistances within mechanical system (flywheel) were determined.

In the considered hybrid drive, electric drive is cyclically supported by hydrostatic drive during acceleration or regenerative braking of the vehicle. The results of experimental studies presented in this article were obtained on a designed and built laboratory station representing a model of a lightweight delivery van for city traffic and equipped with the studied hybrid drive. The obtained results suggest that there is a possibility considerably to increase the effectiveness of energy conversion in the electric drive of the vehicle by means of hydrostatic support. By applying the hydrostatic support in the electric drive, the load on the electric battery decreased, which positively influences the length of operation time.

Keywords: *hybrid drive, energy consumption, energy efficiency, regenerative braking, city traffic*

1. Introduction

The object of the studies presented in this article was a designed and built laboratory model of a hybrid electric-hydrostatic drive for a lightweight delivery van for city traffic. The aim of the studies was to establish the possibility of electric drive relief by means of hydrostatic support. Such a support may result in decreasing the traction energy intensity of a vehicle, increasing the driving range, and increasing the durability of the electric battery.

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 [1, 2, 9]. It needs to be stressed, that the idea of the electric drive with hydrostatic support studied in this article has a few disadvantages, which at the current stage of electric drive development may prove to be more important than the advantage considered in this article, namely smaller energy intensity of the hybrid drive. The disadvantages include: greater mass of the hybrid drive and hence a higher cost of the vehicle. The importance of these drawbacks may not necessarily be significant for commercial vehicles with high traction energy intensity caused by driving within urbanized areas, e.g. public transport buses with electric drive.

The article deals with the improvement of effectiveness of energy conversion process in the considered hybrid drive of a hypothetical delivery van, by means of applying electric drive with hydrostatic support. Hydrostatic support is to provide relief of the electric drive during acceleration and braking.

The results of experimental studies as well as concise description of the laboratory station, which was used to perform experimental studies of the hybrid drive, were presented in the article. The studies were done using the assumption that the hypothetical vehicle performs a chosen cycle of city traffic.

2. Laboratory station for studying electric-hydrostatic drive

The discussed hybrid drive was created as a result of parallel combining of electric and hydrostatic drives. Such a combination of drives means that driving torques of the electric engine and the hydraulic pump-engine together affect the drive shaft of the vehicle. In the hybrid drive constructed in such a way, establishing a proportion of both these drives in the resultant driving or braking torque of the vehicle is crucial for the effectiveness of energy conversion. This problem was also discussed in papers [4-7].

While building a laboratory station for experimental studies of hybrid electric-hydraulic drive it was assumed that, it would reflect a configuration of a full-hybrid drive, which allows the operation of both drives or each of the drives in a particular phase of vehicle movement. The scheme of the considered laboratory hybrid drive is shown in Fig. 1. The laboratory model of the vehicle equipped with the studied hybrid drive consists of electric drive, hydrostatic drive, power transmission system, flywheel reflecting the inertia of the vehicle and hydraulic system reflecting resistances of the vehicle movement.

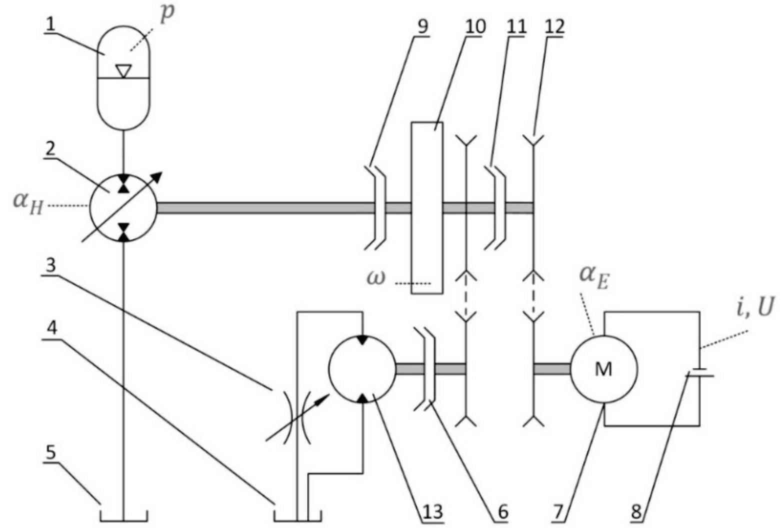

Fig. 1. Scheme of the laboratory station for studying hybrid electric-hydrostatic drive: 1 – hydro-pneumatic battery 2 – pump-engine with a variable unit outlay/absorbing power; 3 – hydraulic pump; 4 – adjustable throttle; 5 – tank 6 – clutch; 7 – electric engine; 8 – a set of batteries; 9 – clutch; 10 – flywheel; 11 – clutch; 12 – belt transmission p – measurement signal of pressure in hydro-pneumatic battery; ω – rotational speed of flywheel; α_H – signal controlling outlay/absorbing power of pump-engine; α_E – signal controlling current intensity of the electric engine i – intensity of the current flowing through the electric battery; U – electric battery terminal voltage

Electric power transmission system was built based on ready sub-assemblies. The basic elements are:

- a set of batteries (8) – consisting of SLA traction batteries (lead-acid) for cyclical operation. The set of batteries was built by joining 6 batteries with 12 V voltage and 64 Ah capacity each,
- engine/generator (7) – direct current unit with BLDC type permanent magnets with 8 kW power manufactured by Golden Motors [3], supply voltage 72 V, maximum rotational speed 4400 RPM, engine cooled with fluid, efficiency up to 91%, resistance 12 mΩ/72V, inductance 154 μH/72 V (100 kHz),
- FOC (Field-Oriented Control) electronic controller manufactured by Golden Motors [3] – electric engine supply voltage – 72 V, nominal current of the engine – 100 A, maximum allowable value of engine current – 300 A, possibility of adjusting maximum parameters of BDLC engine operation.

Electric power transmission system was connected to the flywheel shaft by electromagnetic disengaging clutch (11) and belt transmission (12) with 3/8 transmission ratio reducing rotational speed. The choice of transmission ratios was determined by the optimal parameters of the operation of hydraulic pump-engine.

- axial piston hydraulic pump-engine (2) with SYDFE1X variable swashplate manufactured by Rexroth [8] – this unit has the following basic technical parameters: maximum unit geometric volume 18 cm^3/rev, maximum rotational speed 3300 RPM, maximum value of pumping/operation pressure 28 MPa, maximum power – 27.7 kW, maximum value of moment 80.1 Nm, voltage in the control system: 24 V;
- bladder hydro-pneumatic battery (1) with nominal capacity of 10 dm^3 and initial gas pressure in the battery 5.5 MPa and allowable pressure 35 MPa.

Hydrostatic drive was connected to the flywheel shaft by electromagnetic disengaging clutch (9) manufactured by FUMO with ESMI-80 designation transmitted by maximum moment of 80 Nm. In the laboratory station inertia of the vehicle was rendered mainly by flywheel (10) with the mass m_b = 27 kg and moment of inertia J_b = 0.82 kgm^2. The total mass and moment of inertia of the flywheel, parts of clutches permanently connected to the flywheel and the shaft, on which the flywheel was placed amounts to, respectively: m_{zb} = 44.73 kg and J_{zb} = 0.84 kgm^2 (Fig. 2). The element which, in the station, reflects the properties of the powered vehicle (or machine) is the flywheel, whose moment of inertia *J.* is connected with the mass of the vehicle by the following dependency $m = \frac{i^2}{r^2}J$, where i – transmission ratio of transmission conveying propulsion from the engine shaft to the wheel, r – radius of the wheel.

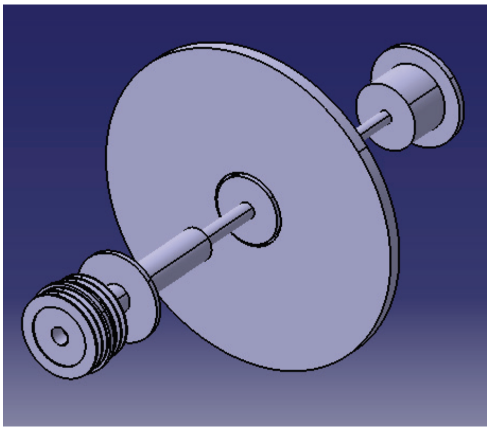

Fig. 2. Geometric model of flywheel and inseparable parts

During its movement, resisting forces of motion act on the vehicle, and they have to be overcome by the vehicle. Within low speeds, these forces result mainly from resistances of rolling motion of the vehicle on the ground and with high speeds, they result from aerodynamic resistances.

Hence, the hydraulic system was built, allowing rendering the resistances of the vehicle motion. The main element of the system, apart from the throttle (4), is the gear pump type 1608 manufactured by Warynski (3) with a constant outlay. The unit outlay of the pump amounts to 14.6 cm^3/rev, and maximum pressure of operation – 17.5 MPa. The allowable rotational speed of the hydraulic unit is 2700 RPM.

As mentioned before, particular power transmission systems were connected to the flywheel by means of electromagnetic clutches. Due to the fact that the hydraulic pump-engine and engine/generator have different maximum and nominal speeds, particular power transmission systems were connected using belt transmissions.

Thanks to such a construction of the station, it is possible to study the processes of energy flow between particular systems, both during acceleration phase, vehicle motion and braking. Operation of the station is particularly possible in the following configurations:

- flywheel connected to the hydrostatic drive,

– flywheel connected to the electric drive,
– flywheel connected to both drives.

The general view of the station is presented in Fig. 3, with the description of systems, sub-assemblies, belt transmission.

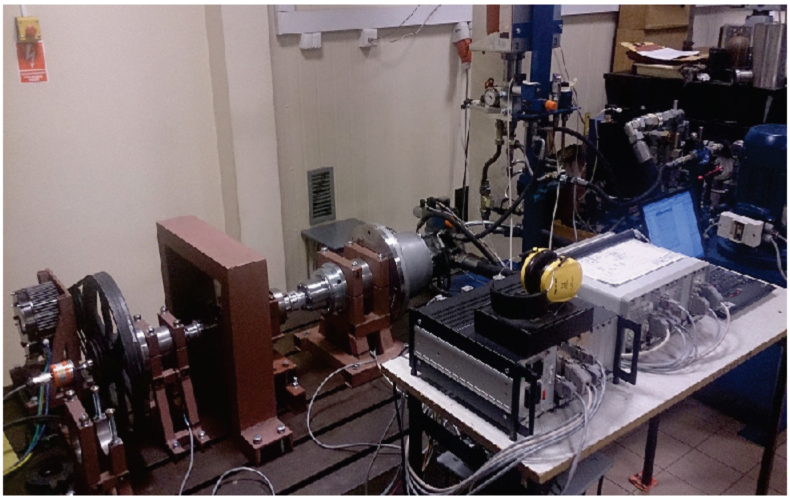

Fig. 3. General view of the station to study hybrid drive

For the needs of the station operation, an original measurement-control system was developed and launched. The system consists of two parts: hardware and software. The hardware part of the measurement system, with the symbol PCI-EPP/PCM is based on a measurement-control system, consisting of three basic elements:

– a controlling PC computer,
– data acquisition station PCI 16/32E,
– a conditioner of measurement-control signals.

The data acquisition station PCI 16/32E is a universal measurement-control system developed by Grapol Electronic. The conditioner of signals is an electronic system built specially for the purpose of the discussed research task and it connects data acquisition station PCI 16/32E to the laboratory station of hybrid drive, in order to control its operation. This connection consists of measurement sensors (analogue and impulse), VEC300 electric engine controller, VT-5041 hydraulic pump-engine controller, hydraulic electrovalves and electromagnetic clutches. Universal measurement sensors were applied as well: analogue pressure sensors (Peltron NPXA 300), analogue temperature sensor (CZAKI Type 363), impulse flow meter (KOBOLD DZR 1010S), and impulse encoders (KUBLER Type 8/3600).

Measurement sensors of current and voltage constitute a part of VEC300 controller, and they control PMCM engine.

During the operation of the station measurement signals connected with the operation of hydraulic system are registered: pressure of gas in the hydraulic battery, pressure of oil in the hydraulic battery, pressure of oil under the non-return valve of the hydraulic battery, the tilt angle of pump-engine blades (input and feedback of the control system), the direction of pump-engine shaft revolution, the angular speed of the pump-engine output shaft, angular speed of the flywheel. Signals of the electric system are also measured: intensity of the current flowing from/to the electric battery, terminal voltage of the battery, rotational speed of the electric engine.

The operation of the hybrid drive is controlled by means of an analogue-to-digital converter, controlling driving moments on output shafts of the hydrostatic pump-engine and electric engine. The station was designed in such a way, so that it is possible to study independently hydrostatic, electric and hybrid drives, mechanical system (flywheel) without the drive and mechanical system with motion resistances. The proper configuration of electromagnetic clutches enables such a solution (6, 9, 11).

3. Power transmission system motion resistances

Hybrid drive is characterized by the possibility of energy recovery during braking, i.e. while a vehicle brakes the hydro-pneumatic or electric battery is charged respectively, and some of the energy is dispersed. The studies connected with establishing motion resistances of the station itself were conducted. The motion resistances of power transmission system are established based on the analysis of the results of speed measurement of the system during its free revolution. In this time, the equation of the power transmission system motion looks as follows:

$$J\dot{\omega} + f(\omega) = 0, \quad (1)$$

where:
ω – angular speed of the flywheel,
J – moment of inertia of the power transmission system reduced to the flywheel axis,
f – function describing motion resistances.
Based on the angular speed measurement of the flywheel ω, function f was established

$$f(\omega) = J\varepsilon(\omega), \quad (2)$$

whereas function ε is a polynomial function of degree 3.

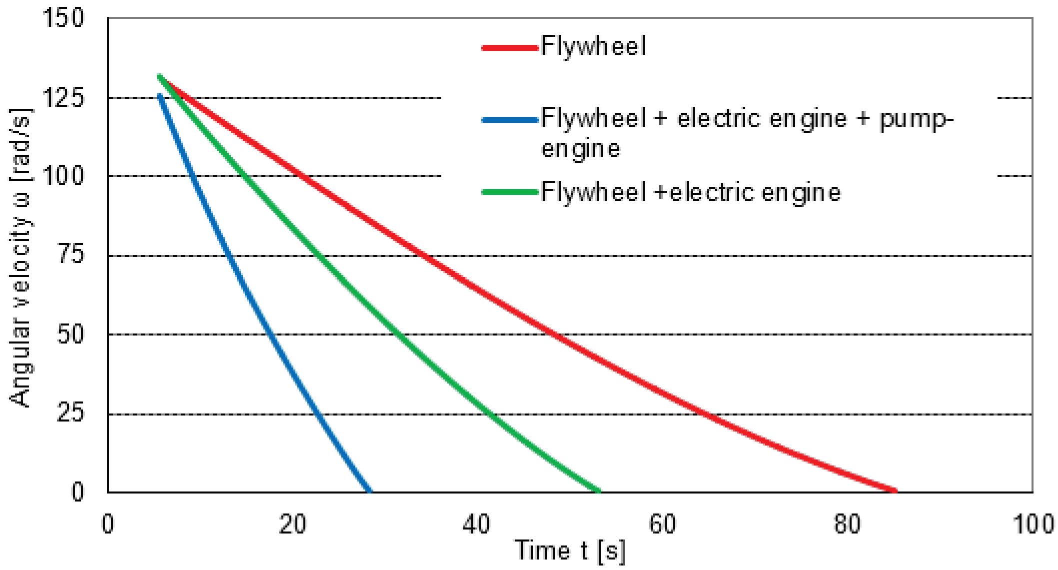

Fig. 4. The course of angular speed ω on the runway: of the flywheel, of the flywheel with electric drive of the flywheel with electric and hydrostatic drives

Based on the conducted studies of the flywheel on so-called runway, characteristics of changes in rotational speeds for the flywheel, the flywheel with electric drive and the flywheel with the hydrostatic drive (Fig. 4) were established. The body of the flywheel was initially accelerated to the speed of 125 rad/s, and then in the 5^{th} second electric drive was started and the system stopped because of the action of resistance moment. While studying the flywheel, the system stopped after 80 s, while studying the flywheel connected to the electric drive, the system stopped after 50 s, and during the trial of the whole system, it stopped after 23 s. Based on the studies, it may be concluded that a swirling flywheel has the smallest resistances, whereas the greatest resistances has the connected, whole power transmission system.

The conducted studies served to establish angular decelerations. Knowing moments of inertia of particular systems based on dependencies (5) the values of function f, describing resistances was calculated. The calculated moment of resistances is shown in Fig. 5.

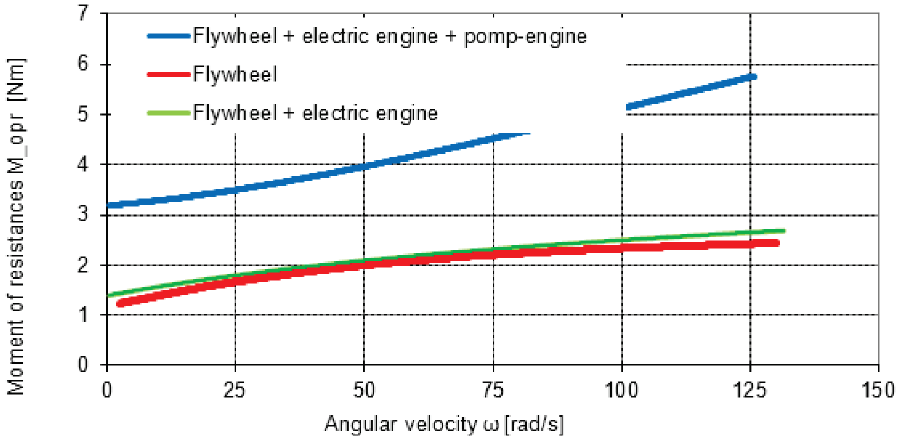

Fig. 5. The course of moment of resistances on the plane of phase angular speed ω

The resistances of the whole power transmission system with the initial angular speed of 125 rad/s amount to 6.4 Nm, with the electric drive 4.5 Nm and the resistances of the flywheel itself amount to 1.7 Nm. Based on the obtained courses of moments of resistance on the plane of phase angular speed, a following dependency may be observed: the greatest resistances are by pump-engine (hydrostatic drive) with electric engine, whereas the resistances resulting from the operation of the power transmission system of the electric engine are lower by approximately 2 Nm, and the flywheel resistances are relatively low and do not exceed 2 Nm within the whole measuring range.

4. Study of the hydro-pneumatic battery

In the hydraulic system, the energy is stored in the hydro-pneumatic battery. In the hydraulic system there was no thermal insulation, and thus while charging and discharging the battery thermodynamic transformations occurred in the gas bladder. For this reason, studies aiming at establishing the influence of transformations on the gas pressure in the gas bladder were conducted. The experimental studies of properties of hydro-pneumatic battery were conducted while charging the battery to 12 MPa and discharging to atmospheric pressure. During the studies, the signals of pressure and volume outlay were registered.

Based on the conducted studies the characteristics of the battery were established. Fig. 6 shows the course of pressure changes in the function of volume. The studies were conducted with the volume outlay of 27.75 dm^3/min. Additionally, in the graph there are also the theoretical courses of adiabatic and isothermal processes. The experimental course (p – ex) corresponds to the courses of adiabatic process (p – adiabate).

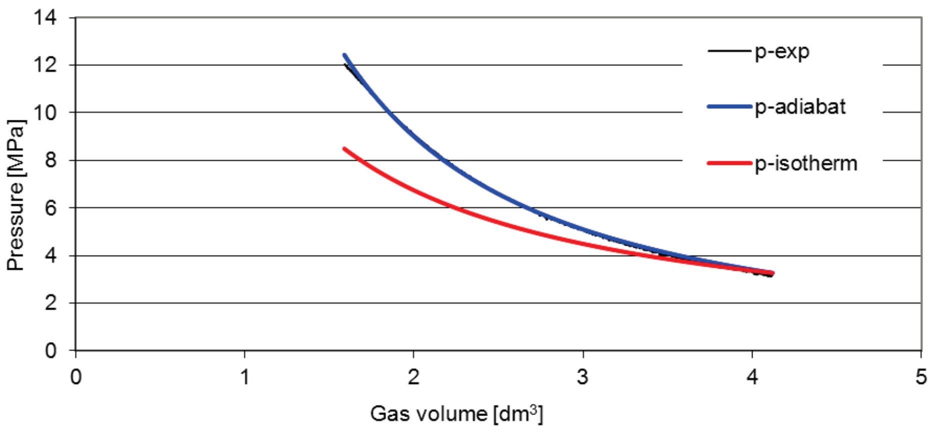

Fig. 6. Characteristics of the hydro-pneumatic battery while charging 12 MPa pressure experimental course, adiabatic process, isothermal process

While filling and emptying the battery, with a volume outlay of approximately 28 dm^3/min no heat exchange with the environment occurred. If after filling or emptying the battery the valve was closed for about 10 min, the isochoric process occurred. Fig. 7 shows the cycle of filling the battery, stopping the filling process, outflow and stopping the outflow. Two adiabatic processes during filling and outflow and two isochoric processes after stopping the filling and after stopping the outflow are visible. Additionally, the graph shows an isothermal process, where the final points of isothermal process and isochoric process overlap.

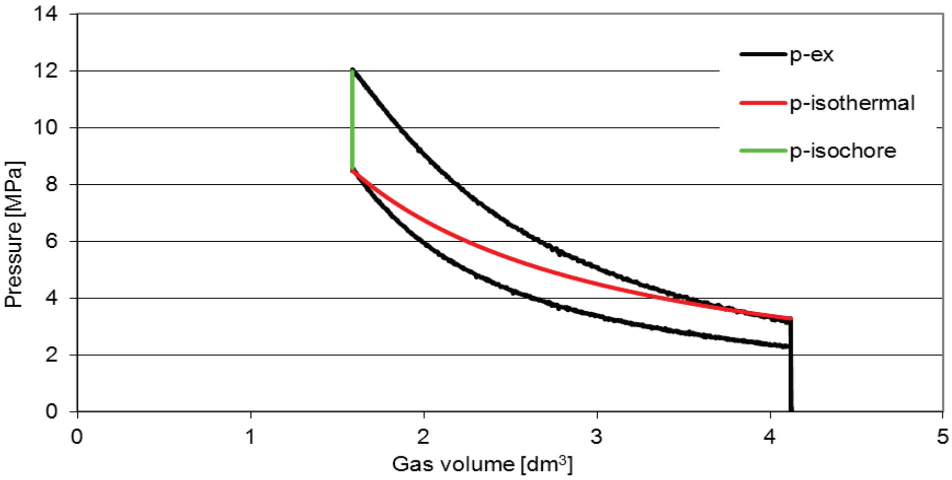

Fig. 7. Characteristics of the operation cycle of the hydro-pneumatic battery while charging and discharging with isochoric process, p – ex – experimental course; p – isotherm – the course of isothermal process p – isochore – the course of isochoric process

5. Experimental studies of the hybrid drive

Experimental studies were divided into two stages. During the first stage, studies of the vehicle model equipped only with electric drive with the possibility of retrieving the energy while the vehicle brakes were conducted. During the second stage, studies of the same model were assumed, however, with the hydrostatic support during braking and further acceleration. The studies were conducted with the assumed course of acceleration, driving at a constant speed and braking. The course of speed changes is shown in Fig. 8.

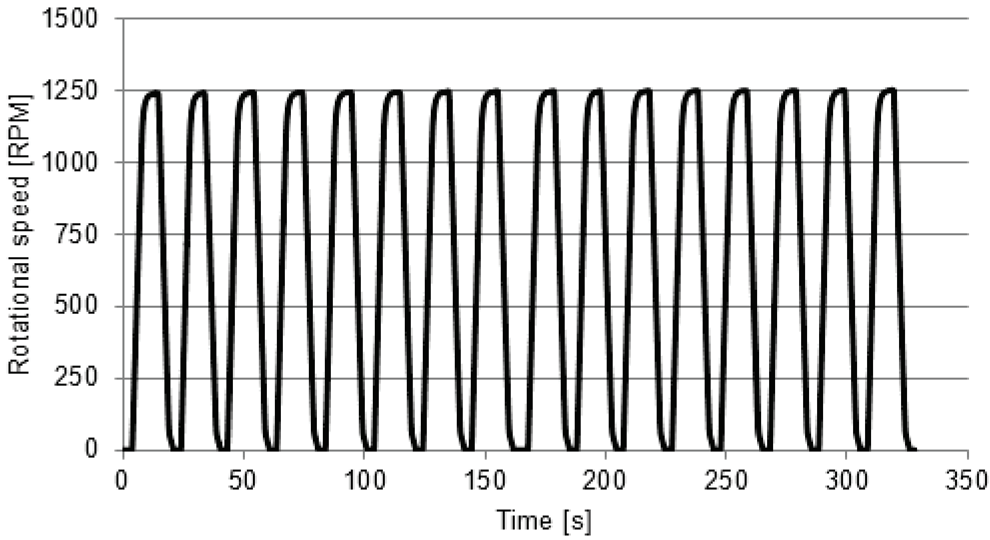

Fig. 8. The course of speed changes while accelerating and braking

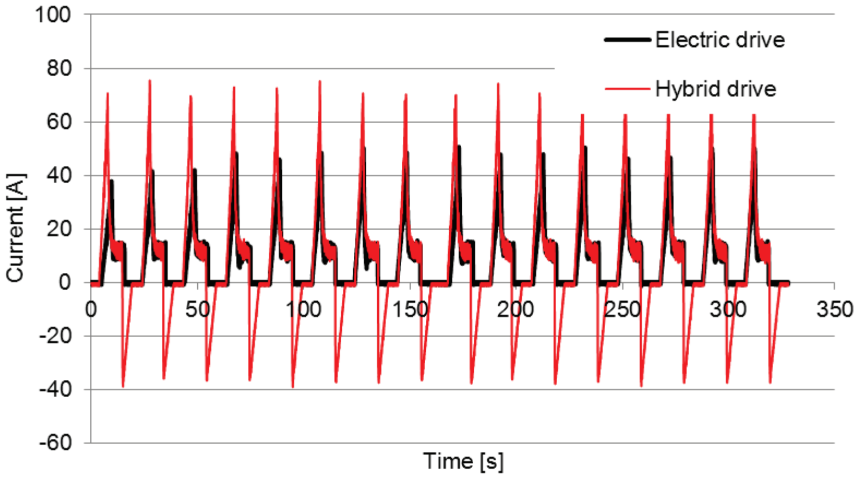

Fig. 9. The course of changes of current intensity while accelerating and braking in hybrid and electric drive

Fig. 9 shows the course of current intensity for two options of controlling the operation of electric drive and of hybrid drive. Sixteen cycles of accelerating and braking of the flywheel were studied. Cycles last for approximately 20 s, during which the acceleration of the flywheel occurs in the electric drive only by means of the electric engine within 5 s to the speed of 1250 RPM, and next the speed is kept for the following 5 s. Braking occurred also only be means of electric engine, however, with electric energy retrieval. The effective value of current flowing during the propulsion process amounted to 22.3 A. The values of currents differ in the hybrid drive, where the electric drive was supported by the hydrostatic drive. In this case, the idea of the hybrid drive operation consisted in common accelerating and keeping a constant speed of the flywheel, both by the electric engine and the hydrostatic engine. Braking of the vehicle model occurred only by means of the hydrostatic drive – the pump pumped and compresses the oil in the hydro-pneumatic battery. Proportions of the share of each type of drives were chosen experimentally in order to achieve the best possible effect in terms of the available parameters of the sub-assemblies of the electric and hydrostatic drives. The effective value of current flowing during the realization of two cycles amounted to 14 A. These values are significantly lower in comparison with the propulsion performed solely by the electric drive.

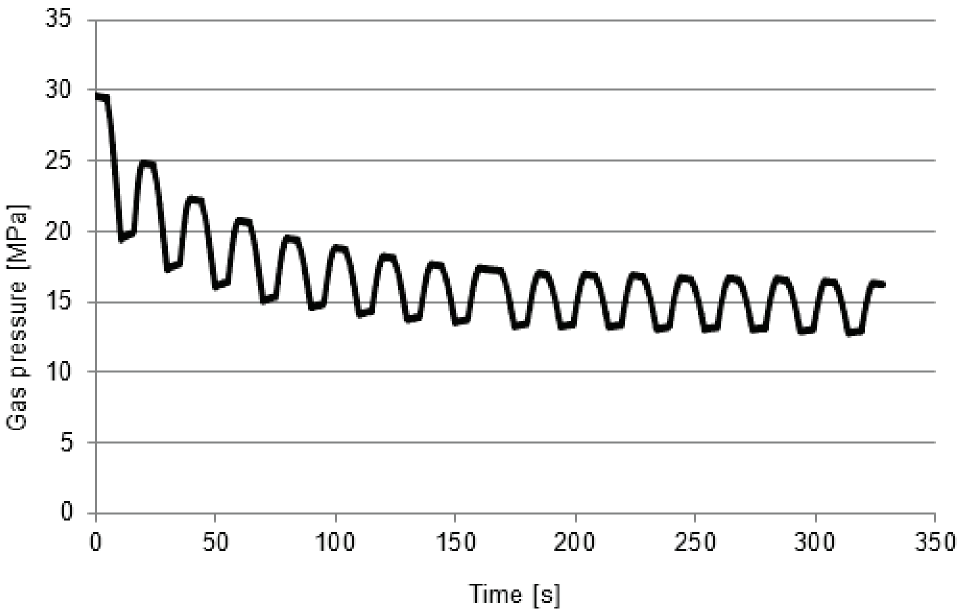

Fig. 10. The course of pressure changes in the hydro-pneumatic battery

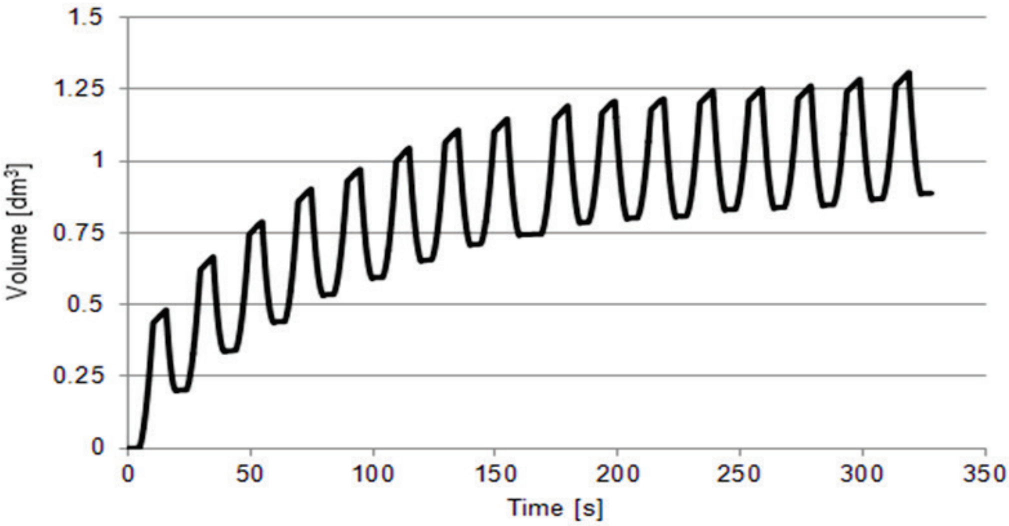

Fig. 11. The change in volume of hydraulic oil flowing into the hydro-pneumatic battery

The course of pressure changes in the hydrostatic drive was shown in Fig. 10. Applying the hydrostatic drive in order to support the acceleration process results in emptying of the hydro-pneumatic battery. The pressure in the battery drops then, which is connected with the outflow of hydraulic oil, which flows through the pump-engine. Using the hydrostatic drive for flywheel braking enables to make up for these losses only in half, approximately. The pressure changes are connected with retrieving the energy and gas transformations, which were presented in the previous point. Especially in the initial phase, where the pressure drop is visible. The motion resistances of the mechanical system do not significantly influence energy dispersion, the way it occurs the in the case of the transformations in the gas bladder.

Analysing the course of pressure in the hydro-pneumatic battery, it has to be stated that with the its initial full charge to approximately 30 MPa, the pressure drops after the 8th braking cycle to about 13 MPa. In the following cycles, it oscillates between 13 MPa and 16 MPa. Taking into consideration the fact that the initial pressure in the battery amounts to 5 MPa, these operating parameters have to be deemed advantageous.

Summarizing the course of studies, the ratio of the electric load of the battery θ in one cycle was established:

$$\theta = \frac{1}{\mathrm{N}} \int_0^T i^2(t) dt \ \ [A^2 s], \tag{3}$$

where:

i – current intensity,

T – time (320 s),

N – number of cycles (16).

Based on the conducted studies (16 cycles) the ratio of the electric load of the battery θ was established and in the electric drive, it amounted to $10.15 \cdot 10^3$ A^2s and in the hybrid drive, it was $10.15 \cdot 10^3$ A^2s. As a result of conducted experimental studies, the ratio decreased by about 2.5 times.

6. Conclusions

The obtained results of experimental studies confirms the thesis on the possibility of increasing the effectiveness of energy conversion process in the electric drive of an urban vehicle by means of supporting the electric drive with the hydrostatic drive. The support boils down to collecting energy from hydro-pneumatic battery during vehicle acceleration and returning the energy during regenerative braking.

The results of studies confirmed the thesis that with a short time of hydraulic oil outflow from the battery, the course of changes of gas pressure in the gas bladder is close to adiabatic process. During the course of the process, the heat exchange with the environment takes place in a small range, and the accumulated energy is the energy retrieved from braking.

The aim of the conducted experimental studies was experimentally to show the possibility of decreasing energy intensity of the electric drive thanks to hydrostatic drive support. The results of studies presented in the article demonstrate that a significant relief of the electric drive occurred. The results of experimental studies of multiple starting and braking of the vehicle are presented in the article. As a result of the conducted studies, in the system with electric drive with the hydrostatic support, in relation to the electric drive, the ratio of the load of battery decreased 2.5 times.

Additionally, a similar decrease in the effective values of currents was observed, e.g. from 22.3 A for the electric drive, to 14 A for the hybrid drive. This result suggests that there is a possibility to increase the effectiveness of energy conversion in the electric drive of the vehicle by means of the hydrostatic support.

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