Hybrid power-generating system with inertial energy-storage device

P D Balakin, O S Dyundik, I P Zgonnik and M A Fedorova

Omsk State Technical University, 11, Mira Pr., Omsk 644050, Russia

Abstract. Detailed quantitative analysis of the energy and technical capabilities of various hybrid power-generating system combinations for a transport machine is performed. Prospective combination of compression ignition engine and inertial energy-storage device made by the superflywheel is shown. Engineering analysis of superflywheel parameters and features of the dynamics of the flywheel drive is given.

Key-words: hybrid power-generating system, inertial energy-storage device, superflywheel.

1. Introduction
The traditional thermal internal combustion engine (ICE) is known to be the basis for the power-generating system. The exceptions in design are gas-turbine engines (GTE) of aviation, shipbuilding, heavy dump trucks and other unique equipment, as well as electric transport. During the transformation of energy occurs dissymmetry of its conversion. If motional energy is converted to thermal energy for 100%, then the reverse conversion of energy is possible up to 40% as a maximum. All thermal engines use the combustion of a hydrocarbon fuel to generate motional energy. Combustion products are chemically active, their complete neutralization is impossible, and partial neutralization is expensive. The problem of preserving a safe environment is becoming more actual and requires solutions at all stages of creation and operation of technogenic industry, especially transport machines [1, 2].

2. Problem statement
Multiduty operation of power-generating systems of transport machines leads to irrecoverable energy losses. In most cases, the motional energy of movement of the machines, units and components of the machines during braking is converted into thermal energy, and then it is dissipated, while simultaneously reducing the average coefficient of efficiency of the engine with an increase in fuel consumption in urban operation. The solution to the problem of break energy recuperation of transport machines is relevant [3-6]. Technical solution to this problem is implemented, for example, in metro trains. Their power system is based on the use of electric motor-generators, but the recoil pulse of electricity powers degrade the quality of the installation in the metro systems power supply chain.

The idea of creating hybrid power-generating systems that combine a combination of ICE and electric drive from energy-storage devices has been implemented in transport engineering recently [7-10]. This idea is not new, it is known and widely used in the drives of diesel-electric submarines, for example. Leading concerns for automobile transport offer to use serial samples of passenger cars with electric
drive and self-contained travel up to 200 km, with a combined drive with a low-power ICE, used both for driving and for energy-storage devices. Promising direction for the development of transport machines is the creation of power-generating systems. Determining the most effective, technically feasible combinations of such power-generating systems, it is necessary to analyze the potential components of the hybrid according to the criteria of specific energy intensity and specific power.

3. Theory

Single terms of reference (TOR) for the design of a transport machine is formulated to correctly compare the capabilities of the components of a hybrid power-generating system. For example, consider a machine weighing one tone passing on the road a distance of 100 km without ascents (descents) at a speed of (60-80) km/h.

Experimentally determined by towing the machine, the pull force \( P = 250 \text{ N} \). The work of this force \( A \) on a 100 km path will be equal to \( A = 25000 \text{ N} \times \text{km} \) or 25 megajoules \( (25 \times 10^6 \text{ J}) \). Fuel consumption for a machine with an ICE, in the range of (6-10) liters, which is close to the weight of (5-10) kg \([7]\).

If the gravitational energy-storage device (weight) is used as a power-generating system, then with the accepted TOR for charging it is necessary to lift a 5-tons piece to a height of 1 km, or a weight of 2.5 thousand tons to a height of 1 m. These two options are not technically feasible.

Using the potential energy of elastic deformation in the battery, it is taken into account that 1 kg of the mass of a steel spring is able to accumulate only 0.5 kJ of energy. Then the spring energy-storage device gets a mass of 50 tons for the transport machine designed according to the TOR. Natural rubber energy-storage device is capable of accumulating 30 kJ per 1 kg of mass with an acceptable stretch of the elastomer of 4 times and the necessary 25 megajoules realize 900 kg of elastomer, but the problem of placing the energy-storage device will arise. For example, a bundle with a cross section of a square decimeter has an initial length of 100 meters, and when stretched, its length reaches 400 meters. If such a bundle is thrown over the blocks, the friction practically absorbs the accumulated energy. If the bundle is folded repeatedly, its tension is also folded repeatedly according to the number of bends. The total power of such a charged energy-storage device will "fold" any machine body.

Built on compressed air energy, energy-storage device with a pressure of 500 ATM (50 MPa) (this is a lot) will require compressing 1 m\(^3\) of air weighing 1 kg 500 times. This cubic meter is placed in a cylinder with a capacity of 2 liters. One thousandth of a cubic meter (liter of air) at 50 MPa, it can contain 50 kJ of energy and 25 MJ requires 2500000:50000:2=250 cylinders, which is known. The air accumulator weighs 1.25 tons, if the weight of a two-liter cylinder is taken at least 5 kg.

Any gas cools during expansion. The problem of removing condensate or using it as a working fluid separated from the compressed gas by a sealed elastic partition occurs. This significantly complicates the design of the pneumohydraulic drive of the transport machine.

Thermal energy-storage device with external heating of the thermal-bearing mass is used as part of a hybrid power-generating system. Each kilogram of steel or copper when cooled at \( \Delta t = 100 \text{ }^\circ \text{C} \) is able to release 10 kilocalories, which is known. Each contains a kilocalorie of heat is 4.2 kJ of energy. The resulting required value of \( 25 \times 10^6 \text{ J} \) of energy is created by a thermal energy-storage device with a mass of \( 25 \times 10^6:42\times103=600 \text{ kg} \).

Thermal energy-storage device has a coefficient of efficiency of no more than 40% due to the dissymmetry of the conversion of thermal energy into motional energy, as noted earlier. A Stirling engine with a similar thermal storage unit forms a power unit weighing about 3 tons.

In a hybrid power-generating system, the role of a energy-storage device is performed by electric capacitors. The maximum density of its energy is 3.6 kJ per 1 kg of weight, therefore, the capacitor will have a weight of \( 25 \times 10^6:3.6\times103=6944 \text{ kg} \) for the performance of the accepted TOR indicators. The technical problem of metered discharge of a set of composite elements of the capacitor is also solved by a special program.
At the moment, chemical (galvanic) energy-storage devices are practically implemented in the drive of passenger cars. With an increase in power capacity, the following types of energy-storage devices are used: lead-acid; alkaline nickel-cadmium; silver-zinc; hot (sulfur-sodium) or (chlorine-lithium); copper-lithium; fluoride-nickel-lithium, etc.

Galvanic energy-storage devices are used as a component of a hybrid in combination with ICE, and only in electric machines, which are electric cars. However, with a high energy density, electric energy-storage devices have a small density of output power. This power depends on the speed of the chemical reaction in them.

Oxygen-hydrogen fuel elements are very promising. The energy density is about 1 MJ per 1 kg of mass considering only the mass of gases. However, the power unit is complex and cumbersome. The energy density will not be equal to or less than that of electric energy-storage devices, given its mass (about 50 W per 1 kg of device weight).

The energy and technical capabilities of the flywheel (inertial) drive as the main one and as part of the hybrid power-generating system of the transport machine will be analyzed as a result.

The flywheel is traditionally an integral part of most machines. The purpose of the flywheel is the angular speed leveling in of the main shaft of the machine and to use as the motional energy of energy-storage device. Motional energy helps to power shortage the drive during peak external loading.

The parameters of a traditional flywheel and its moment of inertia are determined based on the irregularity ratio \( \delta \) of machine travel and excessive work \( A_{exc} \) external forces. Excessive work \( A_{exc} \) is compensated by the motional energy \( T \) of the flywheel.

Because \( \omega_{max} = \omega(1 + \frac{\delta}{2}) \); \( \omega_{min} = \omega(1 - \frac{\delta}{2}) \); their difference are \( \Delta \omega = \omega_{max} - \omega_{min} \)

\[
J_F = \frac{2 \cdot A_{exc}}{\Delta \omega^2}
\]

In a hybrid power-generating system, the role of the flywheel differs in that the motional energy stored by it is spent on the movement of the transport machine.

The speed of rotation of the flywheel can be significant to minimize its size and it is structurally executed by a superflywheel.

Super flywheels are created now. Flywheel rims are structurally made with a wound tape or wire. Materials used for manufacturing flywheel rims: steel, titanium, kevlar, duralumin, quartz, glass fiber, graphite fiber, etc. The operating running speed \( n=30000 \) r/min is reached, the velocity of rotation on periphery of the rim is more than 500 m/s. The flywheel rim is held and centered by a magnetic suspension, bearings are taken from gas turbines (graphite sliding and double rolling), and magnetic fluid is used as a lubricant for vacuum chamber seals. Generally, this is a high-tech and expensive power unit. The flywheel is kept in free rotation for 40 days, as a rule, experienced specimens rotate freely for up to 10 years. Special difference between the flywheel drive and the others is that the motional energy of the flywheel is converted into the motional energy of the transport machine with a high coefficient of efficiency of this conversion. Even though the flywheel is integrated as an element of an electric or hydraulic drive, the coefficient of efficiency can reach values of \( \eta = 0.75 \) with this double energy conversion, which is not bad.

The drive with a flywheel is capable of both charging from the ICE on the move, as well as to recover the energy of braking a transport machine and charging at stationary stations.
The algorithm and an example of engineering calculation of superflywheel parameters are shown. The superflywheel is able to meet the requirements of the adopted TOR for the project of transport machine.

Limit the velocity of rotation of the center of mass of the rim to \( V = 700 \text{ m/s} \). The average radius of the flywheel rim is \( R_{av} = 0.25 \text{ m} \). The angular rate of its rotation is

\[
\omega = \frac{V}{R_{av}} = \frac{700 \text{ m/s}}{0.25 \text{ m}} = 2800 \text{ 1/s} \approx 28000 \text{ r/m},
\]

which is quite affordable.

Since the motional energy reserve \( T \) must be \( 25 \times 10^6 \text{ J} \), and, where \( J_{sf} \) is the moment of inertia of the superflywheel, then

\[
J_{sf} = \frac{2 \cdot T}{\omega^2} = \frac{50 \times 10^6 \text{ J}}{784 \times 10^4 \text{ 1/s}^2} = 6.38 \text{ kgm}^2.
\]

Because

\[
J_{sf} = \frac{G \cdot D_{av}^2}{4 \cdot g},
\]

where \( G \) is a weight of the superflywheel, \( D_{av} = 2 \cdot R_{av} \) is a average diameter of the rim, \( g \) is a intensity of gravity, then

\[
G = \frac{4 \cdot g \cdot J_{sf}}{D_{av}^2} = \frac{4 \cdot 9.8 \text{ m/} \text{s}^2 \cdot 6.38 \text{ kgm}^2}{0.25 \text{ m}^2} = 1000 \text{ N} = 100 \text{ kg},
\]

which is quite acceptable.

The weight of the flywheel is concentrated in its rim

\[
G = a \cdot b \cdot \pi \cdot D_{av} \cdot \gamma,
\]

where \( a \) and \( b \) are cross-section dimensions of the superflywheel rim; \( \gamma \) is specific weight of the material (if the material is steel, then \( \gamma = 76000 \text{ N/m}^3 \)). The cross-sectional dimensions of the rim:

\[
a \cdot b = \frac{G}{\pi \cdot D_{av} \cdot \gamma} = \frac{1000 \text{ N}}{3.14 \cdot 0.5 \text{ m} \cdot 76000 \text{ N/m}^3} = 0.0084 \text{ m}^2.
\]

By \( a=b \), receive \( a=b=0.0916 \text{ m} \) or \( 91.6 \text{ mm} \).

The obtained design parameters of the superflywheel meet the main criteria of the accepted TOR for the design of a transport machine.

The dynamics of the flywheel drive has special features. Features are that the moment of inertia of the superflywheel \( J_{sf} \) has the greatest value in the total moment of inertia, reduced to the shaft of the superflywheel \( J_f \).

The Lagrange equation for the reduced rotative system is converted to the form:
\[ J_r \cdot \frac{d\omega}{dt} = M_p^r - M_d^r, \]  

(3)

where \( M_p^r \) and \( M_d^r \) are moments of propulsive forces and drag force reduced to the superflywheel shaft. Flywheel drive refers to machine systems with a high-power engine. This type of flywheel drive is able to feed the power characteristic \( M_p^r = M_d^r \) to the system in the shortest possible time. This type of drive provides stationary steady-state behavior at any value \( M_d^r \).

The difference in values \( M_p^r \) and \( M_d^r \) occurs in the transition mode of movement. The amount of acceleration \( \frac{d\omega}{dt} \) of the reduction link is also determined by the time lag of the system. The step response is dynamic and has a short duration due to the high power capacity of the drive, which is useful when driving in urban conditions.

The difference in power characteristics (excess torque) is linearized in the analytical solution of a dynamic problem, as a rule. The speed variation of the reduction link at this time interval is linear, if \( M_p^r - M_d^r = \text{const} \) at a certain time interval, then \( \frac{d\omega}{dt} = \text{const} \). In the case when \( M_p^r - M_d^r = M_\Sigma = A - Bt \) time dependent, dividing the variables is obtained:

\[ d\omega = \frac{1}{J_r} (A - Bt) dt \]

\[ \omega_{t_1}^{t_0} = \frac{1}{J_r} \int (A - Bt) dt \]  

(4)

the speed variation in (4) is a quadratic function of the transition interval.

When \( M_\Sigma \) linearly depends on the speed \( \omega \) \(( M_\Sigma = A - B\omega \)), the separation of variables is reduced to a dependency:

\[ t_0 - 1 = J_r \int_0^\omega_{st} \frac{d\omega}{A - B\omega}, \]

with known initial conditions, its solution becomes:

\[ \omega = \omega_{st} (1 - e^{\frac{T}{T}}), \]  

(5)

where \( \omega_{st} \) is steady speed after the transition process is complete \(( \omega_{st} \) achieved when \( M_\Sigma = 0 \)) and by (3) this is possible when \( \omega_{st} = \frac{A}{B} \). \( T = \frac{J_r}{B} \) is characteristic time. This value physically means
the transition interval to the new value $\omega_M^{\ast}$, by $M_\Sigma = \text{const}$ for a model of motion with constant acceleration during the transition period.

4. Results discussion
The most promising for a transport machine is the combination of an ICN with an inertial motional energy-storage device, which is shown by a comparative quantitative analysis of the components of a hybrid power-generating system. This combination is made by a high-tech power unit with the main element – the superflywheel. The superflywheel is placed in a vacuum chamber using a magnetic suspension and bearings, structurally similar to the supports of gas turbines.

This combination provides the necessary autonomy for the operation of the machine. It also allows the use of ICE for driving outside localities with simultaneous charging of the energy-storage device and its connection in transient driving modes. A complete transition to purely inertial motion is expected to be in demand in areas with high environmental requirements.

The use of an inertial energy-storage device in a hybrid power-generating system allows to avoid the transformation of energy types. By mechanical means, the power components of the transformed motional energy are harmonized. Energy losses are minimal and result from a high value of the mechanical coefficient of efficiency.

Inertial energy-storage device makes it relatively easy to recuperate energy for recharging when a transport machine is decelerated.

5. Conclusions
- As shown in the article, hybrid power-generating system of a transport machine consisting of internal combustion engine and inertial (flywheel) energy-storage device has an advantage in terms of energy, environmental and technical criteria over other combinations of hybrid components.
- Inertial energy-storage device of motional energy is a high-tech unit. Technical solutions for this unit are rather feasible. The solutions are safe to use and nowadays can be applied not only in transport engineering, but also in space technology, as well as mechanical tools, and other areas.
- The above-mentioned algorithm and the example of engineering calculation of parameters by superflywheel show that inertial energy-storage device can be executed as the power unit. The overall mass characteristics of the power unit meet the TOR for the design of a transport machine.
- Modeling the dynamic behavior of a transport machine with an inertial energy-storage device of motional energy shows that such model is similar to the machine system with high-power engine.

6. References
[1] Sosnina E N, Masleeva O V and Kryukov E V 2015 Comparative environmental assessment of alternative energy installations Thermal engineering 8 2015 pp 3 - 3
[2] Vasiliev V 2007 Hopes of environmentalists Automobile transport 9 pp 50-5
[3] Lyashenko S G 2010 Flywheel energy recuperator Refrigeration and air conditioning 1 pp 31-3
[4] Sokolov V S, Krasnich O V and Kostorniy G V 2009 Use of flywheels in transport Electronic scientific journal of Kursk state University 2009 4(12) pp 12 - 4
[5] Voyna A A and Berezhnoy S B 2016 Calculation of the specific energy consumption of the recuperator of a vehicle equipped with a flywheel and elastic elements Drives and machine components 2016 3(20) pp 5-2
[6] Voyna A A 2017 The heat exchanger of a vehicle equipped with a flywheel and elastic elements Patent RF 2616460
[7] Gulia N V 1982 Inertia (Moscow: Nauka)
[8] Gulia N V 2006 Amazing mechanics. In search of the «energy capsule» (Moscow: NTs ENAS)
[9] Lomanin V V, Shabanov A V and Shabanov A A 2014 To calculate the power balance of the combined power plant of a hybrid car AAI Journal 2014 1(84) pp 24-3
[10] Yaroslavtsev M V 2014 Determining the parameters of a hybrid car power plant by modeling the energy consumption process Electrical engineering 2014 12 pp 17 - 4