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Method for determining the basic energy characteristics of elements of a hybrid car engine

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Abstract. A method for determining the basic energy characteristics of a hybrid car engine is presented. The technique takes into account parameters of the vehicle and parameters of the driving mode during operation. The basis of the technique is traction power and energy calculation. According to the source data, the flow of energy passing through mechanical, electrical chains and through the storage of electrical energy is determined. The technique is implemented in the form of algorithms for the calculation program and allows one to simultaneously receive the main technical characteristics of the vehicle when it is equipped with a hybrid engine of a sequential, parallel and mixed type. The presented method allows one to obtain the following values: the required power of the internal combustion engine, the required power of the motor generator, the minimum capacity of the electrical energy storage device, the estimated fuel consumption. This article presents an example of calculating the basic parameters of a combined power plant for a car weighing 1500 kg when driving it along the standard European driving test cycle. Similar calculations can also be carried out for any other cycle and parameters of the vehicle, including the bus, truck, and tractor.

1. Key points
1.1 A method for determining the basic characteristics of a hybrid power plant of car by the specified parameters is proposed.
1.2 A program has been developed for calculating the basic energy parameters of a hybrid power plant of car.
1.3 The calculation results for basic energy characteristics for a passenger car with a series, parallel and mixed scheme of elements at the power plant are presented.

2. Introduction
Internal combustion engines (ICE) and electric or hybrid power plants (HPP) are used as power plants at modern vehicles operating in periodic mode. The latter are used in cars, buses; tractors [1-2].

The method of assessment the ICE efficiency in unsteady operation was described in [3-4]. However, defining the basic energy characteristics of power plant elements is sometimes difficult and is the subject of an exact energy analysis and calculation [6-11]. First of all, it is because characteristics of power plant elements depend on the vehicle parameters and conditions of its movement during operation.
To determine the optimal power of ICE, working in combination with an electric motor, a calculation method is needed, which takes into account the vehicle parameters (mass, drag area of car), specified dynamic driving conditions and characteristics of the power plant elements (transmission, electric motor, energy storage, power converter, generator).

The method proposed in this paper includes: traction calculation; energy calculation of various types of schemes of hybrid power plants. All sections are connected in such a way to make a comparative analysis of characteristics of elements and to choose the optimal drive scheme for the vehicle, depending on the specified route. For convenience, the technique is implemented in the form of algorithms of a mathematical model and a calculation program, which is called GSU-AVTO [3], which allows theoretical studying and obtaining various dependencies.

3. Materials and methods

The basis of the calculation is driving cycle, which is a plot showing the relation between the vehicle speed, the longitudinal slope of road plane and time (V=f(t), α=f(t)). These dependencies can be obtained in a practical way by recording the change in parameters when moving along a given route, or can be set theoretically. In this case, we used the standard urban cycle according to the test protocol for passenger cars (EU directive 80/1268 2004), (Figure 1).

![Figure 1. The standard European driving cycle for cars testing for toxicity.](image)

Using well-known formulas of traction calculation, the resistance forces acting on the vehicle in each i-th point were found. $N_{Ki}$ is rolling resistance force; $N_{Wi}$ is air resistance force; $N_{Hi}$ is inertia resistance force; $N_{Pi}$ is lifting resistance force.

The total resistance force acting on the vehicle at each measured point is the sum of all forces

$$N_{Ti} = N_{Ki} + N_{Wi} + N_{Hi} + N_{Pi}$$

The graph (Figure 2) shows the curve for average power change when tested on a standard driving cycle.

![Figure 2. The chart for total resistance power (traction force) on driving wheels: $N_{Ti} = f(t)$; $N_{Sr, pol}$ is average positive power at a stage; $N_{T, SR}$ is average negative power (average braking power); $N_{NE, SR}$ is average peak load power (average power storage power).](image)
In a sequential scheme, the mechanical energy produced by the engine (ICE) is converted into electrical energy using a generator (M/G), then part of it is used to charge the traction energy storage device (BAT), and part of it is transmitted to the wheels by an electric motor (W). The block diagram of the common chain of losses in the serial drive is shown in Figure 3, a [5]. ICE in it regulates the speed of movement, and works in an optimal stationary mode, constantly giving all the generated power to TES charge and movement.

If there is no load on the wheels and the battery is fully charged, the power cannot be realized, in this case, ICE is turned off. Based on this, one can make a conclusion that all power generated by ICE will be spent on movement and loss in drive. It can also be affirmed that some spent energy will return due to braking recovery.

Some energy will be transferred from ICE to wheels in a straight chain (Figure 3.b), and some other through the energy storage device (c). The losses will be different for these cases. On this basis, each chain of losses is considered separately.

The average drive power at the stage transmitted directly to the car wheels will be equal to the entire average power $NSR.POL.$ minus the one that is transmitted through the energy storage $NNE.SR.$

A part of braking energy transmitted from wheels will return to BAT, after which it will be reused on movement, passing twice through the chain of losses (Figure 3, d).

The power that is additionally obtained due to recovery at the $N_S$ stage is based on the average braking power on wheels, given by recovery efficiency and efficiency of the drive loss chain (Figure 3 g).

While calculating NICE we take into account the most economically efficient ICE load mode ($K \approx 0.75$), and energy transfer losses in the drive chain.

From a theoretical experiment, it was found that for a car weighing 1500 kg when driving in regards to the standard European urban cycle, according to the calculation results, the required ICE power of a hybrid power plant will be 4.75 kW (Table 1).

The parallel scheme of hybrid drive has fundamental differences. As in a conventional car, it has a manual transmission and automatic transmission. The electric motor is installed parallel to the transmission and is activated only during acceleration, thus unloading the ICE. The excess engine energy when moving is consumed by the generator to charge the drive.

The electric motor in parallel circuit is reversible, i.e. can work in as a generator, but the charge is possible only with medium loads and in the mode of engine braking. Peaks of load are smoothed by an electric motor, which allows one to reduce ICE power, but inefficient modes of operation and idling cannot be eliminated, which causes ICE energy efficiency ratio($K$) [5] to decrease.

According to the peculiarities of parallel circuit, the algorithm for calculating the average required power $N_{SR.POTR}$ of the hybrid traction drive on the route has been included only in the time periods where ICE is involved ($NVIH. > 0$).

The ICE power, taking into account the losses in energy transmission, will be a sum of the power transmitted in a straight line, taking into account the losses in mechanical transmission, and power transmitted through electric motor (parallel circuit). It is also necessary to take into account the losses in the drive chain when transferring energy from ICE to drive, losses in the drive itself and losses in transferring energy to car wheels.
The block diagrams of loss chain in mechanical and electrical gears are shown in Figure 3b.

In the chain of electric drive, the flow of electrical energy during charging passes from the generator to the traction energy storage and back to the generator operating in the electric motor mode. Electric energy in a parallel circuit passes twice through an energy converter and only after that is transferred to an electric motor and transmission.

The recovered energy is transferred to the accumulator, after which, at the time of peak loads, it returns back, passing twice through the transmission, generator-motor, energy converter (Figure 3d).

The mixed scheme of HPP includes the advantages of sequential and parallel circuits. The energy flows in it are calculated in the same way as in the mixed scheme, however, it is assumed that ICE can be turned off at low energy consumption, and movement can be carried out from an electric motor powered by an energy storage device.

4. Results

The main energy characteristics are calculated for 3 typical drive circuits: serial, parallel and mixed. Table 1 presents the calculation results.

| Characteristics                        | Gear type |
|---------------------------------------|-----------|
|                                       | Serial    | Parallel | Mixed   |
| Initial energy in the storage, kJ     | 60        | 62       | 133     |
| Max. energy store in the storage, kJ  | 219       | 122      | 162     |
| Max. ICE power, kW                    | 4.75      | 8.99     | 4.45    |
| Max. Drive power, kW                  | 10.8      | 9.0      | 11.5    |
| Consumption, l/100 km                 | 4.55      | 4.4      | 3.68    |

According to the results of study of the HPP power characteristics, when driving a car along the standard European driving cycle, the lowest fuel consumption of 3.68 l/100 km is achieved with a mixed HPP. As compared to other schemes, it is lower by about 20%.

The smallest energy storage is required for a parallel circuit and is 122 kJ, for a mixed circuit it will be slightly larger. The drive with the largest capacity is required for a sequential drive circuit - 219 kW.

The highest ICE power (8.99 kW) should be in parallel to the drive circuit. The ICE power of sequential and mixed circuit will be approximately the same.

5. Conclusions

Thus, this method allows one to accurately calculate the basic energy characteristics of a hybrid power plant with a series, parallel or mixed scheme for each specific vehicle and a given driving cycle.
Also, this method is used to calculate the optimal characteristics of the electric energy storage device of the hybrid power plant and can be used in assessing the technical condition of a hybrid car according to the method developed by the authors.

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