Simulation-based identification of the parameters of a minibus hybrid powertrain

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Abstract. The bus is one of the most popular types of the road public transport and is much less dependent on the external infrastructure than the tram or the trolleybus. However, buses with conventional powertrains are the active sources of the environment pollution. Buses with hybrid powertrain are known to combine the independence of the motorbuses with a conventional internal combustion engine, a considerable reduction in the environmental pollution and the capability of the braking energy recuperation. This explains the increasing interest to the problems of their construction and development of effective control laws for their units and subsystems. Nowadays, these problems are solved by means of the mathematical simulation of the vehicle operation.

1. Introduction
Currently, the replacement of the conventional buses by the electric buses is one of the most efficient ways to prevent cities from air and noise pollution produced by urban transportation. However, the extensive use of the electric buses is restricted by their disadvantages such as short drive range and a low number of charge stations. The hybrid powertrain is the middle-ground that makes possible the development of a bus with sufficient range, low noise, and high fuel efficiency.

The hybrid powertrain consists of an internal combustion engine (ICE), one or several electric machines (depending on the type of the hybrid powertrain) and energy storage device. As it is known, there are several types of hybrid powertrains: serial, parallel, and series-parallel. Their main difference is the presence or absence of a mechanical connection between the internal combustion engine and the driving wheels. In a serial hybrid powertrain there is no such a connection and the engine gives all the generated energy to the generator which charges the drive and powers the electric motor.

As a collaborative project of BMSTU and GAZ international LCC, a minibus with a series-type hybrid powertrain is being currently developed. The primary task in the development of a hybrid bus is to determine the parameters of the units and the hybrid powertrain control laws which define the traction, dynamic, braking characteristics, as well as fuel efficiency and environmental friendliness. Now, such problems are solved by methods of computer simulation of the bus operation.

2. Mathematical model description
To determine the parameters of the serial hybrid powertrain aggregates and control system a mathematical model of the bus motion has been developed and implemented in MATLAB/Simulink. The structure of a series hybrid powertrain is shown in Fig. 1. Simulation of the power units operation
and the chassis dynamics is carried out using the elements of the Simscape/Driveline and Simscape/Electronics libraries (Figure 2).

![Figure 1. Structure of a series hybrid powertrain: 1 - ICE; 2 - generator, 3 - traction electric motor (TEM); 4 - power converters; 5 - energy storage device.](image1)

The bus dynamics was simulated only for the case of the linear movement along a rigid road without normal reactions redistribution between the sides of the bus [1] because of the little effect of the curvilinear motion on the values of interest: capacity of energy storage devices, TEM, generator and ICE characteristics. For the same reasons the work of the suspension wasn’t taken into account during the creation of the model. Since the bus is operated on hard-surfaced roads, the interaction of the wheel with the road is described by the Magic Formula model with constant coefficients [2], which increases the speed of computational experiments in comparison with the more accurate contact models [3,4,5,6,7].

![Figure 2. Structure of the computer model of the hybrid bus.](image2)
The work of the internal combustion engine is described by the following differential equation:

\[ J_{ICE} \cdot \dot{\omega} = h \cdot M_{ICE} - M_{gen} \]  

(1)

where \( J_{ICE} \) – moment of inertia of the internal combustion engine elements reduced to the crankshaft, 
\( \dot{\omega} \) – angular acceleration of the ICE output shaft, \( M_{ICE} \) – torque developed on the ICE output shaft, 
which is determined by the given engine external speed characteristic (ESC), \( h \) – degree of ICE power use, \( M_{gen} \) – the generator torque.

The fuel consumption is determined by the interpolation table as a function of the ICE speed and power.

The generator and TEM are modeled by the Servomotor element from the Simscape/Electronics library. The Servomotor element initial data are the dependencies of the electric machine maximum moment on the speed, the dependencies of the power of the losses on the torque and speed and the rotor inertial characteristics. The electric machines are controlled by the mechanical torque. The electric motor model is described by the following equations:

\[
\begin{align*}
N_{el} &= I_{cur} \cdot U_{dc} \\
N_{el} &= M_{mech} \cdot \omega + N_{los}
\end{align*}
\]  

(2)

where \( I_{cur} \) – current consumed by the motor, \( U_{dc} \) – DC link voltage, \( N_{los} \) – power loss, \( \omega \) – angular velocity of the electric machine shaft, \( M_{mech} \) – TEM shaft torque. Power loss \( N_{los} \) on each operating mode of the electric machine is determined in accordance with its passport characteristics.

The battery was modeled by the Battery element of the Simscape/Electronics library. The model takes into account the following parameters: rated voltage, capacity, internal resistance. The power loss \( N_{los} \) is estimated by the following relationship:

\[ N_{los} = I_{cur}^2 R_{bat} \]  

(3)

where \( I_{cur} \) – current on the battery, \( R_{bat} \) – internal battery resistance.

The ability to simulate both the standard driving cycles and those which are obtained by recording the parameters of the bus on its route is provided by the driver’s model. The bus control algorithm aim is to keep the set speed by adjusting the torque of the TEM with the help of a P-controller. Control action varies in the interval \([-1; 1]\). Negative values correspond to the brake pedal pressing, positive values – to the accelerator pedal pressing.

The hybrid powertrain control system model is based on the input signals: the degree of the accelerator and brake pedals pressing, bus speed, battery charge level, electric current in the battery, etc. The model determines the modes of operation of the internal combustion engine and generator, as well as the distribution of the braking torque between the TEM and the mechanical brakes.

The developed mathematical model makes it possible to estimate the values of currents and voltages in the electrical part of the hybrid powertrain, to determine the fuel consumption and energy storage device SOC (state of charge), to analyze the losses in the hybrid powertrain units, to assess the amount of the theoretically possible recovered energy during traveling along the route given as the function of time for the velocity. The mathematical model makes it possible to evaluate the operational efficiency and to configure various control algorithms for the hybrid powertrain.

The data obtained during the operation of the LiAZ - 6274 electric bus [8] in Moscow on the M2 route between Fili and Kitay-gorod metro station (Fig. 3) were used when studying the parameters of the bus motion and choosing the characteristics of the hybrid powertrain units using the developed mathematical model [11].
3. Parameter identification of the hybrid powertrain units

The primary evaluation of the traction motor parameters for a vehicle with a hybrid powertrain can be carried out using the calculation of the power balance of the bus. The calculation results are used as the initial data for the mathematical model. The lower estimate of the TEM required maximum power is determined by the following equation:

$$N_{\text{TEM}}^{\text{nom}} = \max(N_{\text{TEM}}^{\text{maxV}}, N_{\text{TEM}}^{\text{maxa}})$$

where the powers $N_{\text{TEM}}^{\text{maxV}}$ и $N_{\text{TEM}}^{\text{maxa}}$ are determined as

$$N_{\text{TEM}}^{\text{maxV}} = (m \cdot g \cdot f + P_w) \cdot V_{\text{max}} / (\eta_{\text{tr}} \cdot \eta_{\text{TEM}})$$

$$N_{\text{TEM}}^{\text{maxa}} = (m \cdot g \cdot (f \cdot \cos(\alpha) + \sin(\alpha)) + P_w) \cdot V_a / (\eta_{\text{tr}} \cdot \eta_{\text{TEM}}^{\alpha})$$

where $m$ – the bus gross weight, $f$ – the road resistance coefficient, $P_w$ – the air resistance, $V_{\text{max}}$ – maximum speed, $V_a$ – the steady-state speed of the up-slope motion given in the technical specification, with the road slope angle $\alpha$, $\eta_{\text{TEM}}$ – the TEM efficiency at maximum speed, $\eta_{\text{TEM}}^{\alpha}$ – the TEM efficiency at the speed $V_a$, $\eta_{\text{tr}}$ – the efficiency of the mechanical part of the transmission [9,10].

Based on the simulation results of the motion along the route, the parameters of the TEM are corrected when needed. For example, the power of the TEM can be increased in order to provide better acceleration dynamics or the use of the mechanical braking system can be reduced in order to increase the braking energy recuperation.

The power of the generator is chosen based on the requirements of ensuring its energy balance: positive or zero for a typical hybrid, negative for a plug-in hybrid [12]. The maximum power of the generator is defined as the product of the TEM power by the generator efficiency, while the bus can do without an energy storage device in all driving modes. The lower limit of the generator power for a bus without recharging is defined as the ratio of the energy expended per cycle of traffic to the cycle time.

Figure 4 shows the results of the generator power calculation for the following conditions: long-term movement at speeds of 70 and 90 km/h, maintaining zero energy balance when driving along the city route (Figure 3). The average speed at the city drive cycle is 14.8 km/h. The results were obtained with the use of the developed mathematical model.
Figure 4. Results of the generator power calculation
(EV – electric vehicle, HEV – hybrid electric vehicle).

The internal combustion engine is chosen according to the conditions that its nominal power corresponds to the calculated generator power. Its nominal power will be considered the ICE power at its maximum torque. For the joint operation of the ICE and the generator in optimal conditions it is necessary to ensure the consistency of their torque and rotation speed characteristics.

Table 1 contains the results of simulating the battery charging process by a generator set consisting of an internal combustion engine developing the maximum power of 81 kW (at 4000 rpm) and a generator that continuously develops a power of 50 kW. It can be seen that the internal combustion engine consumes less fuel while operating in the nominal mode than in the higher power mode to provide the same battery charge. However, the less-efficient modes allow charging the battery in less time so they can be used in the development of the hybrid powertrain control system.

Table 1. Parameters of the battery charging on a stopped bus.

| ICE rotation speed, rpm | 2000 | 2500 | 3000 |
|-------------------------|------|------|------|
| Change of charge, Ah    | 10   | 10   | 10   |
| Charging time, sec      | 572.9| 457.6| 382.3|
| Generator efficiency    | 0.9193 | 0.926 | 0.9287 |
| Battery loss, kWh       | 0.1259 | 0.1578 | 0.1889 |
| Fuel consumption, kg    | 1.755 | 1.787 | 2.07 |

The task of determining the type of the energy storage device and its capacity for a hybrid bus is multi-parametric. The modes of operation are the initial data for this task, in addition to the mass-dimensional characteristics of the vehicle being designed. As a part of the bus hybrid powertrain, the energy storage device performs the following functions:

• stores the energy produced during braking;
• provides the bus movement with zero emissions;
• provides the operation of the internal combustion engine and generator in nominal modes with high efficiency.

In accordance with the described functions, the energy storage device requirements are the following:

• ability to accommodate the energy produced during braking;
• providing the power required for motion;
• capacity should provide the required autonomous motion.

The ability to receive and release energy during the intense braking and acceleration is limited by permissible charge and discharge currents, which depend on the capacity C (Table 2 [9]) and type of the storage device. Currently, energy storage devices of two types: ultracaps and batteries with cells of various types are the most common.
Table 2. Characteristics of energy storage devices.

|                      | NaNiCl₂ | LFP | LMO | LTO | NMC | UltraCap |
|----------------------|---------|-----|-----|-----|-----|----------|
| Max Charge Rate      | +1C     | +1C | +1C | +6C | +2C | +20C     |
| Max Discharge Rate   | -1C     | -2C | -1C | -6C | -2C | -20C     |
| Max operating SOC    | 100%    | 90% | 100%| 85% | 80% | 100%     |
| Min operating SOC    | 20%     | 10% | 20% | 15% | 20% | 10%      |
| Cycle Life (number of 100% DoD* cycles) | 4500 | 2000 | 3000 | 20000 | 1000 | 50000   |

*DoD - depth of discharge

To determine the capacity of the energy storage device, the bus motion is modeled along the standard route, for which the time history of the speed is known. Based on the simulation results, it is possible to determine the specific power consumption, the peak values of the charge and discharge currents, which makes it possible to choose the type of energy storage device and its parameters.

The technique of determining the energy storage device parameters, depending on the used generator power, using time history of speed without using the mathematical model of motion, is described in [10, 11]. The authors note the absence of an unambiguous approach to the choice of the vehicle drive cycle, on the basis of which the optimal characteristics of the hybrid powertrain units could be found.

It is known that the selection of the transmission gear ratio is carried out taking into account the requirements for achieving the vehicle maximum speed and the requirements for overcoming the maximum slope. Buses with a series hybrid powertrain and electric buses do not have a gear box, so the selected gear ratio is realized in the final drive or wheel-hub drive, therefore it is necessary for it to ensure TEM operation with high efficiency in the most frequent driving modes.

Let’s consider as an example the final drive gear ratio identification of a hybrid bus for which the TEM has been previously selected.

The calculation of the final drive gear ratio was carried out taking into account the data obtained by the results of the measuring of the M2 route (Fili/Kitay-gorod metro station) in Moscow. The speed of the TEM shaft at each moment of time at different gear ratios was determined from the speed of the bus (the wheel radius was assumed to be constant). For each value of the gear ratio, the probability of the TEM speed being within the range of the TEM highest operational efficiency was found (Fig. 5).
According to the obtained correlation (Figure 6, a), the final drive gear ratio should be in the interval from 11 to 13 to ensure the TEM operation with a high efficiency on the greater part of the route. However, the condition of reaching a maximum speed of 90 km/h at the maximum speed of the TEM shaft rotation of 3700 rpm does not allow making the gear ratio more than 7.5 (Figure 6, b).
Figure 6. (a) probability of TEM speed values being in the range of \([1000 \ldots 3700]\) rpm at different values of final drive gear ratio; (b) dependence of the TEM rotational speed on the final drive gear ratio at a given speed.

4. Simulation of motion along the route

Figures 7 – 9 show the motion simulation results for a hybrid bus (with 11,500 kg gross weight) operating in the cycle shown in Figure 3. The length of the route is 23.1 km. The average speed on the route was 14.8 km/h. The coefficient of rolling resistance during the simulation was 0.018. The pie chart of the distribution of the energy spent on the route is shown in Figure 7. The average energy consumption was 1.03 kWh/km. The difference between the theoretical and actual recuperated energy equals to the energy of the TEM losses in the generator mode and the energy dissipated in the brake mechanisms and is 8 kWh, i.e. 33.9% of the energy spent on motion. The change in amperage on the battery is shown in Figure 8. The maximum charge and discharge currents are limited by the control system by 200 A, which equals to 3C. The share of the recuperation energy will decrease while using a battery with less permissible charge and discharge currents or with less capacity. That will lead to a decrease in the bus cost-effectiveness. Figure 9 shows the battery charge change.
Figure 7. Distribution of the energy losses during the bus motion.

Figure 8. Electric current in the battery.
5. Conclusion

Mathematical simulation provides a comprehensive solution to the problem of the hybrid powertrain parameter identification and its control system development at the design stage. The mathematical model allows carrying out an estimation of the new bus operational properties prior to the creation of the first prototypes, which reduces development costs.

For a hybrid bus with 11,500 kg gross weight and 30 km drive range, a traction motor with 140 kW of maximum continuous power, 50 kW generator, internal combustion engine with 60 kW of rated power (90 kW of maximum power) and storage battery with the capacity of 22.6 kWh have been selected. The parameters of the units of the hybrid powertrain were obtained from the simulation of the bus operation on the existing city route and will provide acceptable traction and dynamic characteristics of the bus, high fuel efficiency and environmental performance.

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