Development of a design system for synthesis and analysis the motor wheel based on a valve electric motor of combined excitation for hybrid and electric vehicles

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Abstract. The article describes a project to create an electric transmission for ground vehicles. As a layout, a motor-wheel variant is proposed, in which a traction electric motor, power electronics, control system and brake system are integrated into the wheel disk. This arrangement of the traction motor allows you to free up the space of the car for comfort and placement of the electric power storage. A combined excitation machine is proposed as an electric motor, the magnetic flux in which is created simultaneously by permanent magnets and an excitation winding. Permanent magnets allow you to increase the power in the limited dimensions of the disk, and the excitation winding allows you to adjust the magnetic flux, which significantly expands the range of speeds and torques of the vehicle. The design of the electric motor is innovative and protected by a patent of the Russian Federation. To develop a number of similar motor wheels, a design system has been proposed, which consists of two parts: synthesis and analysis. The synthesis system generates the optimal geometry of the electric motor for a specific technical task of the customer. It contains a multi-level structure that allows you to implement developments for various project situations with and without restrictions. The system contains seven such levels. Optimality criteria can be selected depending on the requirements of the project. The analysis system is based on the principle of a digital double. Its methodological basis is the finite element method. The system allows you to conduct a detailed analysis of the electromagnetic and thermal state, to obtain all the necessary integral characteristics. The performance of the design system has been tested on a digital analogue of a real racetrack, which is divided into sections with specified speed modes. The program outputs 15 parameters of both the car and the electric motor. In conclusion, the article shows the design study of a motor wheel for a racing electric car. The design of the prototype and the results of its tests are presented. The design system for the development of motor wheels based on a valve motor of combined excitation can be used for mass production.

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1 Introduction

The development of ground vehicles in recent decades shows that electric traction comes to replace the traditional internal combustion engine as a source of movement. This trend is manifested in an increase in the number of so-called hybrid vehicles, where the internal combustion engine is still present in the transmission, but already as an intermediate link in the generation of electricity.

Of course, this transition is explained by the strict requirements for the ecology of large megacities, but this is not the main thing. Technical systems have patterns of their development. They are born, carefully studied in laboratories, commercialized, then go off the historical scene as morally and technically obsolete, and obsolete [1-3]. The situation is not saved by the use of new materials, computerization of control and functioning systems, improvement of interior design and comfort. Transmissions based on internal combustion engines are becoming obsolete. Of course, they may face the fate of a bicycle, when, remaining at the same level of development, they can exist for quite a long time, but this is unlikely. The automotive industry is backed by hydrocarbon energy, which will also inevitably decline [4, 5]. It is a matter of time.

The bottleneck in the development of electric transport is the accumulation of electricity. It would seem that with the development of lithium-ion batteries, this problem will be solved quickly, but the process dragged on, and the problem remained. Most likely, the accumulation will go the way of fuel cells. They have a great perspective. In a battery, the volume of the electrodes determines the volume of electricity storage, and it is finite and cannot be very large, especially for vehicles where this volume is limited. In fuel cells, electricity is stored in liquid agents, and only the volume of the storage capacity limits this volume, which can be significant.

The problem of accumulation and storage of electricity is included in the list of 12 global problems that will significantly change the economies of leading countries and will be solved, including for vehicles [6]. The developer of electric transmissions must be ready for this and offer viable, technologically advanced and promising concepts and specific technical solutions to the scientific and engineering community. This article makes such an attempt. It is proposed to consider the scientific groundwork for the development of electric transmission based on a motor-wheel with a valve electric motor of combined excitation.

2 Choosing an electric transmission layout

When choosing an electric transmission layout, we will exclude hybrid electric transport options from consideration, as it does not have a long-term perspective. Over time, the internal combustion engine will leave the structure of the vehicle for the reasons mentioned. We will consider only electric transmissions. Fig.1. presents the most common types of existing electric transmission [7-10].
In fig.1.a the most common electro transmission is shown. It is the closest to a modern car and differs only in that the electromagnetic torque of the traction motor replaces the mechanical torque on the wheel axis. Such an arrangement is justified when a gasoline car is converted to an electric car without changing the geometry and structure of the vehicle itself. This direction will develop for some time, but not for long. This is due to a large amount of unused volume, for example, the volume of the wheel rim, the presence of the driveshaft and gearbox, which are obsolete. Attempts to use not a specialized transmission electric motor, but a mass-produced one, are generally doomed to failure.

In Fig.1.b shows an electric transmission in which electric motors are close to the wheel, but not integrated into it. It is more promising because it gives many possibilities to the control system of all four wheels. Serial wheels with a serial rim can be used for this transmission, which is very favorable for the unification of vehicles. However, the problems of unused volumes remain.

Figure 1.c shows an electric transmission based on motor-wheels, that is, a variant where the traction motor and all the necessary drive elements, including brake pads, are located in the volume of the wheel rim. Such an electric transmission is technically quite complex and requires special development for each vehicle, but it lies in the direction of the laws of the development of technical systems. This pattern suggests that a technical system without significant complication and an increase in volume in its development begins to perform more and more functions [1]. Therefore, the wheel itself performs not only the function of rolling, but also the function of traction, motion control, braking, and recovery of mechanical energy into electrical energy. At the same time, the engine compartment is freed up for other important purposes of the vehicle, including comfort. It is clear that such motor wheels need to be developed. To do this, it is necessary to create design synthesis and analysis systems, digital doubles for testing all complex control systems.

Let us choose the latest layout as the base for our perspective vehicle.

3 Choice of traction motor

When choosing a traction motor in relation to a motor wheel, some types can immediately be left without consideration. These are primarily electric motors that have a contact current
supply to the rotating parts. In the aggressive environment in which the wheel is located, these options are not acceptable due to low reliability. Thus, we exclude collector DC motors, synchronous electric motors with an excitation winding on the rotor, asynchronous electric motors with a phase rotor.

For the remaining brushless electric motors, it would be correct to make a project in the same dimensions of the motor-wheel, according to the same technical task, and compare the specific energy indicators obtained, such as power per unit of mass or volume, or the developed electromagnetic moment per unit of mass or volume. However, such scientific research will require a lot of effort, so we will make a choice based on qualitative analysis.

Electric motors that do not have their own source of excitation in the inductor, according to energy indicators, obviously lose to electric motors that have this source. These are synchronous reactive electric motors and valve-inductor electric motors. Both theory and practice show that in terms of the developed torque and power, they make up about 25-40% of the motors with excitation. On this basis, we will exclude them from consideration.

Asynchronous electric motors with a short-circuited rotor have found wide application in existing electric transmissions. Contactless, reliable and cheap are the main arguments for this choice. However, it is known from theory that the asynchronous machine takes the excitation from the armature winding, therefore, the armature winding must be increased by the amount of this reactive energy. This is about 10-15%. For a motor wheel with limited dimensions, this is essential. The complexity of frequency control also limits the use of this option.

Valve electric motors with permanent magnets have found application in motor wheels, but their use for electric transmissions has faced the following difficulties. The drives of vehicles have a wide range of changes in torques and speeds. At the start, the wheel should develop large moments, on the highway it is necessary to have high speeds. With permanent magnetic, which have a constant magnetic flux. It is almost impossible to provide this range. Some companies put two windings in the slots of the armature: one for high moments and low speeds, the other for high speeds and small moments. However, this leads to underutilization of anchor copper and, accordingly, a decrease in specific energy indicators. The control scheme is also much more complicated.

Based on the qualitative analysis carried out, the class of valve electric machines of combined excitation may have an advantage. These electric machines have two sources of magnetic field for excitation: these are permanent magnets and the excitation winding. At the same time, high-coercive permanent magnets allow obtaining good energy performance in a small volume, and the excitation winding allows regulating the resulting magnetic flux. There are known designs of valve machines of combined excitation with the placement of the excitation winding on a fixed stator, that is, they meet the requirements of a brushless current supply. Thus, this type of electric machines in a limited motor-wheel volume can provide the required electromagnetic parameters with a wide range of their regulation. Let us choose this option as the base for further consideration.

4 Description of the design and operating principle of the combined excitation electric motor

In relation to the motor-wheel, the most preferable is the reversed design of a combined-excitation electric motor with an integrated gearbox. The connection of the stator to the rotor is cantilever (Fig. 2)
The electric motor contains a stator consisting of shoved packages pressed onto parts of a massive magnetic circuit. The packages are located at a distance from each other. The anchor winding is located in the grooves of the packages. The excitation winding is located between the stator packages and has a contactless current supply. The inductor is located on the outer rotating part. It consists of two rings in which permanent magnets of radial magnetization and magnetic conducting poles are glued alternately one after the other along the circumference. Moreover, magnets of the same polarity are located on one ring, magnets of the opposite polarity are located on the other ring. The presence of a built-in two-shaft planetary gearbox allows you to significantly reduce the dimensions of the motor wheel. For the operation of the motor wheel, an electronic control system is required, which switches the stator windings according to a signal from the rotor position sensor. The construction is described in more detail in the literature [11].

The motor wheel works as follows. Magnetic flows from permanent magnets and from the excitation winding are closed along their routes, intersecting only in the rotor back and the massive magnetic core of the stator, while in one part of the conductors of the armature winding EMF is induced from the flux of permanent magnets, and in the other part of the conductors of the armature winding EMF is induced from the flux of the excitation winding. The magnetic flux from permanent magnets does not change its magnitude and direction, and
the magnetic flux from the excitation winding can change the magnitude and polarity. The resulting EMF in the armature section is obtained from the addition of EMF from permanent magnets and EMF from the excitation winding, that is, with the help of the excitation winding, it can be adjusted to the required speed. A rotating external inductor transmits the moment to the wheel disk of the car through a planetary gearbox.

5 Description of the design system for the development of the motor wheel

As it was noted, the proposed design is difficult to make uniform for different vehicles, so there is a need to develop a tool for designing motor wheels of this type.

The design system should include a synthesis system and an analysis system. The synthesis system must determine the optimal geometry according to the selected criteria, and the analysis system must confirm that the electric motor with the selected geometry meets the requirements of the technical specification.

Both the analysis system and the synthesis system should contain mathematical models, that is, all mathematically described dependencies that determine output parameters and characteristics. However, there are differences in these mathematical models. The mathematical model of synthesis should be simplified as much as possible and allow for numerous calculations included in optimization cycles. They are usually based on the method of equivalent substitution schemes. The mathematical model of the analysis should be sufficiently accurate and confirm the correctness of the obtained characteristics with high reliability. This is because alterations in the electric machine building are associated with very large time, material and financial costs. As a rule, mathematical models of analysis are based on finite element methods using complex software tools that require large hardware costs.

For the mathematical model of synthesis, the method of equivalent substitution schemes is applicable. The essence of the method consists of integral equations describing the electromagnetic state of an electric machine in separately divided sections: an air gap, a stator magnetic core, a massive stator magnetic core, permanent magnets and an inductor magnetic core. At each site, it is assumed that the magnetic induction has a constant value. A sketch of the magnetic circuit of the combined excitation electric machine is shown in Fig.3.

![Fig. 3. Sketch of the magnetic circuit of the electric motor.](image_url)
The method of equivalent substitution schemes is based on the Arnold equation, which relates electromagnetic power to electromagnetic loads and basic dimensions [12].

\[ P_{3M} = \frac{\pi^2 \alpha_\delta k_b k_{66} AB_\delta D^2 L_\delta n_{HOM}}{60} \]  

(1)

where \( P_{3M} \) – electromagnetic power developed by the motor, W
\( \alpha_\delta \) - pole arc coefficient;
\( k_b \) – field shape coefficient;
\( k_{66} \) – winding coefficient;
\( A \) – linear load, A/m;
\( B_\delta \) – induction in the air gap, Tl;
\( D \) – diameter of the anchor, m
\( L_\delta \) – anchor package length, m
\( n_{HOM} \) – rotation speed, rpm.

The volume of the article does not allow to give all the algebraic equations representing the mathematical model of synthesis. We will show only a block diagram of the main algorithmic steps of the model (Fig.4).

The mathematical model formed the basis of the synthesis system.

It is tested on the calculation of the characteristics for the electric motor of the motor-wheel of an electric car with nominal parameters of 30 kW, 72 V, 16000 rpm, which are shown in Fig.5-8.
Fig. 4. Block diagram of the mathematical model calculation algorithm.
The peculiarity of the motor is that it is possible to adjust the rotation frequency and the torque on the shaft simultaneously through two channels; along the armature circuit and along the excitation circuit.

\[
\begin{align*}
\nu &= \frac{U - I_0 R_a}{c_e \Phi_b}, \\
M &= c_m I_a \Phi_b,
\end{align*}
\]

where \(U\) – power supply voltage of the anchor circuit, V; 
\(I_0\) - armature current, A; 
\(R_a\) - active resistance of the armature winding, Ohms; 
\(c_e\) – EMF coefficient; 
\(c_m\) – torque coefficient; 
\(\Phi_b\) – magnetic excitation flux, Wb.

For this reason, dependencies for a two-dimensional function are of interest. In the Cartesian coordinate system, these dependencies will take the form of surfaces. Fig. 9 shows the surface of the dependence of the moment on the flow (excitation current) and the armature current.
The second component of the synthesis system is the block optimizer, which searches through the main dimensions of the electric motor and searches for their optimal values. As an optimization method, the Gauss-Seidel coordinate descent method is chosen for sorting variables in combination with the Fibonacci method when choosing a step. The block optimizer has its own features. It is built on the principle of multilevel optimization [13-15].

Multilevel optimization makes the synthesis system flexible. Depending on the project situation, it allows you to fix part of the variable variables, and include part of the variables in the iteration cycle. For a design system of a motor-wheel, which has a limited volume, this is very important. The following 7 levels of optimization have been introduced into the design system:

- full optimization, in which all variables are iterated over;
- optimization with a fixed outer diameter;
- optimization with a fixed inner diameter;
- optimization with a fixed outer length;
- optimization with a fixed outer and inner diameter;
- optimization in the specified dimensions;
- optimization for the specified dimensions of a permanent magnet.

These optimization levels cover almost all design situations that may occur when designing motor wheels.

The analysis system is based on the finite element method [16-19]. The analysis system is implemented in the Ansys Electronics Desktop software environment. Allows you to calculate the electromagnetic state of the electric motor.

The results of the analysis of the electromagnetic state of the engine are shown in Fig. 10.
Fig. 10. Results of calculation of the electromagnetic field.

The following are the characteristics learned as a result of digital engine simulation for the motor-wheel racing electric car of the Formula Student program (Fig.11-14).

**Figure 11.** Calculation of phase EMF

**Figure 12.** Calculation of phase currents

**Figure 13.** Calculation of speed during acceleration

**Figure 14.** Diagram of moment pulsations during acceleration
The given curves of the main parameters and characteristics are close to the oscillograms of a real model sample of the motor. This suggests that the created digital model is practically a digital double of a real electric machine.

6 Checking the operation of the motor wheel as part of the electric transmission when passing a real route

When the vehicle is moving along a specific route, the torque and speed of the electric motor vary widely. Before manufacturing a prototype, it is of interest to test a digital twin on a digital highway model with real high-speed loads. Let us model such a route consisting of different sections taking into account the slopes. In the model, we will take into account static loads from friction losses and air resistance and dynamic loads during acceleration and braking. In the model, we will set the driving mode as the average speed on the site.

In the model, we take into account the control of the combined excitation electric motor along the armature circuit and along the excitation winding circuit. The algorithm takes into account the possibility of introducing current limitation into the armature circuit. The algorithm of such control is shown in Fig. 15.
Fig. 15. The algorithm for controlling the electric transmission along the armature circuit and along the excitation circuit.

The algorithm takes into account the possibility of introducing current limitation into the armature circuit.

The digital model of the route and the movement of the vehicle along it is implemented in the Delphi software environment. Up to 60 sections can be stored in the memory of the route (Fig. 16). On the site, you can specify the slope both uphill and downhill. Friction and drag are taken into account by the coefficients and depending on the speed. When determining dynamic loads, the acceleration of the car, the moments of inertia of the rotating parts are taken into account. All moments through the gearbox are recalculated to the shaft of the electric motor.
When the vehicle is moving along the highway, 15 parameters are recorded and displayed in the form of oscillograms. Among them are armature currents and excitation windings, shaft torque, revolutions, losses, temperature, battery consumption, taking into account recovery. The waveforms are shown in Fig. 17.

Digital tests show that the electric transmission and control system cope with the loads of the route. An indirect indicator of this is the engine temperature, which does not exceed the
permissible norm for the insulation heat resistance class. The test results allow us to move on to the next stage – the production and testing of a prototype.

7 Design development. Production and testing of a prototype

The created design system removes a lot of technical risks, but not all of them. At the end of the project, a prototype must be manufactured and tested. These tests should provide answers to the question of the possibility of assembling the structure, the reality of the design parameters, the reliability and energy efficiency of the design option.

![Three-dimensional solid-state motor-wheel models.](image)

**Fig. 18.** Three-dimensional solid-state motor-wheel models.
The design system was created for the development of a number of electric transmissions for vehicles of various purposes [20-25]. To test its efficiency and effectiveness, a project was chosen to create a racing electric car for international student competitions Formula Student.

The design of the motor wheel for an electric car in the format of a three-dimensional solid-state model is shown in Fig. 18. A prototype was made and tested for this model. An electronic control system implementing 120-degree discrete switching was made especially for testing (Fig.19). Due to the absence of a load torque meter, the electric motor was tested in two modes: idle and short circuit. A mechanical characteristic was constructed from these two points, since with a constant flow it is a straight line. The deviation of the experimental characteristic from the calculated one did not exceed 9-12%, which is quite acceptable taking into account the measuring instruments used in the accuracy class.

8 Discussion

The developed design system is designed to create a number of motor wheels for vehicles of various purposes. It is a synthesis system and an analysis system combined into one complex. The synthesis system is built on the principle of multilevel optimization and allows you to design products in various design situations. This gives the system flexibility. The analysis system is built using the finite element method on the principle of a digital double. It comprehensively solves the problem of analysis by solving the related problem of calculating the electromagnetic field, thermal field, field of hydraulic solutions and field of mechanical stresses. Digital testing has been brought to a level where it is possible to test the created electric transmission on a specific track. The created system has an open structure that allows for the adjustment and replacement of its main blocks. This applies to both the synthesis system and the analysis system. Now the design system is in the testing mode for the design of specific motor wheels.

9 Conclusions
Summing up the conducted research, the following main conclusions can be drawn. One of the most promising options in the development of electric transmissions based on motor wheels is a valve electric motor of combined excitation. Its main advantage for this application is reduced dimensions due to the use of high-coercive permanent magnets and the ability to control the speed and torque on the shaft through two channels: the armature circuit and the excitation circuit. To implement this promising option, a design system has been created that allows designing motor wheels for vehicles of various purposes. The design system consists of a synthesis system and an analysis system. The synthesis system allows you to determine the optimal geometry for various design situations, and the analysis system reduces technical risks, allowing you to study the digital twin in detail. The perspective of the system development is end-to-end technology. To date, the reliability and operability of the design system has been tested on the project of creating an electric transmission for a racing electric car under the Formula Student program.

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