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PERMANENT MAGNETS ELECTRIC MOTOR WITH TWO-STAGE MAGNETIC GEARBOX FOR ELECTRIC VEHICLES

SILNIK ELEKTRYCZNY NA MAGNESY STAŁE Z DWUSTOPNIOWĄ PRZEKŁADNIĄ MAGNETYCZNĄ DO POJAZDÓW ELEKTRYCZNYCH

Abstract: The results of a study of the characteristics of an electric motor and a two-stage magnetic gearbox with neodymium magnets for an electric vehicle are presented. For the given dimensions of the electric vehicle (total mass, frontal body area, wheel radius, etc.), the optimal configuration and dimensions of the magnetic system of the electric motor and the two-stage magnetic gearbox are determined. The calculation of the parameters of the two-stage magnetic gearbox was carried out for the NEDC driving cycle and two values of the road inclination angle: $\alpha = 0\%$, $\alpha = 12\%$. It is shown that to reduce the electromagnetic torque of the drive motor, it is advisable to use a magnetic gearbox with a gear ratio $G_r = 15.36$ at an electric vehicle speed of up to 50 km/h, at a speed of more than 50 km/h – with a gear ratio $G_r = 6.4$. When designing a drive electric motor, numerical studies of six configurations of the magnetic system of the electric motor rotor were carried out. The calculation of the characteristics of the investigated electric motor and gearbox was carried out in the Simcenter MotorSolve and Simcenter Magnet software package.

Streszczenie: W pracy przedstawiono wyniki badań charakterystyk silnika elektrycznego z magnesami neodymowymi i dwustopniową przekładnią magnetyczną dla pojazdu elektrycznego. Dla zadanych wymiarów pojazdu elektrycznego (masa całkowita, powierzchnia czołowa nadwozia, promień koła itp.) określa się optymalną konfigurację i wymiary układu magnetycznego silnika elektrycznego oraz dwustopniowej przekładni magnetycznej. Obliczenia parametrów dwustopniowej przekładni magnetycznej przeprowadzono dla cyklu jazdy NEDC i dwóch wartości kąta nachylenia drogi: $\alpha = 0\%$, $\alpha = 12\%$. Wykazano, że w celu zmniejszenia momentu elektromagnetycznego silnika napędowego zaleca się stosowanie przekładni magnetycznej o przełożeniu $G_r = 15{,}36$ przy prędkości pojazdu elektrycznego do 50 km/h, przy prędkości powyżej 50 km /h – przy przełożeniu $G_r = 6{,}4$. Projektując silnik elektryczny napędowy przeprowadzono badania numeryczne sześciu konfiguracji układu magnetycznego wirnika silnika elektrycznego. Obliczenia charakterystyk badanego silnika elektrycznego i przekładni przeprowadzono w pakiecie oprogramowania Simcenter MotorSolve i Simcenter Magnet.

Keywords: magnetic gearbox, permanent magnets, permanent magnet motor, driving cycle, magnetic system configuration

Słowa kluczowe: przekładnia magnetyczna, magnesy trwałe, silnik z magnesem trwałym, cykl jazdy, konfiguracja układu magnetycznego

1. Introduction

Currently, there is an intensive growth in sales of electric vehicles and in this regard, there is a significant increase in investment in the development of traction motors.

In the development and production of electric vehicles, their performance is mainly determined by the range of electric vehicles and energy consumption per kilometer. When calculating these indicators, various driving cycles are used: the new European driving cycle (NEDC), the worldwide harmonized test procedure for passenger cars (WLTP) and many others [1, 2]. As a rule, electric motors with permanent magnets are used for electric vehicles, and the procedure for optimizing their design is carried out taking into account a specific driving cycle [3, 4].

Recently, magnetic gearboxes have been used for electric vehicles, which are becoming very popular and promising, since they have a number of advantages compared to mechanical ones. Magnetic gearboxes are capable of transmitting torque without mechanical contact, do not create additional noise, do not require lubrication, have high efficiency and reliability, and are more durable, which makes it possible to use them instead of mechanical gearboxes [5, 6].

The article [7] shows that the use of a two-stage mechanical gearbox makes it possible to increase both the power and economic indicators of the vehicle. This article proposes a two-stage magnetic gearbox, which allows you to change the gear ratio by turning off one stage. Two stages have a gear ratio $G_r = 15.36$ and are used when starting an electric vehicle up to a speed of $V = 50$ km/h. The second stage (when the first one is off) has a gear ratio $G_r = 6.4$ and is used for driving at speeds over 50 km/h.

The purpose of the research is to determine the optimal configuration and dimensions of the magnetic system of an electric motor with permanent magnets for an electric vehicle with given parameters (gross weight, wheel radius, frontal area of the body, etc.), at which a given value of torque and power is achieved with a minimum mass of permanent magnets. Based on the NEDC driving cycle, determine the optimal configuration and dimensions of the magnetic system of a two-stage magnetic gearbox that achieves the specified torque value.

2. Calculation of the parameters of a two-stage magnetic gearbox for the NEDC driving cycle

This paper demonstrates an approach to the design and optimization of the magnetic system of electric motors with permanent magnets and a two-stage magnetic gearbox for electric vehicles, taking into account the NEDC driving cycle.

The European NEDC driving cycle describes the movement of a vehicle in the city and outside the city (engine operation at minimum speed, starting from a stop and accelerating to a certain speed, engine braking from one speed to another) [2].

The following parameters of the electric vehicle were taken as initial data in the study of an electric motor with a two-stage magnetic gearbox: gross vehicle weight – m = 2000 kg; air resistance coefficient for the chassis body – C_x = 0.33; frontal area of the chassis body – S = 1.9 m2; wheel radius – r = 0.35 m; rolling friction coefficient – f = 0.018.

As a result of preliminary calculations, the gear ratios of two magnetic gearboxes were selected. The first gearbox has a reduction ratio equal to G_r = 2.4 and the second gearbox – G_r = 6.4. In the first gear, both gearboxes are engaged and the total reduction ratio is G_r = 15.36; in the second gear, one gearbox is engaged with a gear ratio G_r = 6.4.

On Fig. 1, taking into account the above initial data for the NEDC driving cycle, the calculated dependence of the moment acting on the wheels on the speed of the electric vehicle is shown for two values of the road inclination angle: α = 0%, α = 12%; and for two values of the reduction ratio: first gear – G_r = 15.36 and second gear – G_r = 6.4.

The reduction factors of the magnetic gearboxes were chosen so that the rotational speed of the electric motor for the NEDC driving cycle was no more than n = 6500 rpm.

In accordance with the given driving cycle for α = 12%, the largest torque on the wheels of the electric vehicle equal to 1670 Nm operates at a speed of 15 km/h. When using two gear stages with a reduction factor G_r = 15.36, it is necessary that the electric motor develops a torque of 109 Nm (Fig. 1). For speeds ≥ 50 km/h, the maximum torque at the wheels is 970 Nm. When using one gear stage with a reduction factor G_r = 6.4, it is necessary that the electric motor develops a torque of 206 Nm. For a driving cycle with an angle of inclination α = 0, it is necessary to provide lower torque values.

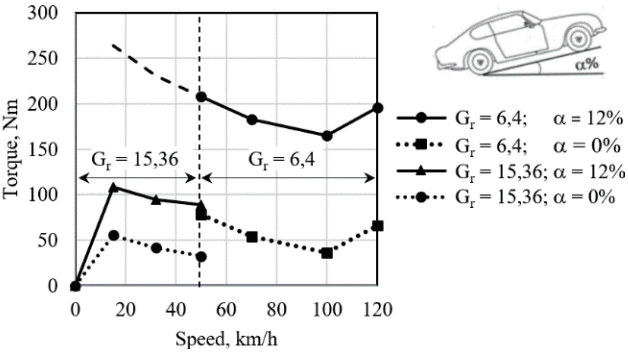

Fig. 1. Torques acting on the wheels of an electric vehicle with a two-speed gearbox

If only one gearbox with a reduction ratio G_r = 6.4 is used, then when starting with a road slope coefficient α = 12%, it is necessary that the electric motor develops an electromagnetic torque equal to – 260 Nm (dashed curve in Fig. 1).

3. Description of 2-stage magnetic gearbox for electric vehicle

The two-stage magnetic gearbox is a combination of two cilindriical magnetic gearboxes with magnetic flux modulators. The first gearbox MG1 with an outer diameter of 280 mm has 12 pairs of poles on the outer rotor 1 (Fig. 2).

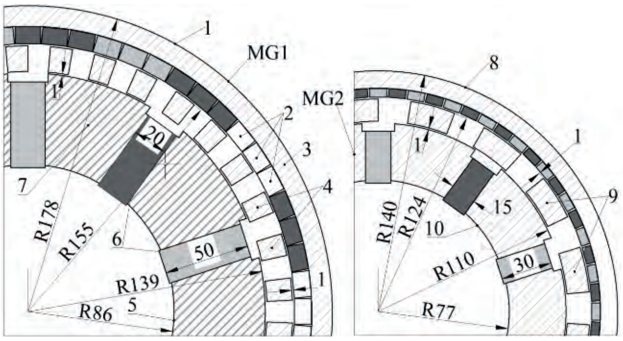

Fig. 2. Magnetic system configuration of MG1 and MG2 gearboxes

Each pole is made up of three magnets 25 mm thick and 10 mm wide fixed on an annular magnetic core 3. The steel elements of the magnetic flux modulator 4 are made of thin sheets of electrical steel. The inner high-speed rotor connected to the motor shaft has 5 pairs of poles with magnets 6 arranged tangentially and fixed between the steel poles 7. The second stage MG2 with an outer diameter of 356 mm consists of an outer low-speed rotor 8 having 32 pairs of poles (64 magnets with a size of 10 mm ×15 mm), a fixed modulator 9 and a high-speed inner rotor 10 with 5 pairs of poles (10 magnets measuring 20 mm × 50 mm). The reduction ratio of the second gearbox is $G_r = 6.4$. From the given driving cycle, it follows that the second stage of the gearbox must provide a torque on the low-speed shaft of at least 1670 Nm, while the first stage on the high-speed shaft must provide a torque of at least 109 Nm. To ensure such high torque characteristics, the high-speed rotors of both stages are assembled with magnets of tangential magnetization.

The static torque characteristics of the magnetic gearbox make it possible to determine the electromagnetic torques acting on a low-speed rotor – T_{LS} and a high-speed rotor – T_{HS} depending on their position: $T_{LS} = T_{LS}(\alpha_{LS}, \alpha_{HS})$, $T_{HS} = T_{HS}(\alpha_{LS}, \alpha_{HS})$, where α_{LS} and α_{HS} are angles turning low speed and high speed rotors. Fig. 3 shows the calculated static torque characteristic of the first magnetic gearbox with a reduction factor $G_r = 2.4$. at $\alpha_{HS} = 0$ and $\alpha_{LS} = 0°–72°$. The maximum torque on the high speed input shaft is 118 Nm. At the same time, we have a torque on the low-speed shaft – 282 Nm.

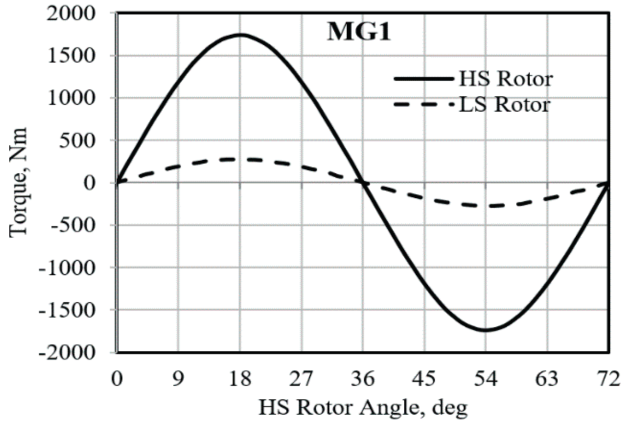

Fig. 3. Dependence of the electromagnetic torque on the rotation angle of a high-speed rotor for a magnetic gearbox MG1 with a reduction factor $K_r = 6.4$

Fig. 4 shows the calculated static torque characteristic of the second magnetic gearbox with a reduction factor $G_r = 6.4$. at $\alpha_{HS} = 0$ and $\alpha_{LS} = 0°–72°$. The maximum torque on the high speed input shaft is 272 Nm. At the same time, we have a torque on the low-speed shaft – 1740 m.

Thus, the calculated static characteristics of the first and second gearboxes show that both magnetic gearboxes provide the necessary torques in accordance with the selected driving cycle of the electric vehicle.

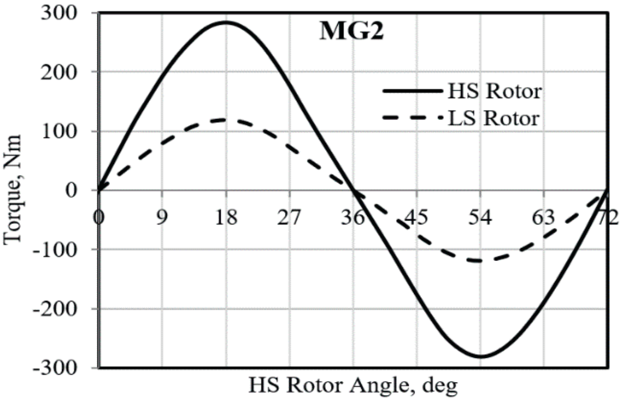

Fig. 4. Dependence of the electromagnetic torque on the rotation angle of a high-speed rotor for a magnetic gearbox MG2 with a reduction factor $K_r = 2.4$

4. Numerical studies of an electric motor with permanent magnets

The torque characteristics of a permanent magnet motor are significantly affected by the configuration and dimensions of the magnetic system. When designing the electric motor, the stator of a standard asynchronous motor with a rotation axis height of 132 mm was taken as a base, the main parameters of which are as follows: the outer diameter of the stator is $D_a = 225$ mm; stator inner diameter – 158 mm; stator package length – $L = 160$ mm, number of stator slots – $Z = 48$; the height of the stator slots is 16.7 mm. The use of a standard asynchronous electric motor, in which the squirrel-cage rotor is replaced by a rotor with permanent magnets, will significantly simplify and reduce the cost of retrofitting existing vehicles with an internal combustion engine to electric vehicles.

When designing the electric motor, six different variants of the M1–M6 rotor were studied, which are shown in Fig. 5.

These configurations differ in the size and arrangement of the permanent magnets in the rotor. The results of calculations of six variants of electric motors are presented in Table. 1.

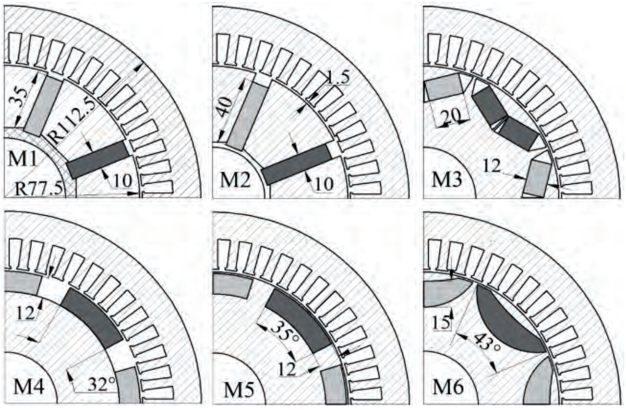

Fig. 5. Configurations of the magnetic system of the studied motors

Table 1. Main parameters and characteristics of six electric motors configurations

Parameter	M1 (opt.)	M2	M3	M4	M5	M6
Mass of permanent magnets, kg	3.36	3.84	4.61	4.6	4.96	6
Optimal switching angle, deg	10	10	20	0	20	10
Maximum moment, Nm	228	233	200	211	207	227
Power (n = 3000 rpm), kW	69.7	73.2	62.8	66.2	64.7	71.3
Power (n = 5800 rpm), kW	123	129	118	123	123	133
Efficiency (n = 5700 rpm), %	97.5	97.6	97.8	97.7	97.7	97.7
Losses in steel (n = 5800 rpm), W	1.9	2.02	139	1.46	1.6	1.84
Specific moment – M_{max}/m_{PM}, Nm/kg	67.9	60.7	43.4	45.9	41.7	37.8
Specific power (n = 5800 rpm) P/m_{PM}, kW/kg	36.6	33.6	25.6	26.7	24.8	22.2

The dimensions of the magnets were selected in such a way that the maximum electromagnetic moment was not less than M_{max} = 207 Nm.

According to the NEDC driving cycle, 207 Nm is the maximum torque required to overcome a road section with a slope α = 12% by an electric vehicle with given technical parameters (weight, frontal body area, etc.).

Since the stator parameters for all the models under study are the same, the mass of the rotor is also approximately the same, and the most expensive element of the rotor is permanent magnets, the following specific characteristics were the criteria for choosing the best option: specific torque is the maximum torque of an electric motor divided by mass of permanent magnets (M_{max}/m_{PM}); specific power is the power at rotor speed n = 5800 rpm, divided by the mass of permanent magnets (P/m_{PM}). The speed of rotation n = 5800 rpm corresponds to the maximum speed of the car V = 120 km/h.

We studied two magnetic systems with tangential magnetization of magnets (M1–M2), one with internal magnets of variable orientation – IPM (M3) and three with radial magnetization of magnets.

The current in the motor phases for all models was set the same and equal to I = 290 A, which corresponds to the current density J = 12 A/mm^2.

The switching moment of the motor windings is determined by the advance angle between the position of the q-axis of the rotor and the middle axis of the switched winding. The value of the advance angle affects the value of the magnetic flux of the rotor and, accordingly, the emf. windings. When conducting numerical studies, the lead angle was varied in such a way as to provide the maximum torque for a given rotor speed. In the second line of the table 1 shows the optimal switching angle for each of the models.

As a result of numerical studies, it was found that magnetic systems with tangential magnetization (M1, M2) have the best specific characteristics. Magnetic systems with radial magnetization of magnets have about 1.5 less specific torque. The M3 magnetic system has a maximum torque equal to M_{max} = 200 Nm, which is lower than the specified one. At the same time, it is not possible to increase the torque to the specified one by increasing the thickness or width of the magnets for this magnetic system.

Analyzing the data given in table 1, it should be noted that the model M1 has the best specific characteristics, so all further calculations were carried out for this model.

As is known, unlike induction motors, in motors with permanent magnets, the dependence of the electromagnetic torque on the rotor speed has an almost constant value up to a certain rotor speed, after which the torque and power of the electric motor have a sharply falling character.

As a result of a series of preliminary calculations, the number of turns of the stator coils was determined, at which the power and torque begin to decrease after the rotor speed is equal to n = 6200 rpm. This number of turns is equal to W = 2. Each phase consists of 4 coils connected in series.

Fig. 6 shows the performance characteristics of the electric motor – the dependence of the electromagnetic torque and power on the speed of the electric vehicle and the rotor speed when driving in first gear, when the reduction ratio of the magnetic gearbox is G_r = 15.36.

In order to obtain the value of the electromagnetic torque that exceeds by the 10% highest peak values of

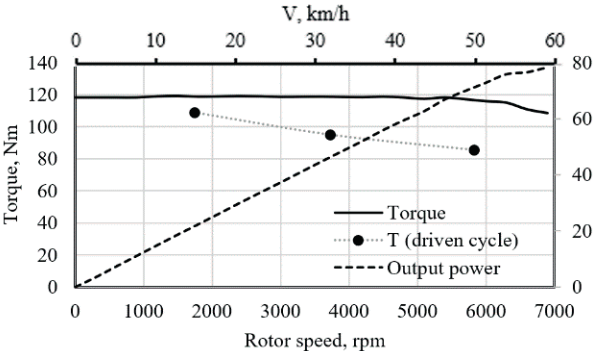

Fig. 6. Dependence of the electromagnetic torque and power on the speed of the electric vehicle and the rotor speed in first gear (G_r = 15.36)

the moment acting on the wheels of an electric vehicle, at a slope angle α = 12%, it is necessary that the electromagnetic torque of the electric motor be equal to at least M = 120 Nm. The phase current should be equal to I_{ph} = 155 A, the current density at this current is equal to J = 6.2 A/mm^2.

The maximum peak torque value acting on the wheels of an electric vehicle at a road inclination angle α = 0% is M = 60 Nm. In order to obtain an electromagnetic torque value slightly higher than this value, the phase current must be equal to I_{ph} = 60 A, which corresponds to a current density J = 3.2 A/mm^2.

Thus, due to the two-stage magnetic gearbox, at a speed of up to 50 km/ h and a reduction factor G_{r} = 15.36, the air-cooled electric motor will not be overloaded, therefore the windings and magnets will not overheat.

Fig. 6 also shows a graph of the peak torques acting on the wheels of an electric vehicle for the NEDC driving cycle at a road inclination angle (α = 12%), which is designated as – T (driven cycle). The results of the calculation show that at the first speed, the performance characteristics of the electric motor ensure the movement of the electric vehicle in accordance with the given driving cycle, both when driving on a straight road section (α = 0%), and when driving with a maximum slope (α = 12%).

Fig. 7 shows the dependences of the electromagnetic torque and power on the speed of the electric vehicle and the rotor speed when driving in second gear, when the reduction ratio of the magnetic gearbox is G_{r} = 6.4. In second gear, according to the driving cycle, the maximum torque acting on the wheels of an electric vehicle at a road inclination angle (α = 0%) is 78 Nm, and at a slope (α = 12%), respectively, is 207 Nm.

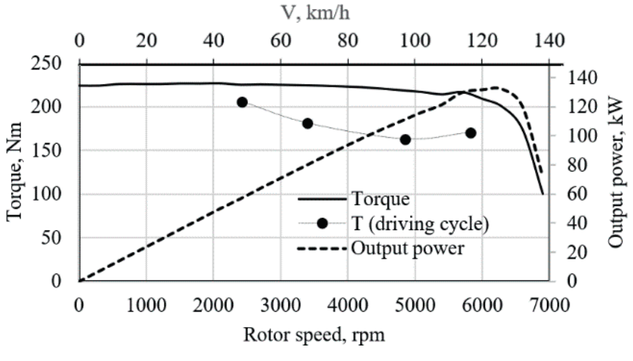

Fig. 7. Dependence of the electromagnetic torque and power on the speed of the electric vehicle and the rotor speed in second gear (G_r = 6.4)

In order to ensure the movement of an electric vehicle in a straight section (α = 0%) in accordance with the driving cycle, it is necessary that the phase current be equal to I_{ph} = 86 A. Then the maximum electromagnetic torque is M = 86 Nm, which exceeds by 10% the torque of resistance equal to M = 78 Nm.

When moving uphill with a slope (α = 12%), it is necessary that the phase current be equal to I_{ph} = 290 A, which provides an electromagnetic torque equal to M = 288 Nm, and the current density is equal to J = 12 A/mm^2. Fig. 7 also shows a graph of the peak torques acting on the wheels of an electric vehicle for the NEDC driving cycle at a road inclination angle (α = 12%), which is designated as – T (driven cycle).

The calculation of the temperature of the structural elements of the investigated electric motor (windings, magnets, iron of the stator and rotor, shaft, housing, end shields) was carried out taking into account the cooling system. The thermal calculation was performed for the NEDC driving cycle. The thermal calculation was performed for an air cooling system. In an air-cooled system, air is forced by a fan along the outer casing of the electrical machine. The initial data for air cooling are as follows: machine orientation – horizontal; the direction of forced convection is axial; cooling flow velocity – V_{flow} = 5 m/s; initial temperature – T = 20°C. The temperature was calculated using the Simcenter MotorSolve software package.

Fig. 8 shows the heating curves of windings and magnets for air cooling at the value of phase currents I_{ph} = 290 A (J = 12 A/mm^2) and I_{ph} = 155 A (J = 6.2 A/mm^2) for the NEDC driving cycle and driving uphill (α = 12%).

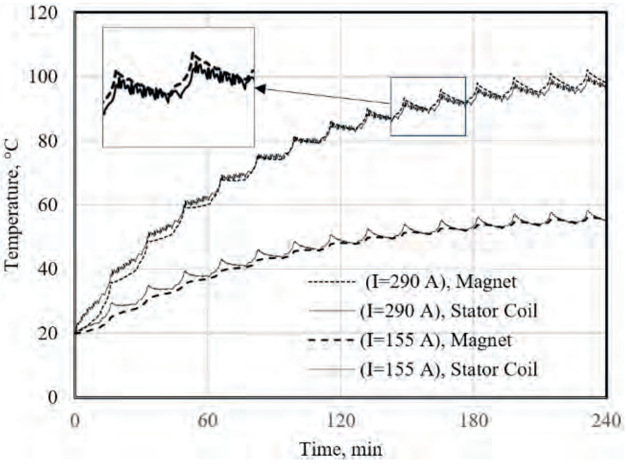

Fig. 8. Heating curve of windings and magnets for air cooling

It follows from these graphs that the steady-state temperature of the windings and magnets, even when moving in second gear, is respectively equal to T_{coil} = 97°C, T_{PM} = 96°C, i.e. for this mode of movement, air cooling provides heating of the windings and magnets no higher than admissible. When moving in first gear, the temperature of the windings and magnets, respectively, is equal to T_{coil} = 55°C, T_{PM} = 95°C.

It should be noted here that the calculation of performance when driving downhill ($\alpha = 12\%$) is carried out for the NEDC driving cycle, in which the maximum speed is 120 km/h. If the climb with a slope ($\alpha = 12\%$) is long, then it is quite obvious that the maximum speed by the driver will be reduced by about half and, accordingly, the power and torque of the electric motor will also be reduced by about half or will be made switch to first gear.

5. Conclusions

As a result of numerical studies, it has been established that the use of a two-stage magnetic gearbox can significantly reduce the torque acting on the shaft of a drive motor with permanent magnets, and therefore reduce its dimensions and weight.

As a result of calculating the forces and torques acting on an electric vehicle with given parameters (the mass of an electric vehicle, the frontal area of the body, the radius of the wheels, etc.), the optimal reduction factors of a two-stage magnetic gearbox were determined, which provide for the NEDC driving cycle the specified values of the electromagnetic torque of the drive motor ($M_{\max} = 228$ Nm) and its maximum speed ($n = 6500$ rpm). At the same time, the torque characteristics of the two-stage magnetic gearbox were matched with the electromagnetic torque of the drive motor.

Numerical studies of various configurations of magnetic systems of the first and second stages of the magnetic gearbox have been carried out and optimal configurations have been determined, which, with given dimensions, provide maximum torque and minimum torque pulsations. Numerical studies of six configurations of the magnetic system of the electric motor rotor were carried out, as a result of which the optimal configuration was determined that provides the maximum value of the specific torque – the ratio of the maximum moment to the mass of the magnets.

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