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DESIGN OF THE ELECTRIC MOTOR WITH PERMANENT MAGNETS FOR ELECTRIC VEHICLE ACCORDING THE DRIVING CYCLE

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The results of modeling a permanent magnet motor are given, which can be used instead of an internal combustion engine for mini cars. The dimensions of the magnetic system of the electric motor and the values of the electromagnetic torque are determined, taking into account the mass and dimensions parameters of the electric vehicle and the European driving cycle. The optimal thickness of the magnets is determined, at which the specified value of the electromagnetic moment is ensured, as well as the optimum performance of the circulation pump, at which a given current density and optimal liquid cooling are provided. All calculations are performed in MotorSolve and Magnet, provided by Infolytica. References 4, figures 6.

Keywords: electric motor with permanent magnets, driving cycle, optimal geometry of the rotor.

When designing electric motors for electric vehicles, it should be taken into account the driving cycle, which describes the movement of the vehicle in the city and outside the city (engine operation in the minimum speed mode, starting and acceleration to a certain speed, braking the engine from one speed to another or to a complete stop) [1].

The European driving cycle NEDC (New European Driving Cycle) consists of two parts. The first part of the cycle is the urban driving cycle UDC (Urban Driving Cycle) which consists of four identical blocks with a duration of 195 seconds each. According to this cycle, the vehicle is accelerated to a speed of 18-32-50 km/h. Country traffic is described by a separate block of the EUDC (ExtraUrban Driving Cycle) with a duration of 400 seconds and speed change between 70-50-100-20 km/h [2].

The purpose of the research is to determine the main parameters of the electric motor with permanent magnets (the dimensions of the magnetic system of the stator and the rotor, the number of turns of the stator windings, the supply voltage, the electromagnetic torque), which ensure the movement of the electric vehicle with the specified overall dimensions and weight, taking into account the driving cycle. In this case, the optimum dimensions of the permanent magnets of the electric motor and the optimum conditions for liquid cooling are determined.

As initial data for calculating the electric motor, the parameters of a mini-class car were taken, for example, Tavria, Citroen C1, Ford Fiesta: full mass of electric vehicle $m = 1500$ kg; coefficient of air resistance for the chassis $Cx = 0.3$; the area of front view of the chassis is $S = 1.93$ m^2; the radius of the driving wheel is $r = 0.273$ m; gear ratio of main mechanical transmission $U_m = 7.94$; rolling friction ratio $f = 0.018$. The following forces act on the vehicle while moving: traction force of driving wheels, frictional force of wheels rolling, strength of resistance to lifting, air resistance force, resistance to acceleration (inertia force). Taking into account the above parameters and the forces acting on the electric vehicle during the movement, the rotor speed and the torque on the rotor shaft of the electric motor are determined.

Fig. 1 shows the dependences of the motor torque and the rotor speed for the urban driving cycle, calculated when electric vehicle moves up a hill (road slope $\alpha = 12\%$) and on a straight section of the road ($\alpha = 0\%$), and Fig. 2 shows the same for suburban driving cycle.

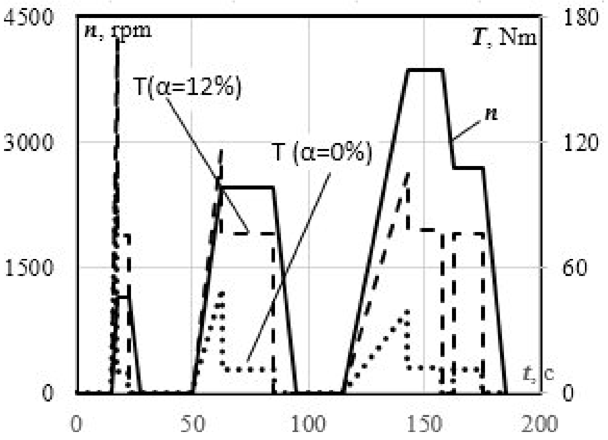

Fig. 1

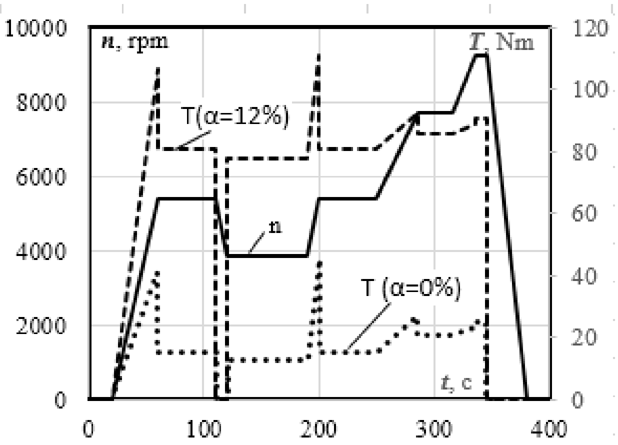

Fig. 2

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It should be noted that at one of the sections of the urban driving cycle (t = 15 ÷ 17.5 s), acceleration to a speed of 15 km/h in 2.5 seconds is performed. In this section, when moving uphill with a slope of α = 12%, the electric motor should provide the largest torque, equal to T (α = 12%) = 170 Nm but when driving on a straight line segment (α = 0%), the torque should be 1.6 times smaller - T (α = 0%) = 65 Nm.

On sections with a constant speed of movement when moving uphill with a slope of 12%, the torque should be more than 6 times greater than when driving on a straight section: t = 17.5 ÷ 22.5 s, V = 15 km/h, $T_{(\alpha = 12\%)}$ = 75.5 Nm, $T_{(\alpha = 0\%)}$ = 10.1 Nm; t = 62.5 ÷ 85 s, V = 32 km / h; $T_{(\alpha = 12\%)}$ = 76.4 Nm, $T_{(\alpha = 0\%)}$ = 11 Nm. For a country driving cycle, the peak torque is T (α = 12%) = 111 Nm. For this driving cycle, the electromagnetic torque of the motor must be 4 ÷ 6 times greater when driving uphill. Thus, the motor must be designed to provide the peak torque value that is observed for one of the sections of the urban driving cycle and is equal to 170 Nm.

When determining the main parameters of the electric motor, the configuration was used with a tooth-slot stator and a rotor with tangential magnetization of permanent magnets, which, as shown by previous studies, has the best specific characteristics [3,4]. The configuration of the magnetic system of the models under study and the distribution of the magnetic field are shown in Fig. 3. In all studied models, the stator has the same configuration and is identic to the stator of the standard asynchronous motor AIR112MB8, that has an outer diameter D_a = 191 mm, the internal diameter of the stator is D_i = 132 mm, the number of slots Zp = 48 and the height of the slots h_s = 18.1 mm, the length of the core stack l_{Fe}. = 130 mm. The air gap between the stator and the rotor is δ = 1.5 mm.

Since neodymium permanent magnets are the most expensive material of all used in the production of electric motors, the influence of the thickness of magnets on the characteristics of the electric motor was investigated. To determine the optimum thickness of the magnets at which the electromagnetic torque is the largest, the simulation of the magnetic field and the calculation of the electromagnetic torque in the Infolytica MotorSolve were carried out for several values of the thickness of the magnets. The initial data for the calculations is as follows: the stator windings are connected in a "Delta"; the number of coils of one phase of the stator is 4, the connection of the coils of one phase of the stator is parallel; the number of turns in the coil – w = 9; battery output voltage – U_{ph} = 400 V; maximal phase current – I_{ph} = 400 A; maximal current density in the phase is J_{ph} = 18 A / mm^2; the stator magnetic core is steel ST2211; rotor core is steel ST20; permanent magnets – N40SH (residual induction is Br = 1.3 T, operating temperature is 150 °C, magnets dimensions are 15 × 130 mm). The calculation is made for four values of the thickness of the magnets: h = 5 mm (model M1); h = 10 mm (model M2); h = 15 mm (model M3); h = 20 mm (model M4). Fig. 3 shows the magnetic field distribution for the four studied models.

The dependency of the electromagnetic torque on the thickness of the magnets that is provided on Fig. 4 shows the speed of increasing torque is lower at magnet thickness h = 15 mm. This is confirmed by the dependence of the difference between the subsequent and previous values of the electromagnetic torque on the thickness of the magnets – T (i + 1) – Ti = f (h). The optimal value of magnet thickness is h = 17.5 mm for these models, but as usually magnets are provided have thickness of a multiple of 5 mm, that is why the thickness h = 15 mm is considered as optimal for all calculations represented below.

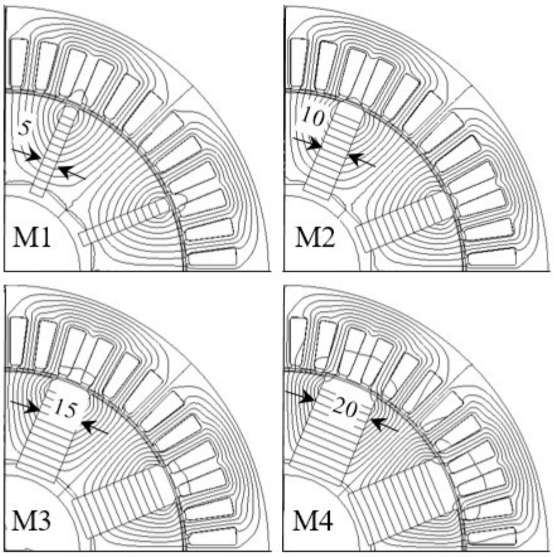

Fig. 3

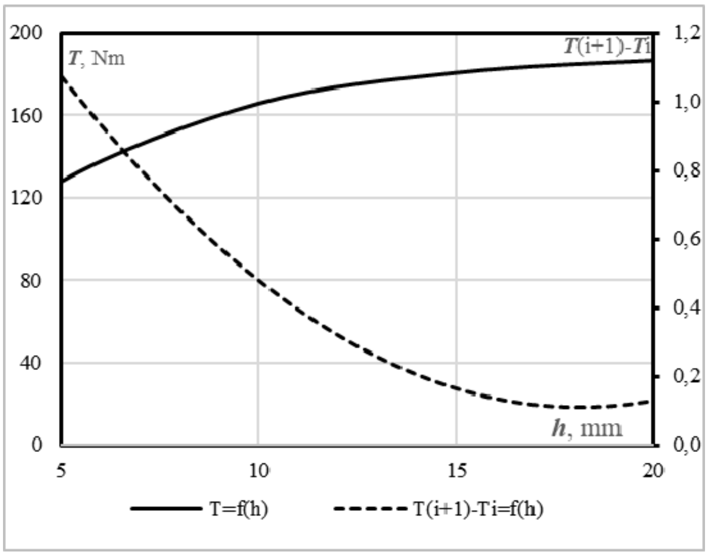

Fig. 4

It should be noted, at a maximal current density J_{ph} = 18 A/mm2 and a magnet thickness h = 15 mm, the highest electromagnetic torque is T = 180 Nm, that is higher than the peak value of the electromagnetic torque according the urban driving cycle. To ensure the operation of the motor with increased current density, it is necessary to use liquid cooling with forced circulation of the cooling liquid. The cooling system is a series of channels located evenly over the entire outer surface of the motor housing and oriented along the axis of motor rotation. Through these channels, a coolant (water) is pumped by the circulation pump. Moving along the channels of the cooling system, the coolant takes away the heat generated by the windings of the motor.

The temperature of the motor parts (windings, magnets, steel cores, shaft, housing, bearings) was calculated in the Infolytica MotorSolve taking into account the cooling system when motor operates according to the European driving cycle. Initial data for thermal calculation: the ambient temperature $T_{at} = 20°C$, the temperature of the cooling liquid at the inlet channels is $T_{in} = 40$ °C; the number of channels is $n_{ch} = 60$; the number of parallel paths in the cooling system is $n_p = 60$; the cross-sectional shape of the channel is round; the diameter of each channel is $d_{ch} = 3$ mm. With the aim of determining the optimal cooling conditions in the heat calculation, the performance of the circulation pump was varied in the range: $Q = 1 \div 5$ lit/min.

Fig. 5 shows the dependency of the temperature of the permanent magnets of the motor M3 on the capacity of the circulation pump. The temperature of the windings, as it is shown by calculations, is $4 \div 5$ °C higher than the temperature of the magnets. Fig. 5 shows the temperature of the magnets only.

If forced cooling is absent the magnets temperature rich 130 °C during 120 min of driving cycle and magnets temperature can be higher if operation time is longer so the magnets can be demagnetized irreversibly as the magnets N40SH have an operating temperature of 150 °C. If motor has forced cooling system and pump capacity is Q = 3 l/min the temperature of stator windings is lower than 67 °C (at current density J = 18 A/mm^2) that is lower than max temperature allowed by class H of winding insulation. The temperature of magnets is lower than 63 °C and that will not couse the irreversible demagnetization. For ambient temperature $T_{at} = 40°C$ permanent magnets and coils temperature stays within acceptable range. According to calculations when pump capacity increases higher than Q = 3 l/min the temperature of the windings and magnets decreases slightly that is why following results are executed at pump capacity Q = 3 l/min.

Fig. 6 shows the load characteristics of electric motor M3, calculated in the Infolytica MotorSolve. This figure also shows the peak torques for the urban driving cycle and country driving cycle. To obtain the value of the electromagnetic torque higher than the peak values of the torque needed for the urban driving cycle for the motor M3, the highest phase current must be equal to $I_{ph} = 400$ A and the highest current density – $J_{ph} = 18$ A/mm^2. For a country driving cycle, the maximum peak torque value is 110 Nm, in order to obtain the value of the electromagnetic torque slightly higher than this value, maximal phase current must be equal to $I_{ph} = 267$ A and current density – $J_{ph} = 13$ A/mm^2. Thus, the results of the calculation show that the design of the electric motor for the electric vehicle must be carried out taking into account the driving cycle.

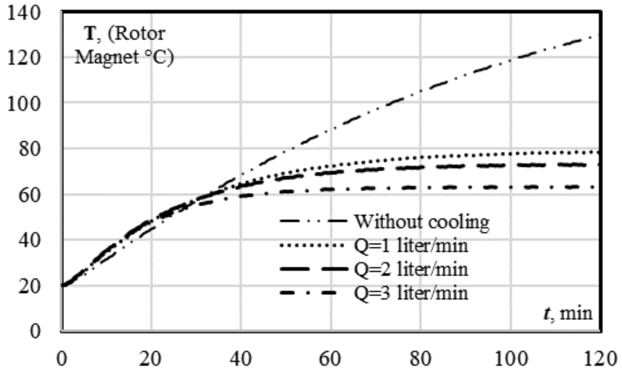

Fig. 5

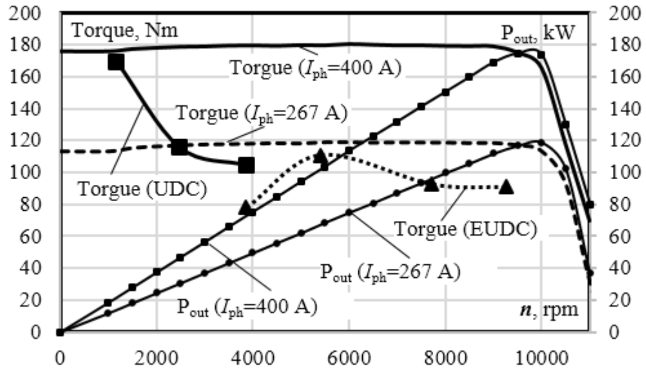

Fig. 6

Conclusions.

1. At the preliminary design stage, it is necessary to determine the dimensions of the magnetic system of the electric motor for an electric vehicle taking into account its weight and size parameters and the driving cycle (UDC and EUDC).

2. For the specified overall dimensions of the motor, the optimal thickness of permanent magnets is determined, at which the peak value of the electromagnetic torque, which is determined by the mass-size parameters of the electric vehicle and the driving cycle, is ensured.

3. Liquid cooling of the electric motor makes it possible to increase the current density in the windings up to a value at which the necessary electromagnetic torque is provided. As a result of the thermal calculation of the electric motor, the optimum capacity of the circulation pump is determined, at which a given current density is ensured and the coils and permanent magnets are not overheated above the permissible value.

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ПРОЕКТУВАННЯ ЕЛЕКТРОДВИГУНА З ПОСТІЙНИМИ МАГНІТАМИ ДЛЯ ЕЛЕКТРОМОБІЛІВ З УРАХУВАННЯМ ЇЗДОВОГО ЦИКЛУ

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Наведено результати моделювання електродвигуна з постійними магнітами, який може бути використаний замість двигуна внутрішнього згоряння для автомобілів класу міні. Визначено розміри магнітної системи електродвигуна і значення електромагнітного моменту з урахуванням масогабаритних параметрів електромобіля і європейського їздового циклу. Визначено оптимальну товщину магнітів, за якої забезпечується задане значення електромагнітного моменту, а також оптимальну продуктивність циркуляційного насоса, при якій забезпечується задана щільність струму і оптимальне рідинне охолодження. Всі розрахунки виконано в пакетах MotorSolve і Magnet, наданих компанією Infolytica. Бібл. 4, рис. 6.

Ключові слова: електродвигун з постійними магнітами, їздовий цикл, оптимальна геометрія ротора.

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ПРОЕКТИРОВАНИЕ ЭЛЕКТРОДВИГАТЕЛЯ С ПОСТОЯННЫМИ МАГНИТАМИ ДЛЯ ЭЛЕКТРОМОБИЛЕЙ С УЧЕТОМ ЕЗДОВОГО ЦИКЛА

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Приведены результаты моделирования электродвигателя с постоянными магнитами, который может быть использован вместо двигателя внутреннего сгорания для автомобилей класса мини. Определены размеры магнитной системы электродвигателя и значения электромагнитного момента с учетом массогабаритных параметров электромобиля и европейского ездового цикла. Определена оптимальная толщина магнитов, при которой обеспечивается заданное значение электромагнитного момента, а также оптимальная производительность циркуляционного насоса, при которой обеспечивается заданная плотность тока и оптимальное жидкостное охлаждение. Все расчеты выполнены в пакетах MotorSolve и Magnet, предоставленных компанией Infolytica. Библ. 4, рис. 6.

Ключевые слова: электродвигатель с постоянными магнитами, ездовой цикл, оптимальная геометрия ротора.

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