

STUDY OF THE TWO-ROTOR ELECTRIC MOTOR OF A DRIVE OF VEHICLE DRIVE WHEELS

Nikolay SERGIENKO¹, Valeriy KUZNETSOV², Borys LIUBARSKYI³, Mariia PASTUSHCHINA⁴,
Piotr GOŁĘBIOWSKI⁵, Sławomir TKACZYK⁶

^{1, 3, 4} National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine

² Railway Research Institute, Warsaw, Poland

^{5, 6} Warsaw University of Technology, Faculty of Transport, Warsaw, Poland

Abstract:

In recent years, electric and hybrid vehicles have taken more and more attention due to their apparent advantages in saving fuel resources and reducing harmful emissions into the environment. Even though electric vehicles can solve the ecological problem, their operation is faced with a number of inconveniences associated with a limited driving distance from a single charge due to limited storage of energy from an independent power source and a lack of the required service and repair infrastructure. In hybrid and electric vehicles one of the main parameters is the curb weight, which affects energy consumption, vehicle speed, stability, controllability and maneuverability. In this regard, leading car manufacturers use parts with a low specific weight (non-metallic, aluminum alloys, etc.) in the design and also exclude some units from the design. Due to these technical solutions, the vehicle's operating is improved. One of the groups of parameters to be defined when designing a new electric vehicle is the parameters relating to the electric motor. The purpose of the article is determination of the mechanical characteristics of a two-rotor electric motor during magnetic flux control and assessment of the possibility of organizing the drive of the drive wheels of the vehicle. The electric motor has two mechanically independent outputs. For the study, an electrical equivalent diagram has been developed for the given two-rotor electric motor. A simulation model of the equivalent diagram has been built. Simulating the interaction processes of the rotors with the stator made it possible to obtain data for building the mechanical characteristics for each output of the electric motor. Analysis and processing of the mechanical characteristics data of the electric motors showed the conformity and the range of changes in the torque on each of the rotors when changing their slip and revolution, which are required when building algorithms for the operation of electric motor control systems as part of drives for various purposes. Analysis of the simulation results made it possible to assess the possibility of using the considered two-rotor electric motor for the drive of drive wheels in an electric and hybrid wheeled vehicle.

Keywords: two-rotor electric motor, torque, revolution, slip, drive, drive wheels, vehicle

To cite this article:

Sergienko, N., Kuznetsov, V., Liubarskyi, B., Pastushchina, M., Gołębiowski, P., Tkaczyk, S., 2021. Study of the two-rotor electric motor of a drive of vehicle drive wheels. Archives of Transport, 60(4), 245-257. DOI: <https://doi.org/10.5604/01.3001.0015.6933>



Contact:

1) nesergienko@gmail.com [<https://orcid.org/0000-0001-5168-1924>]; 2) lboris1911@ukr.net [<https://orcid.org/0000-0002-2985-7345>]; 3) mashapastushina72@gmail.com [<https://orcid.org/0000-0003-3153-2627>]; 4) vkuznetsov@ikolej.pl [<https://orcid.org/0000-0003-4165-1056>]; 5) piotr.golebiowski@pw.edu.pl [<https://orcid.org/0000-0001-6885-7738>] – corresponding author; 6) slawomir.tkaczyk@pw.edu.pl [<https://orcid.org/0000-0001-7677-9573>]

1. Introduction

In recent years, electric and hybrid vehicles have taken more and more attention due to their apparent advantages in saving fuel resources and reducing harmful emissions into the environment (Gołębowski et al., 2020), (Jacyna et al., 2014), (Jacyna-Gołda et al., 2014). Even though electric vehicles can solve the ecological problem, their operation is faced with a number of inconveniences associated with a limited driving distance from a single charge due to limited storage of energy from an independent power source and a lack of the required service and repair infrastructure (Jacyna and Semenov, 2020), (Szaciłło et al., 2021). Overcoming these disadvantages is possible by using hybrid vehicles (Jacyna et al., 2018), (Pielecha, 2021) that have two energy sources. Their use is currently considered as a perspective direction for particular operating conditions.

In hybrid and electric vehicles (Czerepicki, 2019), (Izdebski and Jacyna, 2018), one of the main parameters is the curb weight, which affects energy consumption (Jacyna et al., 2016), (Urbaniak et al., 2019), vehicle speed, stability, controllability and maneuverability. In this regard, leading car manufacturers use parts with a low specific weight (non-metallic, aluminum alloys, etc.) in the design and also exclude some units from the design. Due to these technical solutions, the vehicle's operating is improved.

Expanding the use of electricity in road transport can help industrialized countries reduce their dependence on hydrocarbon imports. Pollution caused by electric vehicles is only a small fraction of the pollution caused by vehicles with combustion motors (at the same mileage), even if we are taking into account the pollution from the generation of electricity by power plants and batteries, as well as the disposal of waste and dead battery. The cost of energy required to travel by an electric vehicle is less than the cost of energy consumed when traveling in a fossil fuel vehicle for the same distance. In some areas, taxes are being eliminated or reduced for those who are using electric vehicles. With a certain correcting, electric vehicles can be partially or fully recharged not from the network, but from other sources. At the same time, vehicles equipped with an electric drive have some disadvantages. For example, the maximum mileage of an electric vehicle from full charge to full battery discharge is less than the mileage of a

typical car with a full tank of fuel before it is empty. At negative temperatures, the capacity of the battery decreases and the ability to a long time deliver the required current decreases. An electric car may not be efficient and reliable enough if it is necessary to use it in harsh climates, especially at low temperatures. The design of electric vehicles does not provide for their widespread use in off-road conditions; due to the underdeveloped service network for electric vehicles, and their operation can be complex. Despite the existing problems today, we can boldly say that these cars are perspective.

One of the groups of parameters to be defined when designing a new electric vehicle is the parameters relating to the electric motor. Therefore, the purpose of the article is determination of the mechanical characteristics of a two-rotor electric motor during magnetic flux control and assessment of the possibility of organizing the drive of the drive wheels of the vehicle. The article is divided into three sections. The first section defines the problem. The second section is devoted to the description of the research. For the study, an electrical equivalent diagram has been developed for the given two-rotor electric motor. A simulation model of the equivalent diagram has been built. Simulating the interaction processes of the rotors with the stator made it possible to obtain data for building the mechanical characteristics for each output of the electric motor. The last section discusses the obtained research results.

2. Analysis of literature sources and problem setting

When designing vehicles with electric or electromechanical transmission with individual adjustment of the input power, the problem of providing the kinematic and power coordination of the drive wheels becomes urgent. On vehicles built according to traditional differential layout schemes, this problem is solved using a power distribution device (differential). According to the conclusions of work (Belousov and Shukhman, 2013), the ideal mechanism for distributing the input power between the wheels should provide:

- 1) high traction and dynamic properties of the vehicle, achieved with the maximum use of the wheel adhesion forces;
- 2) the distribution of the input power to the wheels; the proportional distribution of the adhesion forces at each moment of time when the vehicle

is moving in a straight line under normal conditions;

- 3) the power input to the wheel limitation to the level of wheel slip, which is corresponding to the maximum adhesion of the wheel to the supporting surface;
- 4) the distribution of power between the wheels, which does not affect the directional stability of the vehicle;
- 5) lack of redistribution of braking power during the operation of anti-lock braking systems (ABS);
- 6) smooth flow of transient processes, excluding their negative impact on stability and comfort at a high speed of reaction to input and output influences;
- 7) the optimal values of the wheel rotational speeds of the vehicle during turning;
- 8) high efficiency of the system.

However, at present there are no systems that simultaneously satisfy all of the above requirements. The existing options for technical solutions find certain compromise options (Andreev et al., 1987). On vehicles built according to traditional differential layout schemes, the most popular are free symmetric differentials (SD) and limited slip differentials (LSD). On vehicles built according to the schemes of an individual drive of the input power, the kinematic and force matching of the input power is carried out by an electronic control unit (ECU) via the "CAN" interface (Bokarev, 2014).

At the same time, the automatic control system allows us to program the imitation of the operation of mechanical power distribution devices (differentials). In foreign literature, there is an alternative name for the system of individual control of the supplied torque through electric drives; it is an electronic differential.

Currently, researchers are widely studying the proposed ways to optimize the control of the distribution of power flows in the design of hybrid vehicles, but they are focusing on the creation of mathematical models. This approach does not allow assessing the possibility of integrating an electric machine with two rotors into an electromechanical system (Sergienko et al., 2019).

In the article (Jichao and Yangzhou, 2016) scientists analyze a two-rotor controlled jet motor for dividing the power flow of hybrid vehicles, but the principles of building a control system are not applicable to an

electric machine based on the use of the Lorentz force, therefore it is impossible to adapt it to an asynchronous motor.

When developing appropriate control systems to increase stability, sliding mode controllers are used (Son and Ha, 2015). Another component of optimizing the energy consumption of the system is the use of advanced energy converter schemes. In the possibility of power optimization, electric traction drives of alternating current are presented in (Gruosso, 2014), however, in these publications, machines are considered with only one mechanical rotor. Consequently, the issue of synthesis of a two-rotor electric motor and analysis of its operating modes and characteristics for a hybrid or electric self-propelled vehicle is still relevant.

3. Materials and results

The standard induction motor used in electric and hybrid transmissions consists of a stationary component (stator) and a rotating component (rotor). One of these components is designed to work as a field and the other as an armature for an electric machine. When such an electric motor is under voltage and an electric current flows through its windings, the interaction between the electromagnetic forces of the field (Paś et al., 2021), (Toruń et al., 2019) and the armature causes the rotor to rotate and generates mechanical energy. When the rotor of a standard electric generator rotates under the influence of external mechanical forces, a magnetic field rotating relative to the armature windings cuts through the armature windings and creates a voltage at the generator output terminals.

Two-rotor electric motors, although rarely used yet, are well known in the automobile industry. In this type of electric motor, both rotors are coaxially located in the stationary stator of the electric motor.

When a two-rotor electric motor is under voltage and an electric current flows through its windings, the interaction between the electromagnetic forces of the stator and the armature causes the two rotors to rotate and generate mechanical energy. A feature of a two-rotor electric motor is that two shafts of each of the rotors can rotate at completely different speeds (Tong et al., 2014). This contributes to the implementation of an electronic differential in the vehicle.

When a two-rotor electric motor is included in a split drive system, the two rotors drive the two wheels of

the drive axle, respectively, through two mechanically independent drive gears having the same gear ratio. The two drive gears are configured to provide the same direction of rotation of the two wheels of the drive axle with opposite directions of rotation of both rotors. In such a design, the two-rotor electric motor generates substantially both equal and different tractive forces on the drive wheels, while providing the required wheel speeds when the vehicle is turning. Thus, the drive system for drive wheels with a two-rotor traction motor does not require a mechanical interaxle differential (Yang et al., 2015). The advantages described above result in a simple, compact, and highly efficient split wheel drive system that leaves behind traditional mechanical drive systems.

The above-described unique features make two-rotor electric motors very attractive for separate drive applications not only for four-wheel electric or hybrid vehicles, but also for six and eight-wheel vehicles.

The characteristics of electric vehicles are not only changes in power, torque, but also rotational frequency, current and voltage. The parameters of the car's movement depend on the value of the torque and the rotational frequency, and their implementation depends on the electrical ones in accordance with the control algorithm. The concept of an asynchronous motor with two rotors along one axis and one stator was presented in 1993 (Xiang et al., 2015). This particular type of motor has two shafts protruding at two sides, which are mechanically

independent of each other and therefore can meet the requirements of an electrically driven vehicle differential drive. The electric motor with two rotors, which is investigated in this work, it has one common stator and two rotors, as shown in Figure 1.

The two rotors are identical and are located coaxially to each other inside the stator. The rotor shafts are mounted on two bearings. Because the length of each rotor does not cover the entire length of the stator, the reactance of leakage between the stator and each of the rotors will be higher than between the stator and rotor in a standard induction motor. A 3D model of a two-rotor electric motor (without installing rotor bearings) is shown in Figure 2.

This scheme of the electric motor makes it possible to realize the function of controlling the traction vector of each electric motor and the corresponding drive wheels. This is mean that in addition to redistributing wheel revolutions in a turning, electric motors can "direct" the electric vehicle's traction vector along the desired trajectory by controlling the torque of each wheel individually. Thus, the drive of the drive wheels system with a two-rotor electric motor allows us a quick and accurate response to changes in the power and kinematic parameters of the drive wheels of the vehicle. Due to the presence of 2 independent drives from two rotors instead of one, it is possible to adjust the torque supplied to the drive wheel individually and to provide an improvement in the stability, controllability and maneuverability of the vehicle.

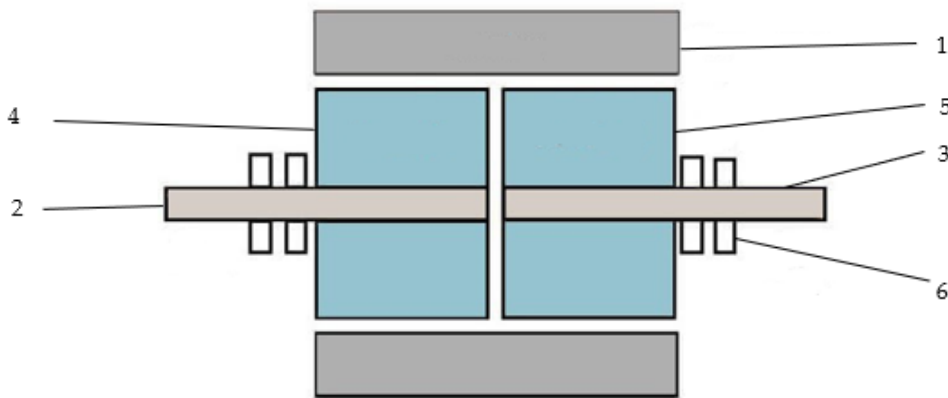


Fig. 1. Schematic diagram of an electric motor with two rotors: 1– stator; 2, 3 - shaft 1 and shaft 2; 4,5 - rotor 1 and rotor 2; 6 – bearings

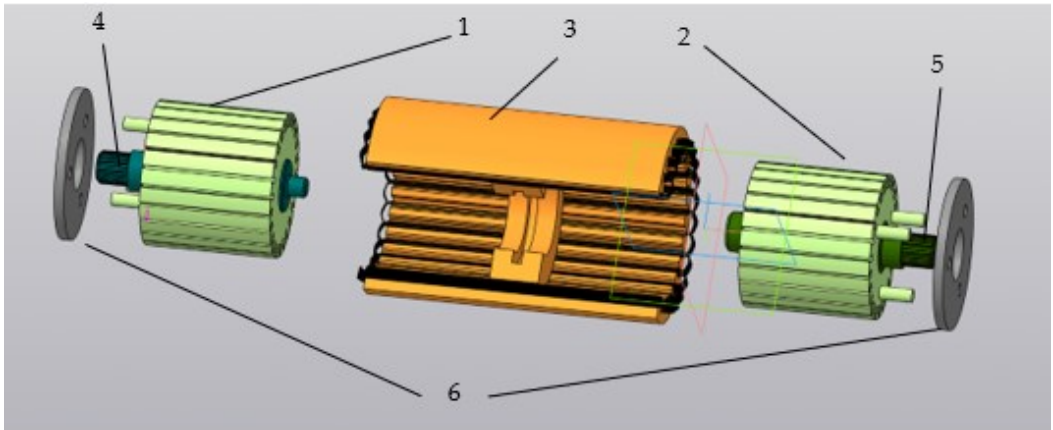


Fig. 2. 3D model of a two-rotor electric motor: 1 - rotor 1; 2 - rotor 2; 3 - stator; 4, 5 - shafts of rotor 1 and rotor 2; 6 - short-circuited rings

The torque on the right and left drive wheels of the vehicle axle are determined by the correspondence:

$$M_i = (P_f + P_j + P_{air} + P_{lifting}) \cdot r_i(Q_i, M_i) \quad (1)$$

where i is the wheel designation index: 1 - right, and 2 - left;

- P_f is the rolling resistance force,
- P_j is the force of inertia of the vehicle,
- P_{air} is the force of resistance to air,
- $P_{lifting}$ is the force of resistance to lifting,
- r_i is the radius of the i -th wheel,
- Q_i is the loading on the i -th drive wheel,
- M_i is the torque on the i -th drive wheel.

Dependence of the radius of the i -th drive wheel on the torque:

$$r_{ki} = r_{k0i} - \lambda_{ti} \cdot M_i \quad (2)$$

where:

- r_{k0i} is the rolling radius at zero torque, which corresponds to the rolling radius of the wheel in the driven mode,
- λ_{ti} is the coefficient of tangential elasticity of the tire, depending on the type and construction of the tire.

Dependence of the radius of the i -th wheel on the normal loading:

$$r_{ki} = r_{ci} \cdot \frac{r_{ci} \cdot P_{bi} + v_1 \cdot Q_i}{r_{ci} \cdot P_{bj} + v_2 \cdot Q_i} \quad (3)$$

where:

- v_1 and v_2 are proportionality coefficients,
- r_{ci} is the radius of the i -th wheel (static),
- P_{bi} is the pressure in the tire of the i -th wheel,
- Q_i is the loading on the i -th drive wheel.
- The coefficient of torque redistribution between the drive wheels, for example, with a drive on one axle, is determined by:

$$\chi = \frac{M_1}{M_2} \quad (4)$$

When the vehicle is turning, the value χ changes from 1 to 1.3 (Zhao and Niu, 2016). When the vehicle is turning on slopes, on hillside, uneven distribution of the load weight on the drive wheels, the range of change of the value χ increases.

The distribution of torque on the drive wheels under normal operating conditions without excessive wheel slip is based on traditional differential control algorithms, which are determined by clear dependencies and are based on imitating the operation of

mechanical power distribution devices (differentials).

The magnetizing reactance and their stator core loss resistance are presented as variable parameters and not constant.

If both wheels are equally loaded and have the same coefficient of adhesion, the rotors rotate at the same speed in the same direction and the control system distributes the supply voltage evenly in sequence. However, applying a differential loading to the drive wheels requires the two output shafts to rotate at different speeds, changing with the slip on each rotor s_1 and s_2 .

To determine the mechanical characteristics and study transient processes in a two-rotor electric motor, an induction motor was calculated for the given parameters of the active and inductive resistance of the stator winding. The initial electrical data are given in Table 1.

The following designations are adopted in Table 1: σ_1 is the correction factor; r_2' is the active resistance of the squirrel cage phase, corresponded to the stator; x_1 is the leakage inductive resistance of the stator winding; x_2' is the leakage of the stator winding.

For further research, an electrical equivalent diagram has been developed for a two-rotor electric motor, which is shown in Figure 3.

For modeling in Matlab Simulink, the appropriate blocks were selected and a simulation model was built (Figure 4). After setting the initial parameters, transient processes were studied.

In the data setting window, the initial parameter and the calculated dependences of the change in inductive resistance are indicated. Using the given slip data, the rotational frequency of the right and left rotors, the moment on each shaft of the rotors was determined.

Table 1. Initial data of the elements of the equivalent diagram.

Active resistance of the stator winding phase, Ohm	Active resistance of the rotor squirrel cage phase, Ohm	Leakage inductive resistance of the stator winding, Ohm	Leakage inductive resistance of the rotor 1 winding, Ohm	Leakage inductive resistance of the rotor 2 winding, Ohm
$R_1 = r_1 \cdot \sigma_1$	$R_2 = r_2' \cdot \sigma_1^2$	$R_c = R_1 + R_2$	$X_1' = x_1 \cdot \sigma_1$	$X_2'' = x_2' \cdot \sigma_1^2$
0.0131	0.0141	0.0272	0.181	0.157

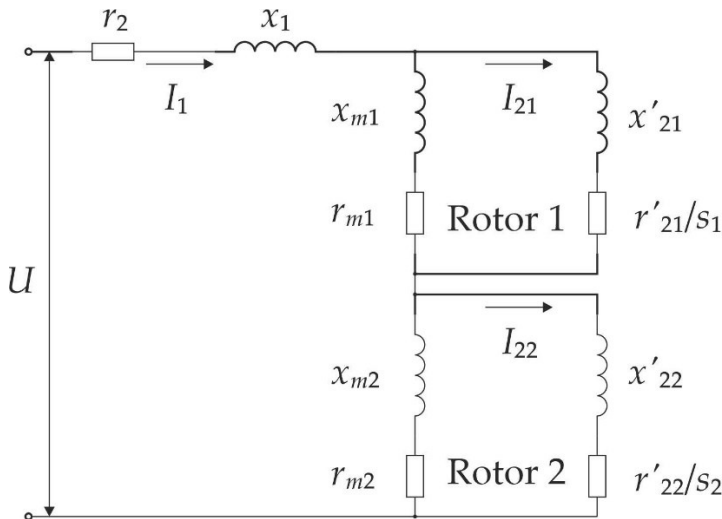


Fig. 3. Electrical equivalent diagram of a two-rotor electric motor

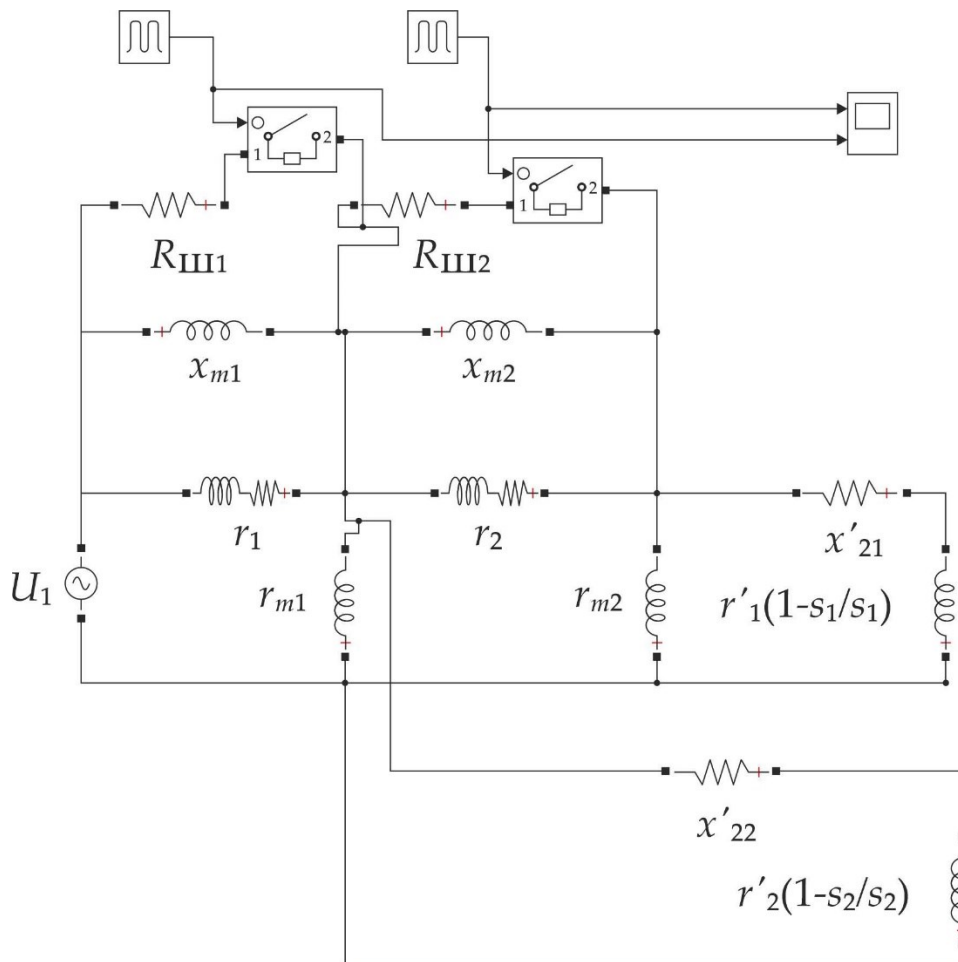


Fig. 4. Simulation model of the equivalent diagram of a two-rotor electric motor

After inputting the above calculated values into the parameters setting window of the equivalent diagram elements, we obtain the values of the torque on each rotor. The change of the torque on each rotor occurs according to a sinusoidal dependence. The maximum value of the sinusoid corresponds to the torque that is taken from each rotor shaft and transmitted from the electric motor to the corresponding drive wheel.

At the selected step of the given revolutions for the given slip s_1 and s_2 , the value of the torque M_1 of the right and M_2 of the left rotor was determined. As can be seen in Figure 5 the dependences of the torque on the shaft of each rotors with a change in revolutions.

The values of the torques and revolutions are different for the right and left rotors due to different slip on each rotor shaft. The amount of sliding is determined by the correspondence:

$$s_i(n_i) = 1 - \frac{p}{n_i \cdot 60} \cdot \frac{1}{f \cdot n_i}, \quad (5)$$

where:

- p is the number of pole pairs,
- f is the frequency of the current in the rotor.

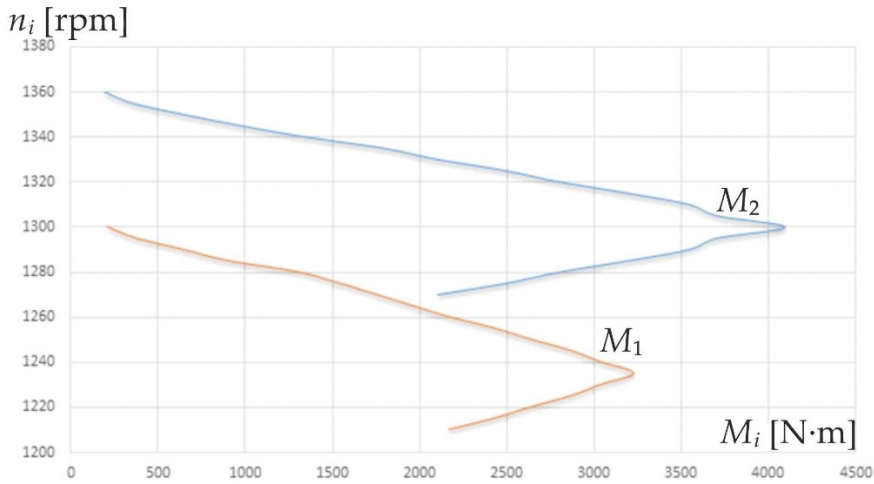


Fig. 5. Dependence of the torque M_1 and M_2 on the right rotor on revolutions n_1 and n_2

When the loading on the wheels is the same, the slip of the right and left rotor is equal. As soon as the loading on the wheels changes (when the vehicle is moving under difficult road conditions, rough terrain, etc.), the slip for each of the rotors changes individually and the required torque is applied to the drive wheels. The value of the torque on each output shaft is set by the two-rotor electric motor control system, changing the active resistance of the corresponding stator magnetic circuits. In this case, the algorithm of the control system takes into account the control action on the steering wheel, the loading on each drive wheel, and other parameters.

To obtain an analytical dependence of the mechanical characteristics of a two-rotor electric motor, namely, the dependence of the torque on each armature (wheel) on the change in revolutions and slip, an approximation of the obtained data was carried out.

The analytical dependence of the change in torque on the values of slip and the rotational frequency of the rotor in general form was chosen as follows:

$$M = \sum_{j=0}^J \sum_{k=0}^K \left(A_{jk} (MJ \cdot n + ZJ)^j (MK \cdot s + ZK)^k \right), \quad (6)$$

where:

- n and s are rotational frequency and slip of the motor,

- J and K are the polynomial degree in the rotational frequency and slip,
- A_{jk} is the coefficient of the polynomial regression, which approximates the force,
- MJ and MK are current and gap scaling factors, respectively,
- ZJ and ZK are current and gap offset, respectively.

For the selected parameters of the two-rotor electric motor, the coefficients $J = 14$ and $K = 8$ were determined by the brute-force search. Accordingly, the dependence takes the form:

$$M = \sum_{j=14}^J \sum_{k=8}^K \left(A_{jk} (M \cdot 14 \cdot n + ZJ)^{14} (M \cdot 8 \cdot s + ZK)^8 \right). \quad (7)$$

Using the analytical dependence obtained during processing the results of the study of a two-rotor electric motor, 3D-graphs of the mechanical characteristics were built for each motor output as can be seen in Figure 7 and Figure 8.

The torque is controlled by the control system of the active resistance in the rotor circuit r'_2 . This is made by changing the gap between the stator and the lateral short-circuited rings. For the selected parameters of the electric motor design with an increase in the gap from 0 to 30 mm, the active resistance r'_2 changes from 11.295 Ohm to 11.869 Ohm.

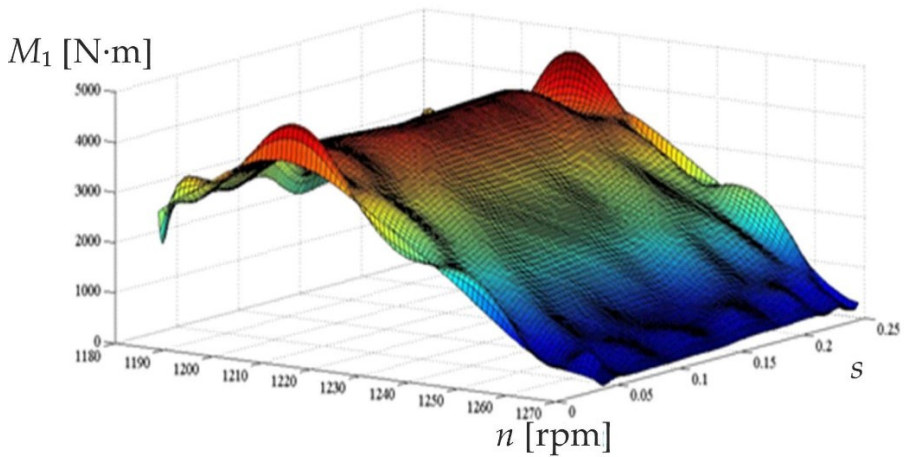


Fig. 6. 3D graph of the dependence of the torque M_1 on the right rotor on revolutions n_1 and slip s_1

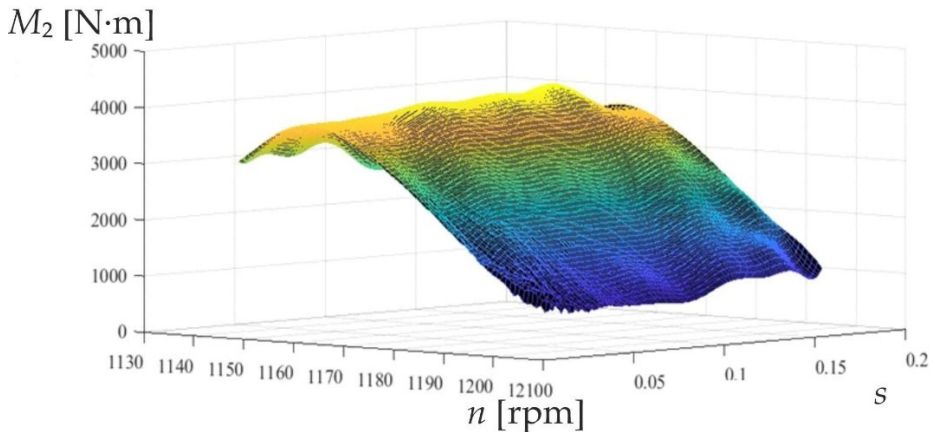


Fig. 7. 3D graph of the dependence of the torque M_2 on the left rotor on revolutions n_2 and slip s_2

To estimate the effect of active resistance r'_2 on the torque M_2 supplied to the drive wheels, studies were carried out, the results of which are shown in Figure 9 and Figure 10. The analytical dependence of the torque M_1 on the active resistance r'_2 in the rotor circuit r' according to the results of the approximation for the accepted parameters of the electric motor has the form:

$$M_1 = -7.8571 \cdot r_2'^2 - 31.429 \cdot r_2' + 3540. \quad (8)$$

A similar dependence of the torque M_2 on the left shaft on the active resistance in the rotor circuit r' will be as follows:

$$M_2 = -1.8452 \cdot r_2'^2 - 74.345 \cdot r_2' + 4333.6. \quad (9)$$

To estimate the possibility of each drive of the vehicle axle drive wheel with a two-rotor electric motor, it is necessary to determine not only the range of changes in the torques, but also its possible redistribution from one output shaft to another. The resulting difference in torques when changing the active resistance r'_2 on the right and left rotor will have the form shown in Figure 10.

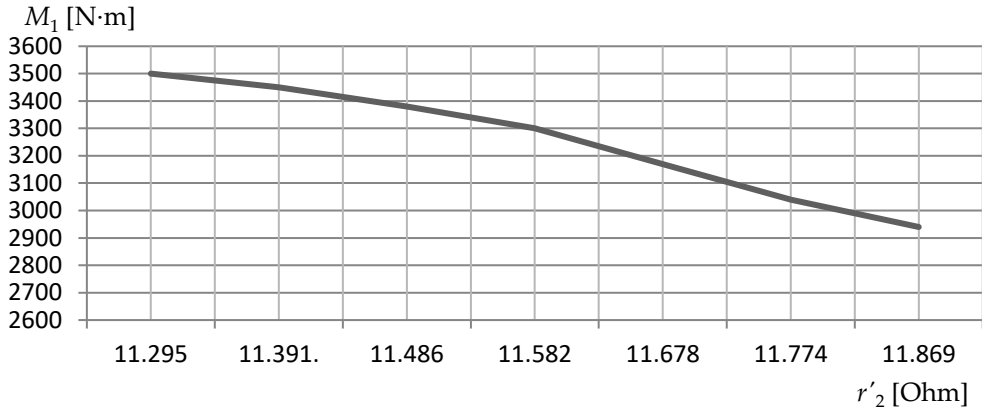


Fig. 8. Dependence of the torque M_1 on the active resistance r'_2

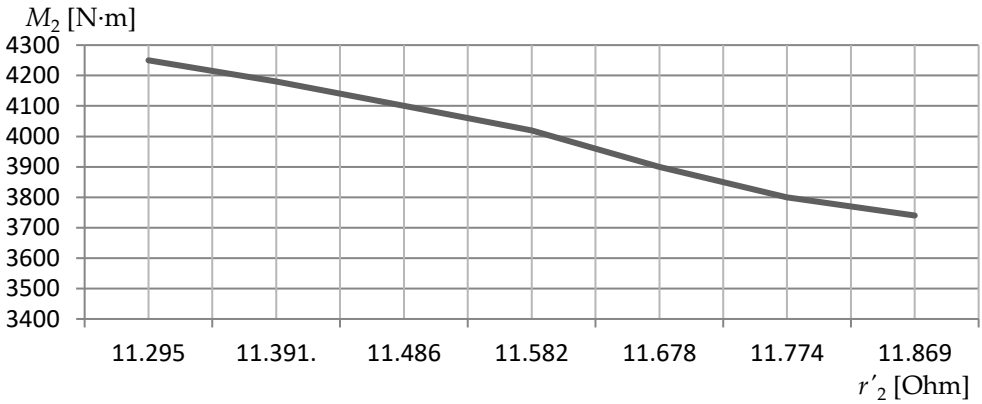


Fig. 9. Dependence of the torque M_2 on the active resistance r'_2

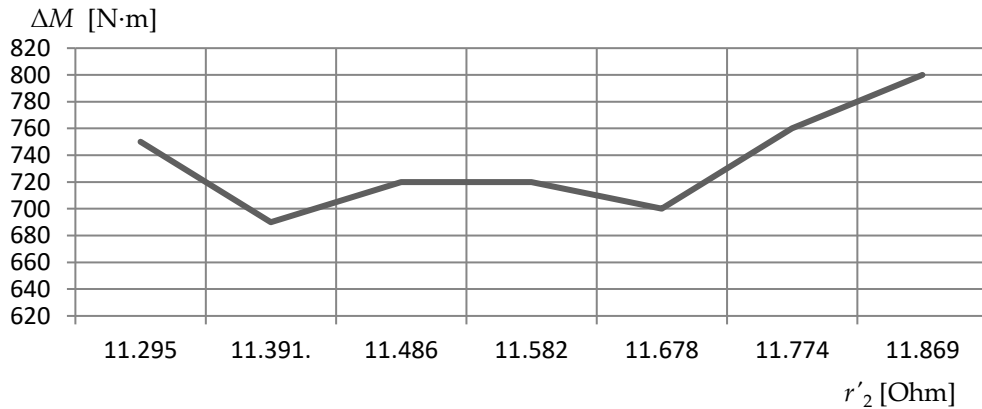


Fig. 10. The difference between the torque on the right and left wheels when changing the active resistance r'_2

4. Discussion

The design of a special type of electric motor is presented, which has two rotors and one stator in its design. A simulation model of this electric motor has been developed, which includes blocks for setting the required parameters for research and the constituent elements of the electrical diagram. The model allows obtaining data for building the mechanical characteristics of a two-rotor electric motor. The mechanical characteristic shows the change in the torque M_1 and M_2 depending on the change in the values of slip s_1 and s_2 , as well as revolutions of the rotors of the electric motor n_1 and n_2 . Due to the possibility of adjusting the slip on each of the rotors individually by control system, the two-rotor electric motor is able to change the input torque on each output shaft. The adjustment of the torque, revolution and slip was carried out by varying the active resistance in the rotor circuit of the electric motor. The value of active resistance and slip in general changes to 2-5%. As a result, the torque M_1 and M_2 supplied to the drive wheels, depending on the loading and other parameters of the vehicle's movement, can vary by up to 17%. This indicates that the individual distribution of torques on the output shaft and, respectively, on the drive wheels, depending on the loading, can provide an electric differential drive of the vehicle drive wheels.

5. Conclusions

An analysis of the characteristics of a two-rotor electric motor showed its possibility of using simultaneously as a driving device and an inter-wheel differential in a vehicle design. The coefficient of torque redistribution between the drive wheels. When the vehicle is turning the coefficient of torque redistribution changes not only from 1 to 1.3 but also higher. Thus, an individual drive of the wheels is possible, which can rotate at different speeds when the required torque is supplied.

The developed equivalent diagram of a two-rotor electric motor and the performed studies made it possible to determine the mechanical characteristics of the electric motor, which is required for building an algorithm for the operation of the control system, when used, for example, in the drive of the drive wheels of a vehicle. When varying the slip and setting the revolution on the right and left rotor of the electric motor with the selected design parameters, the value of the torque supplied to the drive wheels

can differ by up to 17%. The torque M_1 of the right rotor and M_2 of the left rotor varies nonlinearly. During the research, the analytical dependence of the rotor output torque on slip and revolution, as well as on the active resistance in the rotor circuit, was established.

To set the required value of the torque, it is proposed to adjust the active resistance in the circuit of each rotor by changing the active resistance between the stator and the short-circuited ring.

Acknowledgement

The article has been presented on XI International Logistic Systems: Theory and Practice Conference (11-12 October 2021).

References

- [1] Advanced Vehicle Testing Activity (2013). *Electronic text data*. Idaho: Idaho National Laboratory.
- [2] Andreev, A.F., Vantsevich, V.V., & Lefanov, A.K. (1987). *Differentials of wheeled machines*. Moscow: Mashinostroenie, 176 p.
- [3] Belousov, B.N., & Shukhman, S.B. (2013). *Applied mechanics of ground traction vehicles with mechatronic systems*. Moscow: Agroconsult, 612 p.
- [4] Bokarev, A.I. (2014). Prospects for the use of an individual adjustable power drive in active safety systems. *Journal of Automotive Engineers*, 7, 20-25.
- [5] Czerepicki, A. (2019). Study on effectiveness of using column-oriented databases in the processing of measurement characteristics of an electric vehicle. *Archives of Transport*, 51(3), 77-84. DOI: 10.5604/01.3001.0013.6164
- [6] Francfort, J. (2006). *Hybrid Electric Vehicle Fleet and Baseline Performance Testing*. Idaho: Idaho National Laboratory.
- [7] Gołębowski, P., Żak, J., & Jacyna-Golda, I. (2020). Approach to the Proecological Distribution of the Traffic Flow on the Transport Network from the Point of View of Carbon Dioxide. *Sustainability*, 12, 6936. doi: 10.3390/su12176936
- [8] Gruosso, G. (2014). Optimization and management of energy power flow in hybrid electrical vehicles. In: *5th IET Hybrid and Electric Vehicles Conference (HEVC 2014)*, 1-5. DOI: 10.1049/cp.2014.0962.

- [9] Izdebski, M., & Jacyna, M. (2018). The organization of municipal waste collection: The decision model. *Rocznik Ochrona Środowiska*, 20, 919–933.
- [10] Jacyna, M., Gołębiowski, P., & Urbaniak, M. (2016). Multi-Option Model of Railway Traffic Organization Including the Energy Recuperation, In: *Challenge of Transport Telematics*, Springer Int. Pub. DOI: 10.1007/978-3-319-49646-7_17
- [11] Jacyna, M., Wasiak, M., Lewczuk, K., & Kłodawski, M. (2014). Simulation model of transport system of Poland as a tool for developing sustainable transport. *Archives of Transport*, 32(4), 17-28. DOI: 10.5604/08669546.1146982
- [12] Jacyna, M., & Semenov, I. (2020). Models of vehicle service system supply under information uncertainty. *Eksplatacja i Niezawodność*, 22(4), 694–704, DOI: 10.17531/ein.2020.4.13
- [13] Jacyna, M., Wasiak, M., Lewczuk, K., Chamiér-Gliszczyński, N., & Dąbrowski, T. (2018). Decision problems in developing pro-ecological transport system. *Rocznik Ochrona Środowiska*, 20, pp. 1007-1025.
- [14] Jacyna-Gołda, I., Żak, J., & Gołębiowski, P. (2014). Models of traffic flow distribution for various scenarios of the development of pro-ecological transport system. *Archives of Transport*, 31(3), 23-35. DOI: <https://doi.org/10.5604/01.3001.0014.8797>
- [15] Jichao, L., & Yangzhou, C. (2016). An online energy management strategy of parallel plug-in hybrid electric buses based on a hybrid vehicle-road model. In: *IEEE 19th International Conference on Intelligent Transportation Systems*, 927-932. DOI: 10.1109/ITSC.2016.7795666.
- [16] Kozakevich, I. (2017). Investigation of the direct torque control system of an electromechanical system with a matrix converter. In: *Proceedings of the International Conference on Modern Electrical and Energy Systems*, 228-231. DOI: 10.1109/MEES.2017.8248896.
- [17] Morkun, V., & Tron, V. (2014). Ore preparation energy-efficient automated control multi-criteria formation with considering of ecological and economic factors. *Metallurgical and Mining Industry*, 5, 8–10.
- [18] Paś, J., Rosiński, A., & Białek, K. (2021). A Reliability-Exploitation Analysis of a Static Converter Taking Into Account Electromagnetic Interference. *Transport and Telecommunication Journal*, 22(2), 217-229. doi: 10.2478/tjt-2021-0017
- [19] Pielecha, I. (2021). Energy management system of the hybrid ultracapacitor-battery electric drive vehicles. *Archives of Transport*, 58(2), 47-62. DOI: doi: 10.5604/01.3001.0014.8797
- [20] Sergienko, M.Y., Lyubarskiy, B.G., & Pastushchina, M.I. (2019). Mathematical modeling of the electric drive of the wheels of a car with a two-rotor electric motor. *Information technologies: science, technology, education, health: theses of additional reasons XXVI MicroCAD-2019, April 16-18, 2019*. Kharkiv: NTU "KhPI", 208.
- [21] Sergienko, N.Y., Lyubarskiy, B.G., & Pastushchina, M.I. (2018). Features of the use of electric drive and control systems on modern cars. *Vesnik NTU "KhPI". Series: Automobile and tractor construction*. Kharkiv: NTU "KhPI", 49(1325), 40–49.
- [22] Sinchuk, O., & Kozakevich, I. (2017). Research of regenerative braking of traction permanent magnet synchronous motors. *Proceedings of the International Conference on Modern Electrical and Energy Systems*, 92-95. DOI: 10.1109/MEES.2017.824896.
- [23] Sinchuk, O.N., Kozakevich, I.A., & Yurchenko, N.N. (2017). Sensorless control of switched reluctance motors of traction electro-mechanical systems. *Technical electrodynamics*, 5, 62-66. DOI: 10.15407/tech-ned2017.05.062.
- [24] Son, Y., & Ha, J.-I. (2015). The electric variable transmission without slip ring for the hybrid electric vehicle driving structure. In *9th International Conference on Power Electronics and ECCE Asia*, 857-862.
- [25] Szaciłło, L., Jacyna, M., Szczepański, E., & Izdebski, M. (2021). Risk assessment for rail freight transport operations. *Eksplatacja I Niezawodność – Maintenance and Reliability*, 23(3), 476–488, doi: 10.17531/ein.2021.3.8
- [26] Tong, C., Zheng, P., Wu, Q., Bai, J., & Zhao, Q. (2014). A brushless claw-pole double-rotor

- machine for power-split hybrid electric vehicles. *IEEE Transactions on Industrial Electronics*, 61, 4295-4305. DOI: 10.1109/TIE.2013.2281169.
- [27] Toruń, A., Sokołowska, L., & Jacyna, M. (2019). Communications-based train control system - Concept based on WiFi LAN network. *Transport Means - Proceedings of the International Conference*, 911–915.
- [28] Urbaniak, M., Kardas-Cinal, E., & Jacyna, M. (2019). Optimization of Energetic Train Cooperation. *Symmetry*, 11, 1175. doi: 10.3390/sym11091175
- [29] Voliansky, R.S., & Sadovoi, A.V. (2017). Second order sliding mode control of the inverted pendulum. In: *Proceedings of the International Conference on Modern Electrical and Energy Systems*, 224-227. DOI: 10.1109/MEES.2017.8248895.
- [30] Xiang, Z., Quan, L., Zhu, X., & Wang, L. (2015). A brushless double mechanical port permanent magnet motor for plug-in HEVs. *IEEE Transactions on Magnetics*, 51, 1–4. DOI: 10.1109/TMAG.2015.2443048.
- [31] Yang, Y., Schofield, N., & Emadi, A. (2015). Doublerotor switched reluctance machine (DRSRM). *IEEE Transactions on Energy Conversion*, 30, 671-680. DOI: 10.1109/TEC.2014.2378211.
- [32] Zhao, X., & Niu, S. (2016). A novel double-rotor parallel hybrid-excitation machine for electric vehicle propulsion. In: *IEEE Conference on Electromagnetic Field Computation*, 1–5. DOI: 10.1109/CEFC.2016.7816052.