1. Bartłomiej BĘDKOWSKI[1], 2. Piotr DUKALSKI[1], 3. Łukasz CYGANIK[1], 4. Tomasz JAREK[1]

Łukasiewicz Research Network – Upper Silesian Institute of Technology (1)
ORCID: 1.0000-0002-9619-5679; 2.0000-0002-5219-0024; 3.0000-0001-9355-8473; 4.0000-0002-0218-7556

doi:10.15199/48.2023.06.31

Assumptions of the direct drive motor for commercial vehicles

***Abstract**. The article presents the concept of an electric drive for installation in the wheels of commercial vehicles, which will be developed as part of the project "Innovative electric drive unit for commercial vehicles", financed by the National Center for Research and Development under the LIDER XI program. In the article, the Authors presents the advantages and disadvantages of this type of drive and its possible applications. The paper presents the results of design calculations for the electromagnetic circuit along with thermal calculations and the mechanical structure of the drive.*

***Streszczenie.** W artykule przedstawiono koncepcję napędu elektrycznego do montażu w kołach pojazdów użytkowych, która zostanie opracowana w ramach projektu „Innowacyjny elektryczny zespół napędowy do pojazdów użytkowych", finansowanego przez Narodowe Centrum Badań i Rozwoju w ramach programu LIDER XI. W pracy autorzy przedstawili zalety i wady tego typu napędu oraz jego możliwe zastosowania, a także wyniki obliczeń projektowych obwodu elektromagnetycznego wraz z obliczeniami termicznymi, oraz konstrukcję mechaniczną napędu. (**Założenia silnika z napędem bezpośrednim do pojazdów użytkowych**)*

Keywords: electric vehicles, permanent magnets motors, electric drive, in wheel motors.
Słowa kluczowe: pojazdy elektryczne, silniki z magnesami trwałymi, napęd elektryczny, silniki w kołach.

Introduction

Along with the growing interest and ever newer concepts of electric vehicles, various solutions of electric drives are being developed, influencing the broadly understood electromobility [1-18]. Research and implementation in the field of electric vehicle drives concern, inter alia, power sources, control systems, battery power systems, energy transmission techniques and the drive motors themselves [6-14]. In recent years, one of the developed solutions in the field of electric traction drives are motors installed in the wheel hub [11-18]. This solution was first used at the beginning of the 20th century by Ferdinand Porsche to create the world's first hybrid car [7]. At that time, achievable parameters of such powertrain systems did not allow them to compete with internal combustion engines. Currently, with the development of electric motors with high power density, this concept is being developed again [11-18]. Motors of this type can be widely used in the electric vehicle industry for various applications: from small city cars, through vans, buses to demanding commercial vehicles. It should be noted that electric drives installed in wheel hubs can also serve other types of drive support, including diesel, e.g. when starting, when the highest torque values are required from the drive or during maneuvers, increasing the driving dynamics. Taking into account the numerous inquiries from entrepreneurs and the results of observation of the electric vehicle market, it can be noted that the direct drive concept is not limited only to applications in typical road vehicles. The advantages of this type of solution also qualify them for use in many other applications, such as: industrial transport vehicles, service vehicles used in large factories, warehouses, mines or airports, recreational vehicles such as golf carts, quads, ground drones, military vehicles, off-road, police or fire services that require high torque. The Łukasiewicz Research Network - Institute of Electric Drives and Machines KOMEL has undertaken research and design work aimed at developing technical and technological solutions, which resulted in the development of a prototype of the motor for installation in the wheels of the vehicle. These works were carried out under the LIDER VII program financed by the National Center for Research and Development. Currently, under the LIDER XI program, this subject will be further developed, it is planned to develop an electric drive integrated with a mechanical transmission and a brake for commercial vehicles with high torque requirements.

Advantages and disadvantages of direct drives in electric vehicles

Most of the drive systems of internal combustion vehicles that can be found on the market today have been constructed on the basis of the same concept for approx. 100 years. The torque from the engine is transferred to the wheels via the clutch, gear ratios, differential and driveshafts. A similar structure is found in most electric and hybrid vehicles proposed on the market or presented in various review materials. The presented drive systems replace the "central" internal combustion engine with an electric motor [4], and in these solutions the clutch is often omitted, because in the case of an electric motor, it is not needed. With the development of technology and technologies related to drives and the electric motors themselves, manufacturers are able to achieve better and better operating parameters of drives while maintaining their high energy efficiency [8-10]. One of the main directions of the development of drives is to obtain the highest ratio of torque (maximum and possible to achieve in long-term operation) to volume / mass (the so-called power / torque density ratio). This trend fits very well with the direct drive concept, which offers a number of advantages, including:

- elimination of the multi-ratio mechanical transmission, which in addition to reducing the efficiency of the system is an element that requires maintenance and may be damaged,
- providing additional space in the car, which can be used to install power batteries or increase its ground clearance,
- no need for indirect power transmission through drive shafts, differentials and other complex mechanisms,
- the possibility of a relatively simple implementation of a drive for 2, 4 or more wheels,
- more effective recuperative braking (omitting the decrease in the efficiency of the drive system due to the gear ratios),
- relatively easy disassembly of the drive during service,
- better steering of the vehicle due to the possibility of direct torque setting separately on each of the wheels.

In addition to a number of the advantages mentioned, this solution also has some disadvantages and limitations:

- limited space in which the motor must fit,
- impeded motor cooling,
- additional unsprung mass resulting from the mass of the motors installed in the wheels, [12-18]

● structure in some applications more complicated in terms of sealing / maintaining high IP,
● the necessity to cooperate with the braking system.

During the implementation of many e-mobility projects in the Łukasiewicz - KOMEL institute, a lot of inquiries were made about the possibility of developing an electric direct drive for heavy commercial vehicles, requiring off-road or agricultural vehicles, which would have even greater torque, a structure resistant to harsh operating conditions and additionally integrated with the brake. On the basis of the knowledge acquired during the implementation of the e-mobility project and the analysis of various electric vehicle powertrains structures, in order to meet the above-mentioned expectations, it is necessary to develop a drive integrated with a mechanical transmission, which will fit in the wheel of a commercial vehicle.

Assumptions of the drive structure

During the implementation of the electric powertrain project for commercial vehicles, co-financed by the National Center for Research and Development under the LIDER XI program, it was planned to develop an innovative drive for installation in the wheel, characterized by a compact structure, integrated electromagnetic circuit, brake system and transmission, with the possibility of mounting in a wheel with a diameter of 17", and a maximum torque of 2000Nm (ultimately over 3000Nm). The developed drive will also be characterized by innovative design solutions, such as an efficient cooling system, low weight, the possibility of two operating modes ("low" utility and "high" normal). A drive with such functionalities is currently not available on the market. Functionally similar competitive solutions that can be found offer only some of the functions mentioned. They (which are usually not protected against external factors), moreover, they do not offer such maximum moments. The offered solutions of the gears for installation in the wheel for commercial vehicles do not have the possibility of switching the operating modes (only the possibility of disconnecting the drive) and after connecting to the motor they are much larger in size, and they do not have a brake. Summarizing, the final effect of the project will be a developed, manufactured and tested prototype of a drive system for wheel assembly with the following features:
● design that allows installation in a 17" rim with a maximum torque of 2000Nm (ultimately over 3000Nm), consisting of a gear and motor part, and a brake built inside, integrated into one functional unit,
● possibility of obtaining two modes of operation of the drive system: the so-called utility mode. "low" (obtained maximum torque at the level of 2000Nm), and the so-called "high" mode (ratio 1: 1 between the drive output and the electric motor part, the faster travel of the commercial vehicle at a speed of at least 80kmh),
● optimized structure in terms of strength, stiffness, dimensions and technology.

Figures 1 present the analyzed different solutions of the planetary gear located in the wheel hub.

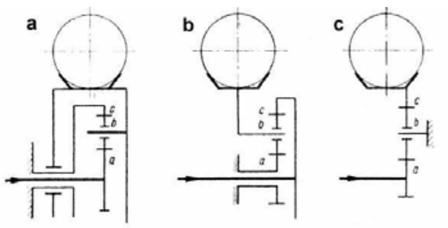

Fig.1. Different solutions of the planetary gear located in the wheel hub

At the current stage of the project, preliminary design calculations of the transmission part and the electromagnetic circuit of the drive were carried out. The MitCalc software was used to calculate the transmission, while the Ansoft Motor-CAD program was used to calculate the electromagnetic circuit, which allows for the implementation of simulations of operation based on coupled models of the electromagnetic circuit, using FEM 2D and a thermal model based on thermal diagrams. Taking into account the conditions of the drive installation in a 17 "rim and the limitations of the drive width, it was decided to use a solution based on a planetary gear in the drive. The 3D Model of developed powertrain is presented on the Fig.2.

Fig.2. 3D model of prototype drive

Various solutions of the epicyclic gear located in the wheel hub were analyzed, based on various kinematic schemes presented in Figure 1. Each of the presented solutions obtains a different kinematic ratio. In the solution based on the kinematic diagram 1a, the yoke of the planetary gear is rigidly connected to the road wheel hub, so it transmits the torque to it. The ring wheel is fixedly connected to the housing. The torque to the gearbox is introduced by the sun gear. In this solution, the gear ratio i> 3 can be obtained. In the solution based on the kinematic diagram 1b, the gear yoke is rigidly connected to the wheel hub and transmits the torque to it. The torque for the gearbox is supplied to the ring gear. The sun gear is fixedly connected to the housing. This solution allows for moderate gear ratios i = 1.0 - 2.0. In the solution based on the kinematic diagram 1c, the gear yoke is rigidly connected to the housing, and the driving sun gear drives the ring gear associated with the road wheel hub by rotating the satellites. We are dealing here with a change in the direction of the rotational speed, and the size of the ratios obtained is approximately i = 2.5 - 2.8. Due to the possibility of obtaining high gear ratios and integration with the electromagnetic circuit, the solution 4a was used in the drive structure. Preliminary analyzes allowed to estimate that in the given dimensions it is possible to obtain even a gear ratio i = 3-3.5. Then, the analysis of an electromagnetic circuit possible to be made in the assumed dimensions was started. A motor with 48 magnetic poles and 54 slots was adopted for the calculations, this assumption results from the rotor angle sensors available on the market and possible to use in the analyzed structure and the inverters that support them. Initially, as a solution for the motor winding, concentrated coils were adopted, which guarantees a shorter structure of the fronts, lower winding losses and better winding cooling possibilities. Table 1 shows the motor/drive power supply parameters. Design calculations were carried out in the Ansoft Motor-CAD program. It uses a combination of advance analytical equations and calculations based on 2D FEM. The temperature can be determined in steady and transient conditions. The program uses advanced models in the form of thermal networks.

Table 1. Input data and calculation results for the square configuration with filling of the slot with the impregnating varnish

Parameter	value	unit
Number of slots *Q*	54	-
Number of poles *2p*	48	-
Number of slots per pole and phase *q*	0,375	-
Drive supply voltage V_{DC}	375	V
Maximum current $I_{max.}$	400	A

The supply voltage result from the adopted voltage of the battery supplying the vehicle drive. The currents supplying the motor (rated and maximum) result from the operation of the parameters of the intended inverter. Fig. 3 shows the model of the electromagnetic core with the calculated saturation distribution of the magnetic induction from permanent magnets using the FEM 2D method.

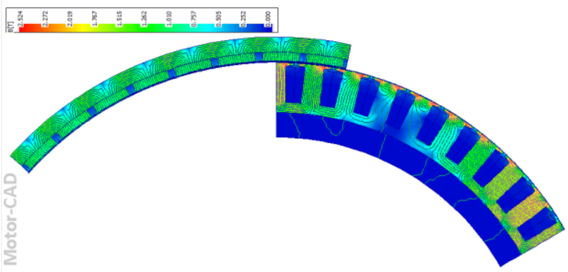

Fig. 3. Calculated magnetic induction distribution from permanent magnets in the magnetic core of the motor

The performed calculations are based on the coupling of the electromagnetic circuit model with the thermal model. The calculations were based on water cooling with flow Q=10l/min, ambient temperature t_{ot}=45℃, coolant temperature (EGW 50/50) t_{ch} = 60℃. Figure 4 presents the results of thermal calculations for the motor operating point: T_m = 450Nm and n = 800 rpm, I_{RMS} = 123A (approx. 13 A/mm^2). The operating point has been selected so that the winding temperature at the warmest point does not exceed the value of t_{Cu} = 150℃. Under these cooling conditions, this operating point can be designated as the rated operating point for the motor.

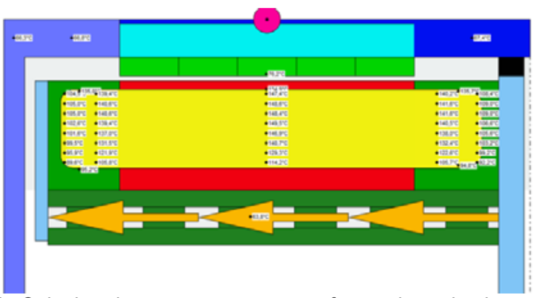
Fig. 4. Calculated motor temperatures for work at the base point Tm = 450Nm, n = 800 rpm at slot cross-section and in the slot in the FEM models of the Motor CAD program

The thermal calculations were verified with the module embedded in the Motor-CAD program, using the finite element method. The method allows to calibrate the schematic model with the FEM model. Table 2 shows the maximum temperatures that have been calculated in the individual elements of the electric motor.

Table 2. Calculated maximum temperatures established for the motor operating point Tm = 450Nm n = 800 rpm

Element of the motor	Thermal diagram
Winding endD	140,6
Winding end ND	141,6
Winding in a slot	149,5
Stator tooth	104,6
Stator side radiatorD	77,4
Stator side radiatorND	80
Magnets	75,8
Air	45
Coolant EGW 50/50	60

The results presented in Fig. 4 and in Table 2 refer to the steady state, assuming the S1 work regime. These are illustrative results, because in fact, the electric motor in the drive of the car works with dynamically changing operating parameters. Fig.5 shows the torque characteristics as a function of rotational speed.

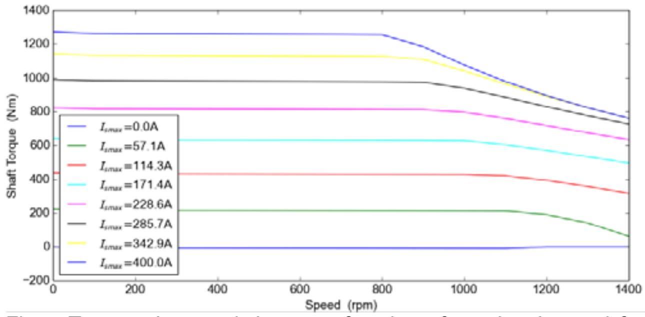

Fig.5. Torque characteristics as a function of rotational speed for supply of various currents

The torque increases with the current intensity, the motor operates in two control zones, in the zone with constant torque and in the zone with weakening of the magnetic flux from permanent magnets. The maximum torque that the motor will achieve with the permissible maximum current of the inverter is T_{max}=1200Nm. Maximum torque is available over a wide speed range from 0 to 600rpm. Fig. 6 shows analogous characteristics of mechanical power as a function of rotational speed.

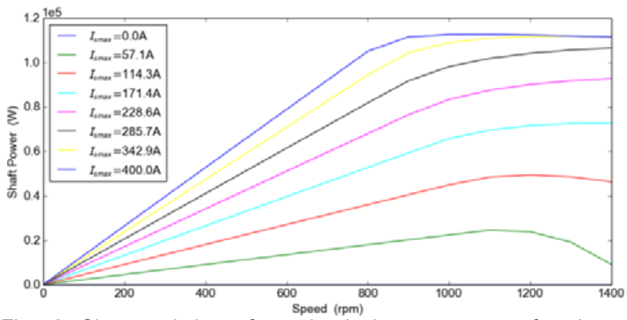

Fig. 6 Characteristics of mechanical power as a function of rotational speed for supply with different currents

The characteristics of the losses in the magnetic core of the stator show the deflection of the characteristics, which is characteristic for the zone with magnetic field weakening. Fig. 7 and the calculated operating temperatures, assuming that the maximum temperature of the winding will not exceed TCu ≤150℃. Fig. 8 shows the calculated map of the efficiency for this work area.

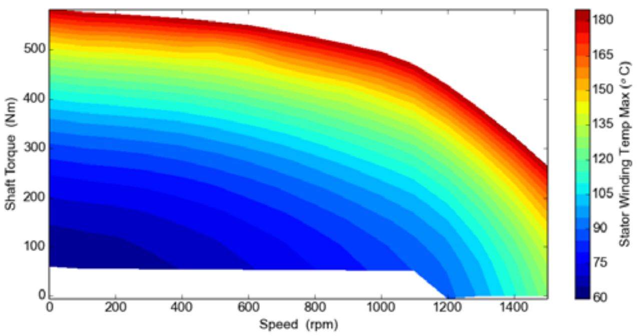

Fig. 7. Calculated maximum temperatures in the motor winding for the operating area with temperature limitation: TCu≤150℃, Tmag≤ 100℃

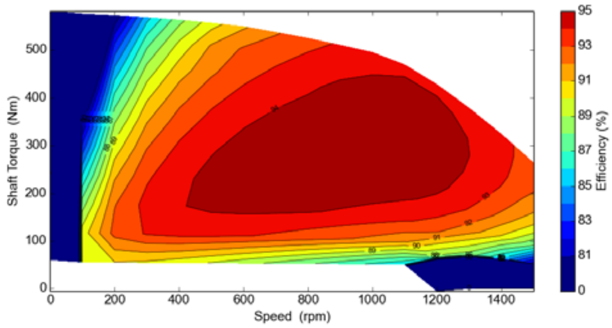

Fig. 8. Calculated efficiency map for the working area with temperature limitation: TCu≤150℃ , Tmag≤ 100℃

Conclusion

The drive for installation in the wheels of commercial vehicles with increased demand for torque, due to the place of application, should be characterized by:

• relatively high ratio of torque (rated and maximum) to weight,

• high energy efficiency, having a direct impact on the range and working time of the vehicle,

• structure ensuring adequate tightness and strength,

• appropriate dynamics of work, high maximum torque, ensuring proper driving parameters of the vehicle,

• built-in brake system, resistant to difficult working conditions.

The calculations presented in the article allowed to simulate the operation of an electric motor with a built-in planetary gear in any commercial vehicle consisting of two or four drive motors.

Presented simulations allow to predict of the maximum operating temperatures of the sensitive points of the motor like winding or magnets.

All the features of the discussed drive and the limitation of the given volume intended for the drive assembly require the design team to look for compromise solutions. The design concept should include design and research activities covering the following issues:

• Design of the electromagnetic circuit,

• Selection and design of the gear construction solution,

• Selection and design of the brake,

• Technological tests,

• Thermal and strength calculations.

The presented results obtained on the basis of the developed models and calculations confirm the correctness of the adopted design concept.

The next stage of work in the project will be a series of technological tests in terms of the feasibility of individual elements of the drive structure. Multivariate work simulations will also be carried out for various designs of the cooling system, and then the possible operating parameters of the drive will be determined for them.

The work was created as part of the project "Innovative electric drive unit for commercial vehicles", financed by the National Center for Research and Development under the LIDER XI program, in accordance with the agreement no. LIDER/15/0060/L-11/19/NCBR/2020.

Authors: *dr inż. Bartłomiej Będkowski, mgr inż. Piotr Dukalski, dr inż. Łukasz Cyganik, mgr inż. Tomasz Jarek, Sieć Badawcza Łukasiewicz – Górnośląski Instytut Technologiczny, ul. Karola Miarki 12-14, 44-100 Gliwice, E-mail: bartlomiej.bedkowski@git.lukasiewicz.gov.pl, piotr.dukalski@git.lukasiewicz.gov.pl, lukasz.cyganik@git.lukasiewicz.gov.pl, tomasz.jarek@git.lukasiewicz.gov.pl.*

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