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Original Study Article

Study of methods of energy efficiency improvement considering operation modes of traction electric drive with use of the methods of virtual mathematical modelling

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ABSTRACT

BACKGROUND: Currently, the problem of making wheeled vehicles more environmentally-friendly is one of the most relevant, as using electric vehicles with on-board traction batteries becomes the most popular technical solution. However, the batteries capacity remains relatively low, so efficiency of using them depends on selection the most optimal components of traction electric equipment and implementing the most advanced algorithms of traction electric drive control. Therefore, development of the methods helping to achieve maximal energy efficiency at all stages of design, manufacturing and operation is highly important.

AIM: Development of fundamentals and methods of improvement of wheeled vehicles energy efficiency at the design stage with the use of virtual mathematical modelling.

METHODS: The study was conducted with the MATLAB/Simulink software package.

RESULTS: Theoretical basis of the improvement methods with the use of mathematical modelling of virtual operation of the vehicle's digital twin in the MATLAB/Simulink is given in the paper.

CONCLUSIONS: The practical value of the study lies in ability of using the proposed methods in development of prosperous wheeled vehicles.

Keywords: operation modes; traction electric drive; probability distribution; mathematical modelling; virtual operation; efficiency.

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Оригинальное исследование

Исследование методов повышения энергоэффективности с учётом режимов работы тягового электропривода методами виртуального математического моделирования

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АННОТАЦИЯ

Обоснование. Вопрос повышения экологичности колёсных транспортных средств является одним из самых актуальных на данный момент, в связи с чем, наиболее популярным техническим решением становится применение электротранспорта с тяговыми аккумуляторными батареями на борту. Однако, ёмкость батарей по-прежнему остается относительно невысокой, поэтому эффективность применения зависит от подбора наиболее оптимальных компонентов тягового энергетического оборудования и применения наиболее совершенных алгоритмов управления тяговым электроприводом. Поэтому весьма важно разрабатывать методы позволяющие на всех стадиях проектирования, производства и эксплуатации добиваться максимума энергоэффективности.

Цель работы — разработка теоретических основ и методов повышения энергоэффективности колёсных транспортных средств на стадии проектирования с применением виртуального математического моделирования.

Материалы и методы. Исследование выполнено в программном комплексе Matlab Simulink.

Результаты. В статье приводятся теоретические основы методов повышения с использованием математического моделирования виртуальной эксплуатации цифрового двойника машины в Matlab Simulink.

Заключение. Практическая ценность исследования заключается в возможности использования предложенных методов при разработке перспективных колёсных транспортных средств.

Ключевые слова: режимы работы; тяговый электропривод; распределение вероятностей; математическое моделирование; виртуальная эксплуатация; эффективность.

Как цитировать:
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BACKGROUND

The most pressing and serious issue currently involves environmental standards and requirements for vehicles. Therefore, electrified vehicles with a traction battery on board are introduced as an alternative to internal combustion engine vehicles.

The efficiency of converting the energy of the storage system into mechanical energy on the shaft of traction electric motors, which depends on operating conditions, is a crucial issue in the use of transport in all sectors of the national economy of Russia and in the world. Therefore, the most optimal components of traction power equipment are selected, and the most advanced algorithms for controlling the traction electric drive are developed to implement energy-efficient movement. The use of wheeled vehicles with environmentally friendly electric traction drives is increasingly observed.

These vehicles have a limited range per charge, restricting their widespread use, while consumer requirements for this key consumer property are becoming increasingly rigid. Reducing the total cost of ownership of such equipment is also important. Therefore, designers must consider various methods for increasing range, one of which involves minimizing energy loss. Overall, improving the energy efficiency of wheeled vehicles is highly relevant. Examining this idea in the early stages of vehicle creation is also crucial.

APPROACHES TO THE CREATION OF ENERGY-EFFICIENT WHEELED VEHICLES

A wheeled vehicle is considered energy efficient if it has energy-efficient units and systems that control them, thereby providing energy-efficient operating modes, and minimizing energy losses.

When organizing energy-efficient control of the traction electric drive of the driving wheels of a wheeled vehicle, information regarding the magnitude of the moment of resistance to movement on the driving wheels is required, and such information is determined by solving the differential equation that describes the dynamics of the drive:

$$J\dot{\omega} = M_t - M_r ,$$

where J is the moment of inertia of the rotating parts of the drive reduced to the traction electric motor shaft; ω is the angular speed of rotation of the electric motor shaft; $\mathrm{M_t}$ and $\mathrm{M_r}$ are the traction electromagnetic moment and the moment of resistance on the electric motor shaft, respectively [1].

As discussed in [2], a method for developing a resistive torque observer is constructed based on the quadratic integral quality criteria containing the object and control coordinates [3, 4] and the theory of analytical design of optimal controllers [5]. The simulation methods of mathematical modeling of the work of an observer in the control system during the movement of a wheeled vehicle (Fig. 1) are performed using a digital twin of the vehicle [6–8]. Simulation results revealed that acceptable prediction accuracy is realized after the attenuation of transient processes caused by starting or stopping the vehicle. Table 1 shows the main characteristics of the object under study.

Fig. 2 presents the general view of the mathematical simulation model of the movement of a digital twin of a vehicle.

Thus, considering the moment of resistance on the drive wheels, optimal control of the traction torque on the shaft of electric motors becomes possible, avoiding ineffective operating modes.

The energy method with high accuracy and operational speed can be used to estimate the traction torque

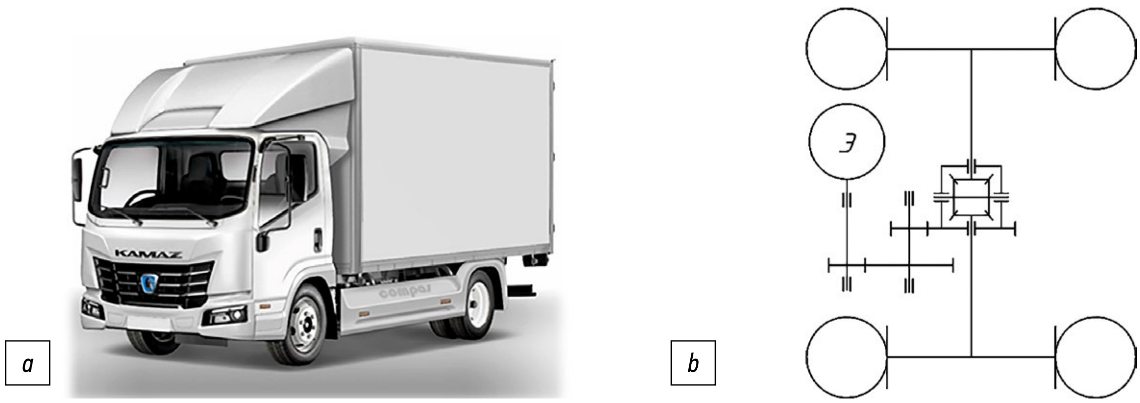

Fig. 1. Main view of the vehicle (*a*) and the drivetrain diagram (*b*).
Рис. 1. Общий вид транспортного средства (*a*) и схема привода (*b*).

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Table 1. Technical specification of the vehicle

Таблица 1. Технические характеристики транспортного средства

Parameter	Value
Wheel configuration	4x2
Gross weight, kg: – on the front axle, kg – to the rear axle, kg	8100 3100 5000
Dimensions: Height, m Width, m	 2,40 2,45
Wheelbase of the motor vehicle, m	4,475
Steering axle track, m	1,710
Drive axle track, m	1,650
Tire rolling radius, mm	215/75 R17,5

in the construction of a drive control system [5, 10, 11]. This method is based on the equation for the instantaneous balance of the active power of electrical machines:

$$P(t) = M_t(t)\omega(t) + P_{tl}(t),$$

where $P(t)$ is the consumed electrical power, $P_{tl}(t)$ is total power losses, $M_t(t)$ is mechanical torque on the motor shaft, and $\omega(t)$ is the angular speed of the electric motor rotor shaft.

Calculating the drive efficiency to determine the control strategy is feasible by estimating the electromagnetic torque, determining the resistive torque, adjusting the operating mode, and eliminating unnecessary losses [12].

DETERMINATION OF THE MOST PROBABLE OPERATING MODES OF A TRACTIONAL ELECTRIC DRIVE

The characteristics of transport vehicles must best comply with the operating conditions to use energy-efficient units and systems in their design. This task is most relevant at the design stages because the basic characteristics of the vehicle and its components are specified in these stages. If an engineer makes a mistake at this stage then he will fail to create an energy-efficient, competitive machine. The traction electric drive may be of considerable interest due to the occurrence of main losses in the traction chain from the energy storage system to the drive wheel. Developing methods for determining the characteristics of components or requirements for these vehicles is also relevant, and their application subsequently enables the creation of energy-efficient technical solutions.

The method for investigating operating modes can be developed based on a statistical study of the functioning of units and systems using a virtual digital twin of the designed vehicle (Fig. 2) and basic motion cycles or motion cycles received from the customer or consumer.

Describing the operating modes in which the equipment is used is often difficult for a customer or a consumer due to several reasons. Therefore, at the initial stage, developers only have requirements for maximum mileage, speed, and possibly the type of roads. In this case, standardized cycles can be used.

Vehicles used in agriculture are generally driven at low speeds. Fig. 3 shows an example of the dependence of the speed of movement on a wheeled vehicle.

As shown in Fig. 4, the most probable speed limit is in the range of 20–35 km/h. In addition, most of the time, the vehicle remains steady (speed 0 km/h).

Considering such a motion cycle, the developer obtains a database of operating modes after performing a virtual operation through the use of a model and mathematical simulation (Fig. 2). The most probable operating modes are determined after statistical processing.

In the case of the object under study (Fig. 1), the distribution of probability densities for the traction electric drive is presented in Figs. 5 and 6. At the early design stages, considering the operating parameters of rotation speed, torque, and power on the drive axle or drive wheels is rational; thus, these parameters can be used to determine the equivalent loading modes of the drivetrain and its key parameters, such as the gear ratio [13].

As shown in Fig. 5, for the vehicle under study (Fig. 1), the most probable rotation speeds of the drive wheels range from 150 rpm to 225 rpm, with a maximum of 350 rpm. The engine shaft displays the most probable rotation speeds of 1,434–2,151 rpm at 3,346 rpm of movement at a maximum operating speed of 52 km/h.

For the traction electric drive, Fig. 6 shows a positive traction torque and a negative regenerative torque on the wheels, corresponding to the electrodynamic braking mode. The most probable values of the traction torque range from 260 Nm to 520 Nm, and from 1000 Nm to 1,500 Nm, with maximum values of 2,660 Nm. These values correspond to the torque on the engine shaft considering Udr = 9.56 and the previously accepted drivetrain efficiency of 95%, ranging from 28.6 Nm to 57.3 Nm and from 110.1 Nm to 165.2 Nm. The regenerative torque at the wheel most probably has a value in the range of up to 1,100 Nm, with maximum values of 3,200 Nm and 109.3 Nm at the engine shaft.

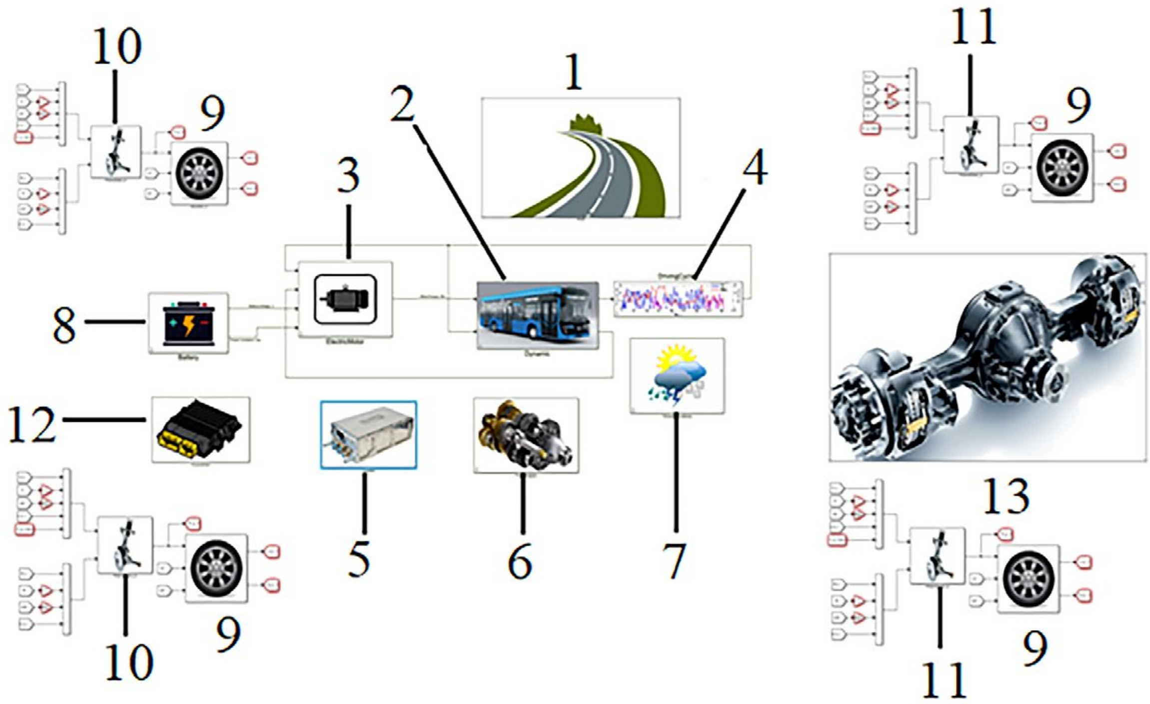

Fig. 2. The simulation model of vehicle motion in the MATLAB/Simulink: *1* — ground surface; *2* — the vehicle dynamics block; *3* — traction electric motors; *4* — a driving cycle; *5* — inverters; *6* — drivetrain; *7* — climatic conditions; *8* — an electricity storage system; *9* —a wheel; *10* — front suspension; *11* — rear suspension; *12* — a control system; *13* — a rear axle.
Рис. 2. Имитационная модель движения транспортного средства в Matlab Simulnk: *1* — опорное основание; *2* — блок динамики движения; *3* — тяговые электродвигатели; *4* — цикл движения; *5* — тяговые инверторы; *5* — трансмиссия; *7* — климатические условия; *8* — система хранения электрической энергии; *9* — колесо; *10* — передняя подвеска; *11* — задняя подвеска; *12* — система управления; *13* — балка заднего моста.

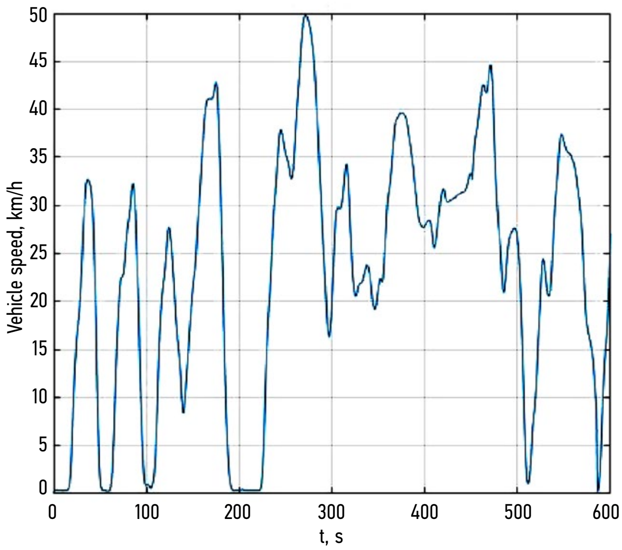

Fig. 3. Time-domain motion velocity of a wheeled vehicle.
Рис. 3. Зависимости скорости движения колёсной машины.

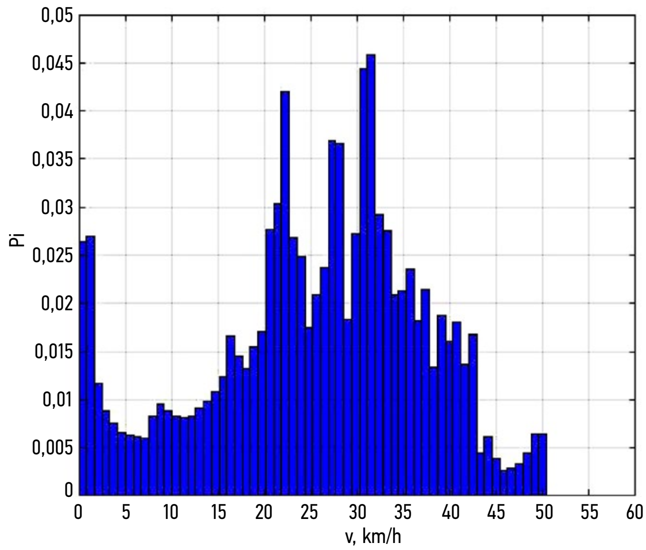

Fig. 4. Probability density distribution of motion velocity.
Рис. 4. Распределение плотности вероятности скорости движения.

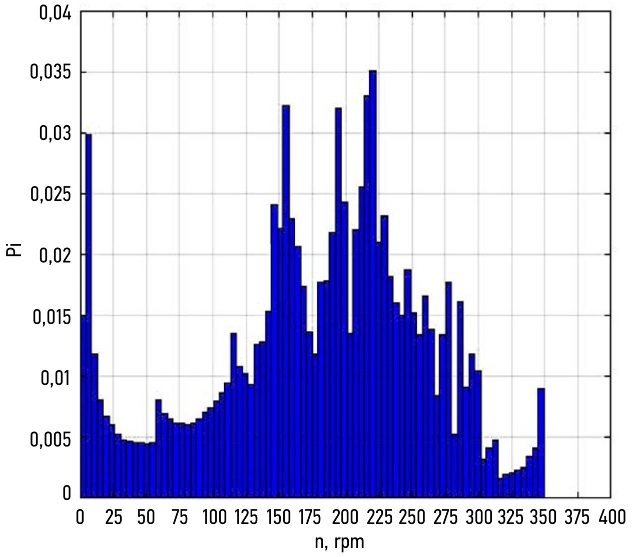

Fig. 5. Probability density distribution of wheel rotation velocity.
Рис. 5. Распределение плотности вероятности частоты вращения колеса.

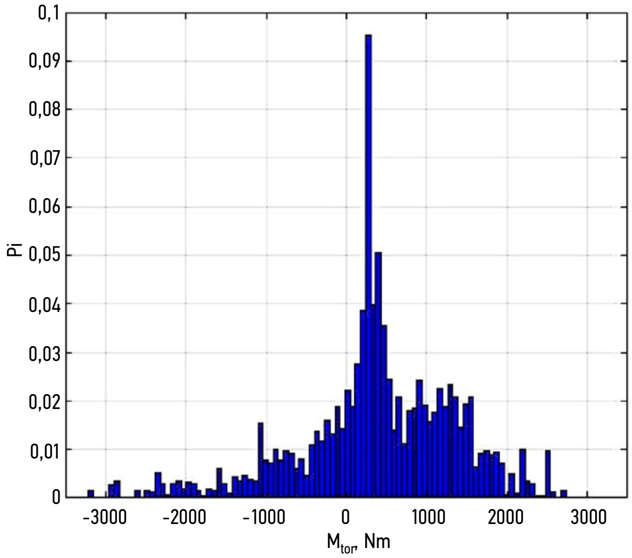

Fig. 6. Probability density distribution of torque at wheels.
Рис. 6. Распределение плотности вероятности крутящего момента на колёсах.

DETERMINATION OF THE OPTIMAL TYPE OF ELECTRIC TRACTION MOTOR

Fig. 7 shows the distribution of operating points of the drive referred to the drive wheels.

Next, determining the following maximum required engine characteristics using well-known equations [1, 6] is necessary: n_{nom} as maximum rotation speed to ensure kinematic traveling speed; $N_{\max}$ as maximum power to provide maximum consumer speed (for example, for driving a motor vehicle on a highway); and $M_{\max}$ as maximum torque in traction and regenerative modes to overcome maximum road resistance and provide deceleration during electrodynamic braking, respectively.

For the vehicle in question, the maximum speed is 90 km/h, the wheel rotating velocity is 685 rpm, and the engine speed n_{nom}=6520 orpm; considering the 10% reserve, it is 7,172 rpm. The required maximum torque

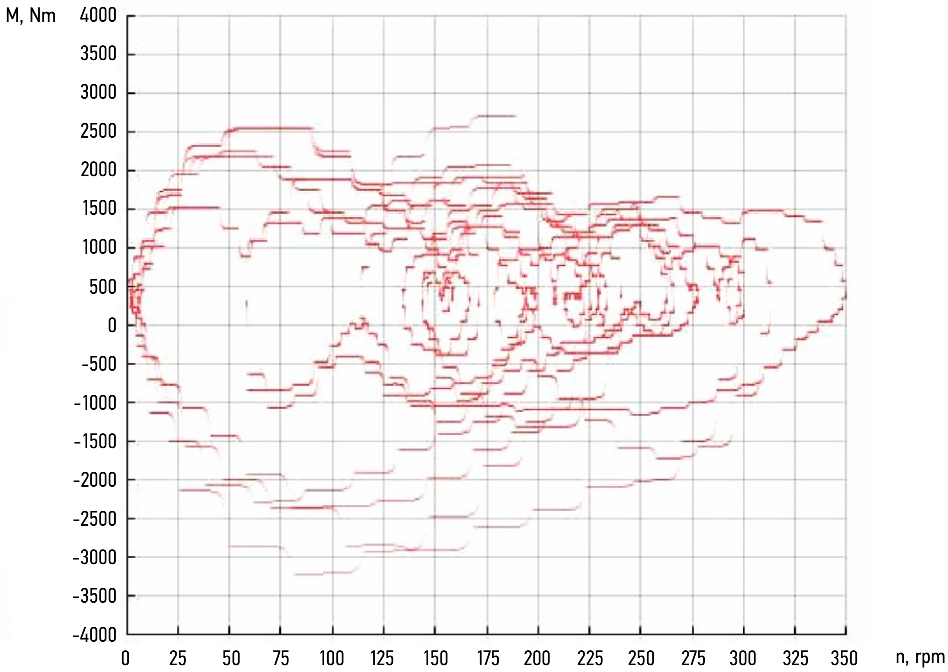

Fig. 7. Distribution of operation points of torque at driving wheels.
Рис. 7. Распределение рабочих точек, приведенных к колесу.

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at the wheel to overcome maximum road resistance (a 25% rise) is 7,725 Nm, and 850 Nm at the engine shaft.

The type of traction electric driving motor should then be determined by ensuring maximum efficiency in the most probable operating conditions. The work [14] provides typical performance characteristics of electric motors, which can be used to determine the required type of motor.

The type of drive motor should be determined after identifying the areas of most probable operation and the maximum required parameters. By superimposing the distribution of operating points (Fig. 9) on typical characteristics, the IPM synchronous reluctance engine is regarded as the most suitable for driving the drive wheels of a wheeled vehicle used in agriculture because the zone of its maximum efficiency is in the region of low and medium torque speeds, thereby maximizing energy efficiency.

CONCLUSIONS

Methods for increasing the energy efficiency of wheeled vehicles using observers in the control system, as well as the utilization of energy-efficient units and systems, are considered.

Considering the operating features of real transport facilities using mathematical simulation modeling through the virtual operation of a digital twin, a method is proposed for determining the key characteristics and types of traction electric drives.

Analysis of operating modes shows that the traction electric drive of a wheeled transport vehicle used in agriculture mainly operates in the zone of partial characteristics in the range of rotation speeds up to n_{nom} and torque up to M_{nom}.

For the machines under consideration, the most energy-efficient technical solution is the IPM synchronous reluctance motor because its maximum efficiency zone is in the region of low and medium torque speeds, allowing maximization of energy efficiency.

The practical value of the study includes the possibility of using the proposed methods for increasing energy efficiency and the proposed method for identifying the key characteristics and types of electric motors for the development of a control system for the traction drive of transport vehicles and their diagnostics.

ADDITIONAL INFORMATION

Author's contribution. A.V. Klimov — development of theoretical fundamentals, development of the method, building of the mathematical model, performing simulations, search for publications on the topic of the article, writing the text of the manuscript, editing the text of the manuscript, creating images. The author confirms the compliance of their authorship with the international ICMJE criteria (the author made a significant contribution to the development of the concept, research and preparation of the article, read and approved the final version before publication).

Competing interests. The author declares that he has not competing interests.

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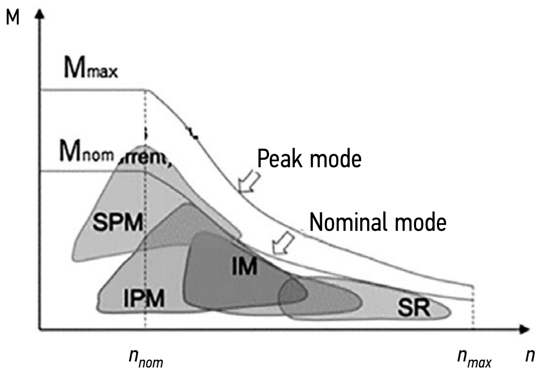

Fig. 8. Typical electromechanical performance diagram of a traction electric motor and areas of the highest efficiency of various types of electric motors: SPM — permanent-magnet synchronous motors; IPM — internal permanent magnet motors; IM — induction motors; SR — switched reluctance motors.

Рис. 8. Типовая электромеханическая характеристика тягового электродвигателя и зоны наибольшего КПД для различных типов электродвигателей: SPM — синхронный с постоянными магнитами; IPM – синхронно-реактивный с постоянными магнитами IM — асинхронный; SR — вентильно-индукторный.

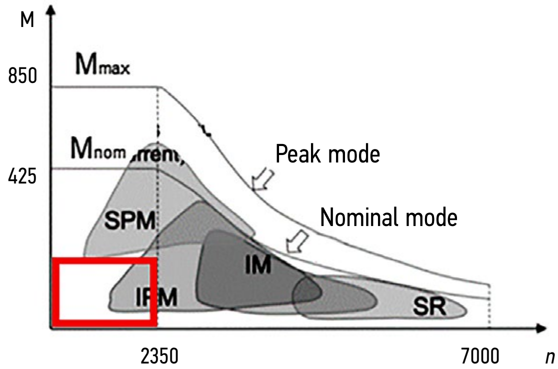

Fig. 9. The operating points combined with the typical performance diagram of electric motors.

Рис. 9. Рабочие точки привода, наложенные на типовую характеристику двигателей.

Education of the Russian Federation within the framework of the “Development of the mathematical model of chassis operation (transmission, chassis and control mechanisms) in static and dynamic state and creation on its basis of a digital twin of a passenger car platform” project).

ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад автора. А.В. Климов — разработка теоретических основ, разработка метода, разработка математической модели, проведение математического моделирования, проведение расчётов поиск публикаций по теме статьи, написание текста рукописи, редактирование текста рукописи, создание изображений. Автор подтверждает соответствие своего авторства международным критериям *ICMJE* (автор внёс существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочёл и одобрил финальную версию перед публикацией).

Конфликт интересов. Автор декларирует отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

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