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CONTROL SYSTEM OF DOUBLE-ROTOR INDUCTION MOTORS FOR HYBRID VEHICLES

Purpose. Analyzing of the principles of construction of a double-rotor induction machine control system as a power divider in hybrid vehicles. Defining the features of the functioning of this electromechanical system during the operation of the internal combustion engine and when it is turned off.

Methodology. The theoretical studies were based on the theory of induction electric machines, the principles of the operation of power converter devices, the laws of transformation of electric energy into mechanical and vice versa. The synthesis of the control system of the double-rotor induction machine was carried out using the theory of field-oriented vector control. The design of the computer model was performed using simulation in the Matlab/Simulink environment.

Findings. The existing structures of hybrid vehicles were analyzed and it was found that the most versatile scheme is a series-parallel scheme. In such systems, the planetary transmission is used as a power divider, but it is a complex mechanical unit. In order to replace the planetary transmission in the hybrid vehicles, the possibility of using a double-rotor induction machine was studied. The structure of the control system for an induction machine with two rotors is developed, the internal rotor of which is connected to the internal combustion engine, and the external rotor is connected to the transmission of the vehicle. The stator and the internal rotor of the machine are connected to a converter that can conduct electric energy in both directions. The results of the simulation of the system during operation of the internal combustion engine, as well as when it is turned off, are presented.

Originality. The structure of the control system of a double-rotor induction machine in the hybrid vehicle, in which the control of the internal rotor is carried out in order to maintain the reference value of the torque, and the control of the external rotor is carried out in order to maintain the necessary speed of the vehicle, is proposed.

Practical value. The proposed system can be used in the structure of existing hybrid vehicles built on a series-parallel scheme. In its structure, a double-rotor induction machine can simultaneously replace both electric machines, one of which is most often used in the generator mode, and the other is used in the motor mode, as well as the planetary transmission, which performs the separation of electrical and mechanical powers.

Keywords: *induction machine, machine with two rotors, hybrid vehicles, energy efficiency*

Introduction. In recent years, electric and hybrid vehicles have been attracting more and more attention due to the obvious advantages of saving fuel resources and reducing harmful emissions to the environment. Despite the fact that the use of electric vehicles allows solving completely the problem of harm to the ecological state of environment, their operation is confronted with a number of inconveniences associated with a limited distance of movement from one charge through the limited capacity of an autonomous power source and the lack of necessary infrastructure. Overcoming these disadvantages is possible with the use of hybrid vehicles that have two sources of energy. Their use is currently considered as a promising direction for increasing the energy efficiency of such systems.

Existing hybrid vehicles are built on the basis of parallel [1], series [1, 2] and series-parallel schemes [3, 4] and it is the series-parallel scheme that combines the advantages of the other two structures, that is, it allows achieving the highest performance indicators at move in urban, extra-urban and highway conditions. However, this structure is the most complicated in comparison with the others, because it contains a power divider, called planetary transmission. This unit controls the power flows from internal combustion engine, the generator and the traction motor, therefore, its functioning is the key in the analysis of such vehicles. As power division is done at the level of mechanical rotation of planetary transmission parts, its use leads to increasing power losses in the system as well as additional noise. Therefore, nowadays researchers are considering the possibility of realizing the process of power division based not on a purely mechanical unit, but on an electromechanical converter which is an electric machine with two rotors.

Analysis of the recent research. Currently, researches are widely exploring the possibility of using an electric machine as a power separator [5]. In [6], the authors propose ways to optimize the management of power distribution processes in the structure of hybrid vehicles, but focuses on the creation of mathematical models of the components. Such an approach does not allow assessing the possibility of integrating an electric machine with two rotors into the structure of the electromechanical system. The paper [7] analyzes a double-rotor switched reluctance motor for separating the power flow of hybrid vehicles, but the principles of constructing a control system cannot be applied to an electric machine based on using of Lorenz force, so it is not possible to adapt it to an induction motor. In [8] a detailed description of the method of double-rotor switched reluctance motors is presented in order to optimize their performance regarding energy efficiency. Since traction electromechanical systems have proved to be quite good when synchronous motors with permanent magnets are used in them, it is topical to analyze the possibility of such machines with two rotors. Relevant studies are presented in [9, 10], but the high cost of rare earth materials used in the construction of this type of machines, leads to increasing interest in machines without permanent magnets. Since the main aim of synthesis of hybrid structures of traction electromechanical systems is to increase energy efficiency indicators, it is expedient to use energy optimization methods [11] when developing the appropriate control systems, and in order to increase robustness – use sliding mode controllers [12]. One more component of the energy optimization of the system is the use of perspective schemes of energy converters. The possibilities of power optimization of traction electric alternative current drives are presented in [13–15], however, in these publications machines are considered with only one mechanical port. Consequently, the issue of synthesis of the control system of a double-rotor induction machine and the analysis of operation modes of such hybrid transport systems in existing publications are not discussed.

Objectives of the article. An analysis of the principles of construction of double-rotor induction machine control system as a power divider in hybrid vehicles.

Presentation of the main research. Planetary transmission is the main component that fulfills matching and separating power flows of the hybrid electric vehicles based on the series-parallel scheme. It is a mechanical device that due to its construction can change, add or divide supplied angular velocities and torques within one rotational axis. Constructively, it is a set of interconnected gear wheels, a part of which has a common geometrically stationary rotational axis and the other part has a movable rotational axis that rotates concentrically around the stationary one. The gear wheals which have stationary rotational axis are not meshing directly but through rotating wheel. According to mechanics, the planetary transmission is the system with two degrees of freedom that is an important difference from any other rotational transmissions which have only one degree of freedom. This very feature, which is a direct consequence of its construction, allows it not only to reduce these speeds, but also to add and divide, and this fact is rather useful for implementation of operation modes of hybrid vehicles. However, as the planetary transmission is a mechanical component, using it means loss of power, acoustic noise, necessity of being served and backlash and eccentricity may appear in this case. Therefore, the idea of using an electrical device instead of mechanical transmission for separating the power flows is quite rational, because such an approach can eliminate all the disadvantages mentioned above. In this case an electric machine with two rotors becomes the main element. The use of the electric machine with two rotors significantly simplifies the structure of the traction electromechanical system. Such a machine has two concentric rotors called internal and external rotors. In this scheme internal combustion engine rotates the internal rotor and its power is divided into two parts: the first part through the internal rotor and the external rotor is transmitted to the wheels, and the other part goes through the internal rotor, the controlled rectifier, the battery, the inverter, the stator and is transmitted to the wheels through the external rotor. Consequently, the external rotor is the point of scheme where two rotational torques are added.

In order to create an adequate mathematical model of this electromechanical converter, it is necessary to fulfill a number of requirements: 1. One set of windings should be located on the stationary part of the machine, the other should be on one of the two moving parts. In this case, the electric energy is supplied to the rotating part of the machine with help of contact rings or brushes. 2. The central part of the machine separated from the inner and outer ones with air gaps is the point where the electromagnetic torques created by independent electromagnetic subsystems are added. 3. Two mechanical outputs can be freely assigned to any of three components of the machine according to the application. 4. Two mechanical outputs have to be able to transmit energy in two directions, i.e. to move the mechanical body, which is connected to them or to be moved by this body. 5. The electrical components of the model have to be able to transmit energy in two directions, i.e. to operate either in the electric energy consumption mode or in the generator mode.

Consequently, the stator and internal rotor winding are connected to the common battery with help of two bi-directional converters. Such a system will have characteristics which are similar to the series-parallel structure of the hybrid vehicle with planetary transmission and two independent electric machines. The advantage of using the machine with two rotors is the fact that the same functionality will be provided by one compact device, as well as the system will have higher energy efficiency.

Then, taking a positive direction of d-axis as a position of flux-linkage vector of external rotor, equations of electric equilibrium can be written as follows

$$u_{d1} = R_1 i_{d1} + \frac{d\psi_{d1}}{dt} - \left(\omega_s - p\omega_{m1}\right)\psi_{q1};$$

$$u_{q1} = R_1 i_{q1} + \frac{d\psi_{q1}}{dt} + \left(\omega_s - p\omega_{m1}\right)\psi_{d1};$$

$$0 = R_2 i_{d2} + \frac{d\psi_{d2}}{dt};$$

$$0 = R_2 i_{q2} + \omega_{??}\psi_{d2},$$

where u_{d1} and u_{q1} are the projections of the vector of the phase voltage of the internal rotor on the dq axises; R_1 is the active resistance of the internal rotor windings; i_{d1} and i_{q1} are the projections of the phase current vector of the internal rotor in the *dq* frame; ψ_{d1} and ψ_{q1} are the projections of the flux linkage of the internal rotor in the *dq* frame; ω_s is the synchronous speed; p is the number of pole pairs, ω_{m1} is mechanical speed of the internal rotor; R_2 is the active resistance of the external rotor windings; i_{d2} and i_{q2} are the projections of the phase current vector of the external rotor in the dq frame; ψ_{d2} is the projection of the flux linkage of the external rotor on the d axis; $\omega_{??}$ is slip frequency.

The corresponding flux-linkages can be calculated by the following dependencies

$$\psi_{d1} = L_1 i_{d1} + L_m i_{d2};$$

$$\psi_{q1} = L_1 i_{q1} + L_m i_{q2};$$

$$\psi_{d2} = L_m i_{d1} + L_2 i_{d2};$$

$$0 = L_m i_{q1} + L_2 i_{q2},$$

where L_1 is the self-inductance of the internal rotor windings; L_2 is the self-inductance of the external rotor windings; L_m is the mutual inductance.

In most cases, the angular speed and torque required from the traction drive of a hybrid vehicle do not correspond to the optimal values considering energy efficiency of the ICE. Therefore, the goal of controlling the power set of a hybrid vehicle is to choose the optimal distribution of powers of individual components at every moment to minimize energy consumption when driving in a given cycle. Thus, the development of hybrid vehicle control systems should take into account both a requirement for the implementation of reference driving requirements and increasing fuel efficiency. To simplify the analysis, the double-rotor machine can be considered as two independent ones, which greatly simplifies the synthesis of the control system. Then the task of controlling the internal rotor of the machine is to provide a reference speed in order to compensate the difference between the angular speed of the ICE and the reference value needed for the vehicle to move. At the same time, the task of controlling the external rotor of such a machine is to minimize the difference between the real value of the ICE torque and the reference value needed for the movement of the vehicle.

The main source of energy for a hybrid vehicle is the ICE. When a double-rotor machine is used, the energy coming from it with the help of an electric machine is converted into electric and recharges the battery. On the one hand, it seems that such a transformation of energy reduces the efficiency of a hybrid power set; however, energy conversion quality indexes significantly improve through choosing the optimal operation point. A remarkable advantage of a double-rotor machine is the possibility of continuous change of gear ratio, which allows, due to this change, the drive to operate in the zone of high efficiency, regardless of the parameters of motion.

Fig. 1 presents a structure that describes the general concept of controlling the double-rotor machine of a hybrid vehicle. As you know, the ICE has low energy efficiency at low angular speeds and low loads [7]. Therefore, the main task realized by this system is to maintain the working point of the ICE in the area of highest efficiency.

Considering the design of the double-rotor machine control system, first of all, it is necessary to find out the rational logic of turning on and turning off the ICE. When the vehicle is in motion, the internal combustion engine works at the point of optimal efficiency, in any other case it is turned off. For the battery pack, the optimum working interval for the level of charge $S_{\min}$–$S_{\max}$ is set in advance, which is the key for determining the moments of the turning on and turning off times of the internal combustion engine. The internal combustion engine will be switched off, when the battery state of charge is sufficient, i.e. exceed the value $S_{\max}$. In this case, the vehicle will be moved by electric traction. When the battery state of charge is low, that is, lower than the value $S_{\min}$, the internal combustion engine generates constant power, which is used for charging the battery and move the vehicle.

In such a case the internal combustion engine is connected to the internal rotor of the induction machine and operates at a constant rotational speed. Thus, when the control system of rotor circuits of such a motor is synthesized, it is necessary to proceed the following conditions: in the case when the external rotor is able to provide the necessary traction force to realize current reference signal on the vehicle and the state of the battery corresponds to the level requiring its recharging, the internal rotor operates in the generator mode, converting the mechanical energy obtained from the ICE into electrical one. In the case when the traction force of the external rotor is not enough, the sign of the reference torque changes to the opposite one, and the electromechanical processes in the internal rotor corresponds to motor operation mode, which allows increasing the indexes of performance of the vehicle, such as maximum speed, ability to overcome the rise and acceleration indexes significantly. Consequently, the principle of the internal rotor control is providing reference value of torque T^* applied to the shift of the ICE, and the principle of the external rotor control is obtaining the required speed of the vehicle. The control system consists of internal and external rotor subsystems and is based on the principles of vector field-oriented control, which allows having independent channels of control of the flux linkage of the external and internal rotor. The compensation of the internal cross-connections of the motor is not shown for simplification.

In order to analyze the double-rotor induction machine operation modes in the hybrid vehicle, an imitation model has been developed and the operation of the system with the turned off ICE (Fig. 2) and with the turning on the ICE (Fig. 3) during the performance has been studied. From the analysis of the obtained graphs, we can make the following conclusions:

1. When the system operates with the turned off internal combustion engine (Fig. 2) a smooth discharge of the battery can be noticed. In this mode of operation the main task of double-rotor induction motor control system is to provide the required value of the angular speed of the external rotor and to monitor the level of charge of the battery in order to involve the ICE in the operation on time when the level of charge becomes lower than the reference level (in the model is used the 40 % level).

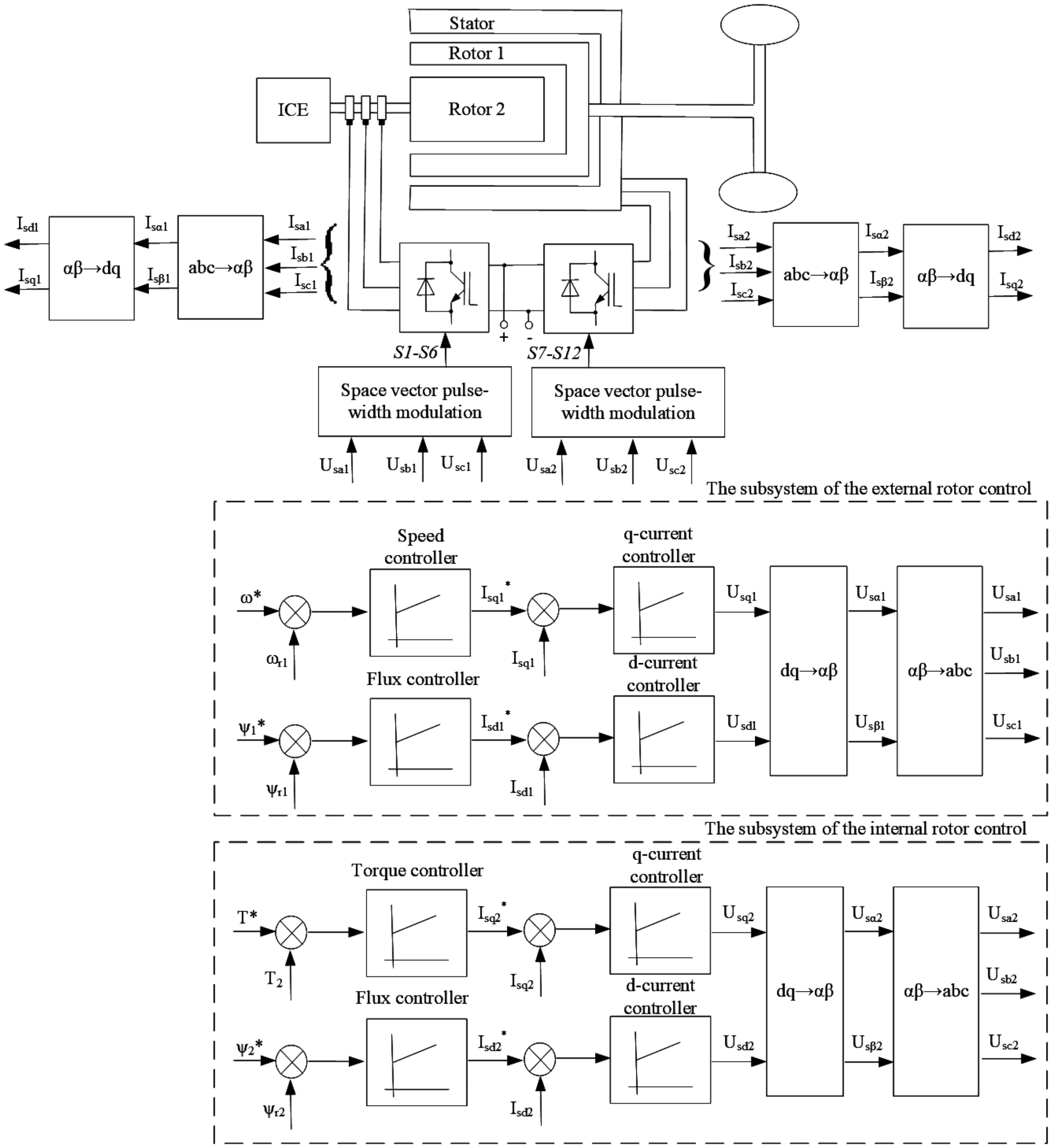
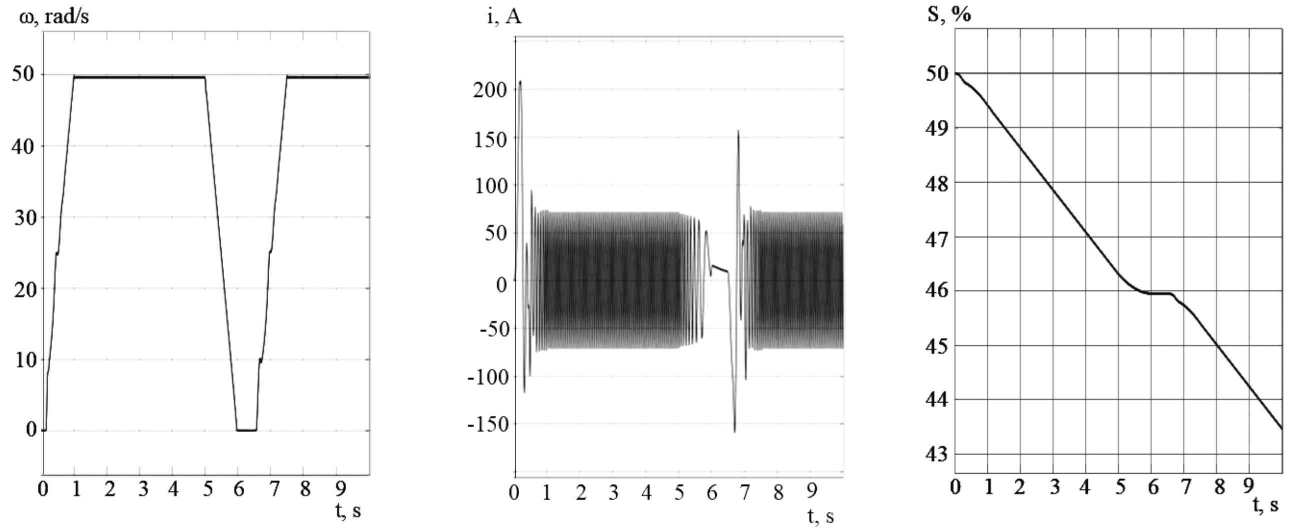


Fig. 1. Structure of the control system of the double-rotor induction machine in the hybrid vehicle

2. From the graph of the angular velocity of the external rotor (Fig. 3, *a*) it can be seen that when the ICE is turned on ($t \approx 1.5$ s) due to the large value of starting current of internal rotor, there are oscillations of the angular speed of the external rotor, which can be explained by the electromagnetic interaction of two subsystems. In order to eliminate this, it is necessary to develop current-limiting control circuits for the electrical scheme of the internal rotor. In this case, it is necessary to take into account the fact that the short-term exceeding of rated current in this circuit is allowed in the motor mode for increasing the vehicle performance indexes.

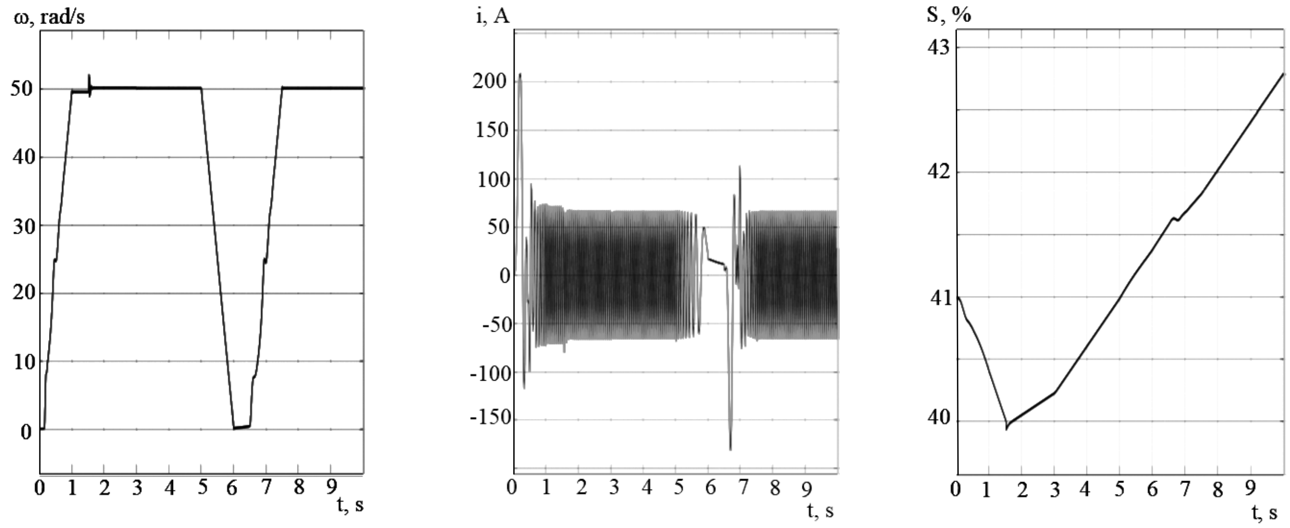
3. When the ICE is turned on and we need quick acceleration (period 6.5–7 c in Fig. 3), the electromechanical system of the internal rotor operates in the motor mode, fulfilling the addition of electric power consumed from the battery and the power of internal combustion engine. At this time there is a slow discharge of the battery. The implementation of such a mode is necessary to ensure high value of productivity indexes of the vehicle.

Conclusions and recommendations for further research. The work of the control system of the double-rotor induction machine in the hybrid vehicle has been investigated. It has been proved that its functioning



a *b* *c*

Fig. 2. Graphs of the angular speed (a), stator current of the motor (b) and state of charge of the battery (c) when the hybrid vehicle operates with a double-rotor induction machine with the ICE which is turned off



a *b* *c*

Fig. 3. Graphs of the angular speed (a), stator current of the motor (b) and state of charge of the battery (c) when the hybrid vehicle operates with a double-rotor induction machine with the turning-on of the ICE

meets the important requirements for the separation of electrical and mechanical powers that are necessary to such systems. The use of this type of machine will eliminate the mechanical power divider that currently serves as a planetary transmission, which will improve the energy efficiency and reliability of such systems.

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Система керування асинхронними машинами із двома роторами для гібридних транспортних засобів

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Мета. Аналіз принципів побудови системи керування двороторною асинхронною машиною в ролі розділювача потужності у складі гібридного транспортного засобу. Виявлення особливостей функціонування даної електромеханічної системи при роботі двигуна внутрішнього згорання та при його відключенні.

Методика. Теоретичні дослідження базувалися на теорії асинхронних електричних машин, принципах функціонування силової перетворювальної техніки, закономірностях перетворення електричної енергії в механічну та навпаки. Синтез системи керування двороторною асинхронною машиною здійснювався з використанням теорії векторного полеорієнтованого керування. Конструювання комп'ютерної моделі виконувалося за допомогою імітаційного моделювання в середовищі Matlab/Simulink.

Результати. Проаналізовані існуючі структури гібридних транспортних засобів та виявлено, що найбільш універсальною схемою є послідовно-паралельна схема. У таких системах у якості розділювача потужності використовується планетарна передача, що є складним механічним вузлом. Із метою заміщення планетарної передачі у складі гібридних транспортних засобів вивчена можливість застосування двороторної електричної машини. Розроблена структура системи керування для асинхронної машини із двома роторами, внутрішній ротор якої підключається до двигуна внутрішнього згорання, а зовнішній ротор – до трансмісії транспортного засобу. Статор і внутрішній ротор машини підключаються до перетворювача, що може пропускати електричну енергію в обох напрямках. Представлені результати моделювання роботи системи при роботі двигуна внутрішнього згорання, а також при його відключенні.

Наукова новизна. Запропонована структура системи керування двороторною асинхронною машиною у складі гібридного транспортного засобу, в якій керування внутрішнім ротором здійснюється з метою підтримання заданої величини моменту, а керування зовнішнім ротором – з метою підтримання необхідної швидкості руху транспортного засобу.

Практична значимість. Отримана система може бути використана у структурі існуючих гібридних транспортних засобів, що побудовані за послідовно-паралельною схемою. За своєю структурою двороторна асинхронна машина може одночасно замінити обидві електричні машини, одна з яких найчастіше використовується в режимі генератора, а інша – у режимі двигуна, а також планетарну передачу, що виконує розділення електричних і механічних потужностей.

Ключові слова: *асинхронна машина, машина із двома роторами, гібридні транспортні засоби, енергоефективність*

Система управления асинхронными машинами с двумя роторами для гибридных транспортных средств

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Цель. Анализ принципов построения системы управления двухроторной асинхронной машиной в качестве разделителя мощности в составе гибридного транспортного средства. Определение особенностей функционирования данной электромеханической системы при работе двигателя внутреннего сгорания и при его отключении.

Методика. Теоретические исследования базировались на теории асинхронных электрических машин, принципах функционирования силовой преобразовательной техники, закономерностях преобразования электрической энергии в механическую и наоборот. Синтез системы управления двухроторной асинхронной машиной выполнялось с использованием теории векторного полеориентированного управления. Конструирование компьютерной модели выполнялось с помощью имитационного моделирования в среде Matlab/Simulink.

Результаты. Проанализированы существующие структуры гибридных транспортных средств и определено, что наиболее универсальной схемой является последовательно-параллельная схема. В таких системах в качестве разделителя мощности используется планетарная передача, которая является сложным механическим узлом. С целью вытеснения планетарной передачи в составе гибридных транспортных средств изучена возможность использования двухроторной электрической машины. Разработана структура системы управления для асинхронной машины с двумя роторами, внутренний ротор которой подключается к двигателю внутреннего сгорания, а внешний – к трансмиссии транспортного средства. Обмотки статора и внутреннего ротора машины подключаются к преобразователю, который способен пропускать электрическую энергию в двух направлениях. Представлены результаты моделирования работы системы при работе двигателя внутреннего сгорания, а также при его отключении.

Научная новизна. Предложена структура системы управления двухроторной асинхронной машиной в составе гибридного транспортного средства, в которой управление внутренним ротором осуществляется с целью поддержания заданной величины момента, а управление внешним ротором – с целью поддержания необходимой скорости движения транспортного средства.

Практическая значимость. Полученная система может быть использована в структуре существующих гибридных транспортных средств, которые построены по последовательно-параллельной схеме. По своей структуре двухроторная асинхронная машина может одновременно заменить обе электрические машины, одна из которых чаще используется в режиме генератора, а другая – в режиме двигателя, а также планетарную передачу, которая выполняет разделение электрических и механических мощностей.

Ключевые слова: *асинхронная машина, машина с двумя роторами, гибридные транспортные средства, энергоэффективность*

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