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B. V. VOROBIOV

ENERGY EFFICIENT ASYNCHRONOUS ELECTRIC DRIVE OF AN ELECTROMOBILE

The introductory part of the article describes the relevance of developments in the field of electric vehicles, as well as an economic analysis of the feasibility of using electricity as fuel instead of gasoline on the example of some mass-produced cars. Based on the general requirements for vehicles, a functional diagram of an asynchronous electric drive of an electric vehicle with a supercapacitor battery was built and justified as an intermediate link for the accumulation of electrical braking energy, all elements of the electric drive are described and justified. The parameters of a supercapacitor battery are obtained that can provide the necessary capacity for energy recovery. The optimal structure of the power energy converter was selected, as well as the necessary control algorithms. A mathematical computer model of the electric drive has been built, taking into account all the loads that the electric car experiences during movement, and also allowing modeling the necessary coordinates in various urban cycles of vehicle traffic. A computer simulation of the characteristics of the system was carried out when driving on a horizontal road, as well as when driving from a slope at an angle of 20 °. The characteristics of changes in the voltage on the battery of supercapacitors during regenerative braking are obtained, which allow us to obtain data on the nature of the processes in the battery at each stage of the motion cycle. Transient processes of engine speed and torque are obtained that correspond to the driving influences and the selected control method. The adequacy of the computer model is confirmed and the obtained data are compared with the experimental data presented in the sources. Quantitative indicators of energy recovered in a supercapacitor battery are obtained.

Keywords: electric drive, supercapacitor, regenerative braking, saving energy.

Б. В. ВОРОБЙОВ

ЕНЕРГОЕФЕКТИВНИЙ АСИНХРОННИЙ ЕЛЕКТРОПРИВОД ЕЛЕКТРОМОБІЛЮ

У вступній частині статті описується актуальність розробок у напрямку електромобілебудування, а також проведено економічний аналіз доцільності використання електроенергії в якості палива замість бензину на прикладі деяких серійних автомобілів, що випускаються у наш час. Спираючись на загальні вимоги, що пред'являються до транспортних засобів, була побудована і обґрунтована функціональна схема асинхронного електроприводу електромобіля зі суперконденсаторною батареєю у якості проміжної ланки накопичення електричної енергії гальмування, описані та обґрунтовані всі елементи електроприводу. Отримано параметри суперконденсаторної батареї, які зможуть забезпечити необхідну ємність для рекуперації енергії. Обрана оптимальна структура силового перетворювача енергії, а також необхідні алгоритми управління. Побудовано математичну комп'ютерну модель електроприводу, що враховує всі навантаження, які випробовує електромобіль під час руху, а також дозволяє проводити моделювання необхідних координат в різних міських циклах руху транспорту. Проведено комп'ютерне моделювання характеристик системи, що рухається по горизонтальній дорозі, а також при русі зі схилу під кутом 20°. Отримано характеристики зміни напруги на батареї суперконденсаторів під час рекуперативного гальмування, які дозволяють отримати дані про характер процесів, що відбуваються в батареї на кожному з етапів циклу руху. Отримано перехідні процеси швидкості та моменту двигуна, які відповідають задаючій дії та обраному методу управління. Підтверджено адекватність комп'ютерної моделі електроприводу та отримані дані зіставлені з представленими в джерелах експериментальними даними. Отримано кількісні показники уведеннях в суперконденсаторна батарею енергії.

Ключові слова: електропривод, суперконденсатор, рекуперативне гальмування, енергозбереження.

Б. В. ВОРОБЬЁВ

ЭНЕРГОЭФФЕКТИВНЫЙ АСИНХРОННЫЙ ЭЛЕКТРОПРИВОД ЭЛЕКТРОМОБИЛЯ

Во вступительной части статьи описывается актуальность разработок в области электромобилестроения, а также проведен экономический анализ целесообразности использования электроэнергии в качестве топлива вместо бензина на примере некоторых серийно-выпускаемых автомобилей. Опираясь на общие требования, предъявляемые к транспортным средствам, была построена и обоснована функциональная схема асинхронного электропривода электромобиля с суперконденсаторной батареей в качестве промежуточного звена накопления электрической энергии торможения, описаны и обоснованы все элементы электропривода. Получены параметры суперконденсаторной батареи, которые смогут обеспечить необходимую ёмкость для рекуперации энергии. Выбрана оптимальная структура силового преобразователя энергии, а также необходимые алгоритмы управления. Построена математическая компьютерная модель электропривода, учитывающая все нагрузки, которые испытывает электромобиль во время движения, а также позволяющая проводить моделирование необходимых координат в различных городских циклах движения транспорта. Проведено компьютерное моделирование характеристик системы при движении по горизонтальной дороге, а также при движении со склона под углом 20°. Получены характеристики изменения напряжения на батарее суперконденсаторов во время рекуперативного торможения, которые позволяют получить данные о характере протекающих процессов в батарее на каждом из этапов цикла движения. Получены переходные процессы скорости и момента двигателя, которые соответствуют задающим воздействиям и выбранному методу управления. Подтверждена адекватность компьютерной модели и полученные данные сопоставлены с представленными в источниках экспериментальными данными. Получены количественные показатели рекуперированной в суперконденсаторную батарею энергии.

Ключевые слова: электропривод, суперконденсатор, рекуперативное торможение, энергосбережение

Introduction. Consuming a significant amount of oil resources, as well as the deteriorating environmental situation in large cities, associated with an increase of the concentration of car exhausts (one liter of burned gasoline leads to the formation of approximately 16 m^3 or 16,000 liters of a mixture of different gases), require a transition to alternative energy sources. This problem is especially relevant for Ukraine, which is provided with own resources only by 48%. In this case, a strong dependence on imports of petroleum products leads to the fact that gasoline prices are rising rapidly. According to statistics [1], Ukraine in January-August 2017 imported petroleum products in monetary terms by 2.466 billion dollars, which is 30% more than the same period last year.

As a result, imports accounted for more than half of the domestic oil products. In addition, research shows that oil reserves are inexorably declining. In this regard, it is necessary to seek new means that will help in solving existing problems.

An alternative to existing internal combustion engines is an electric drive (ED). The development of electric vehicles worldwide is extremely relevant now. At this stage of development, electric vehicles are inferior in a number of respects to gasoline or diesel cars, but their advantages are undeniable: high energy efficiency, environmental friendliness, simplicity of design and maintenance, using of cheaper energy (in comparison with gasoline), noise reduction. Already, more than 2 million electric vehicles are in operation in the world, and the monthly increase in sales (2016) is about 15% [2]. According to the latest calculations, the total energy efficiency of the electric vehicle (0.97 km / MJ for Tesla Roadster) is significantly (almost 3 times) higher than the energy efficiency of gasoline vehicles (0.38 km / MJ for Honda Civic VX) [3].

Due to the mass production and limited mining of rare earth metals, which are the basis of permanent magnets for traction synchronous motors of electric vehicles, they will be gradually replaced by asynchronous electric motors (AM), which at a lower maximum moment have a number of undeniable advantages: simplicity of design, lower cost, etc. The main goal of the electric vehicles market segment (today it is occupied by budget models, such as Nissan Leaf) is to reduce the cost of electric vehicles by reducing the cost of battery, as well as optimizing modes of regenerative braking.

Main part. The purpose of this work is to create a computer model of an asynchronous electric drive of an electric vehicle using a supercapacitor battery as a buffer source of electric power, do the computer modeling and researching of recuperative braking modes.

The form of the functional scheme is determined by the nature of the energy conversion during the movement of the electric vehicle. The energy source is a rechargeable battery of accumulators (BP), which provides a constant voltage Ub as the output. The conversion of the DC voltage into an AC is provided by a three-phase autonomous power inverter (PI), which performs the frequency and voltage regulation functions according to Kostenko's law [4].

$$\frac{U}{f}=\frac{U_{\text{nom}}}{f_{\text{nom}}}=\text{const} \qquad (1)$$

The inverter is controlled by a microprocessor unit (MCU), which switches the keys of an autonomous inverter according to the PWM algorithm. The transformation of electrical energy into mechanical energy is carried out by the AM, on the shaft of which the driving moment is formed. Increasing torque on the shafts of the wheels with a corresponding reduction in speed is achieved with the help of a mechanical gearbox. Thus, it is advisable to perform the functional diagram of the ED in the form shown in Fig. 1. The power channel of the electromechanical system includes the MCU, the power semiconductor converter, the electric motor, the mechanical transmission, the differential and the pair of wheels.

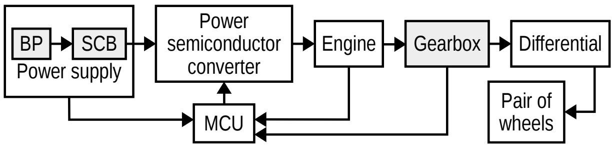

Fig. 1. Functional diagram of electric vehicle electric drive

The power system contains the main power source – BP and connected in parallel supercapacitor battery (SCB) for the regeneration of the braking energy.

This scheme contains one electric motor, which transmits energy to the wheels using a mechanical differential. As a power electronic unit, an inverter is used. It converts the DC voltage of the battery into an AC supply. While braking, it goes into rectification mode to recover energy into the SCB. The control unit of the inverter implements the PWM principle.

The signals generated when the acceleration and brake pedals are goes to the input of the electronic control unit of the inverter and then to the power electronic converter that controls the operation of the electric machine part of the drive. It is assumed that the mechanical part of the car remains unchanged. The gearbox, front-wheel drive, as well as data on the required torque at start-up are stored. The advantage of this scheme is the possibility of using recuperative operation modes of the ED, which ensure the return of the braking energy into the SCB and its further use during further acceleration. Such modes occur with prolonged descents, as well as braking, which are especially frequent in the urban cycle of motion. Figure 2 shows a simplified schematic electrical diagram of the power part of the electric drive of an electric vehicle.

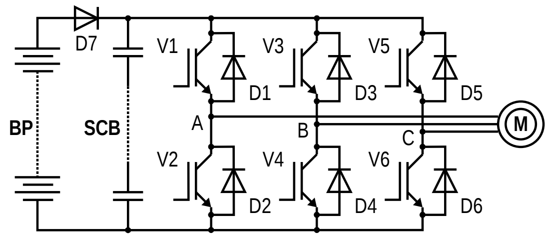

Fig. 2. Schematic diagram of the power part of the electric drive electric vehicle

In this scheme, the BP is a rechargeable battery that acts as a source of electricity. In the propulsion mode, the PI is powered by a battery of accumulators, modulating the three-phase sinusoidal voltage for the motor. Some of the kinetic energy of the motion being converted into an electromagnetic one and accumulating in the inductance of the stator circuit. While switching to braking mode, the PI enters the rectifier mode. The rectified current enters the SCB, charging it with electrical energy. At the same time diode D7 prevents the charging current, reaching 300 A, from flowing through the BP. The charging process is accompanied by a decrease in the electromagnetic energy in the inductance, raising the voltage on the SCB.

After the end of the braking mode and the transition to driving mode, the electric energy for the electromobile movement is first taken up from the SCB until its voltage is equal to the voltage of the BP, after which it comes into work.

The values of the motor and braking torques of the electric drive are set by the microprocessor controlling the state of the keys of the PI, and are determined by the position of the acceleration pedal.

The required capacity of the SCB is determined from the condition:

$$E_{SCB} \geq (E_K + \Delta E_P - A_{fr}) \cdot \eta_{ED}, \qquad (2)$$

where E_K – kinetic energy before braking, *J*;

ΔE_P – change in potential energy, *J*;

A_{fr} – work done to overcome frictional forces on the road and air resistance, *J*;

η_{ED} – efficiency of the electric drive, $\eta_{ED} \leq 90\%$.

$$E_k = \frac{m V_{\text{in}}^2}{2}, \qquad (3)$$

where V_{in} – initial speed of movement, m/s.

$$\Delta E_P = m \cdot g \cdot \Delta h, \qquad (4)$$

where Δh – change in altitude above sea level, m.

$$A = \int_0^{S_T} (F_{fr} - F_{fact})\, dS, \qquad (5)$$

where S_T – stopping distance, m;

S – coordinate of the path, m.

Calculations from relations (2) ÷ (5) showed that for an electric vehicle weighing 1500 kg, taking into account possible long runs, a SCB of about 2.75 F is sufficient at a maximum voltage of 600 V, which corresponds to 500 kJ.

The computer model of the system shown in Fig. 3, is built according to the functional scheme (Figure 1) in the Matlab package and is compiled on the standard elements of the SimPowerSystems library.

The model consists of the following main blocks:

– Power supply system;
– Inverter (IGBT-Inverter);
– Asynchronous motor;
– Control system;
– Load torque forming unit;
– Transmission;
– Measuring unit;
– Parameter initialization block.

The results of simulation of acceleration, steady-state motion and regenerative braking of an electric vehicle while driving on a flat road (α = 0) are shown in Fig. 4, 5.

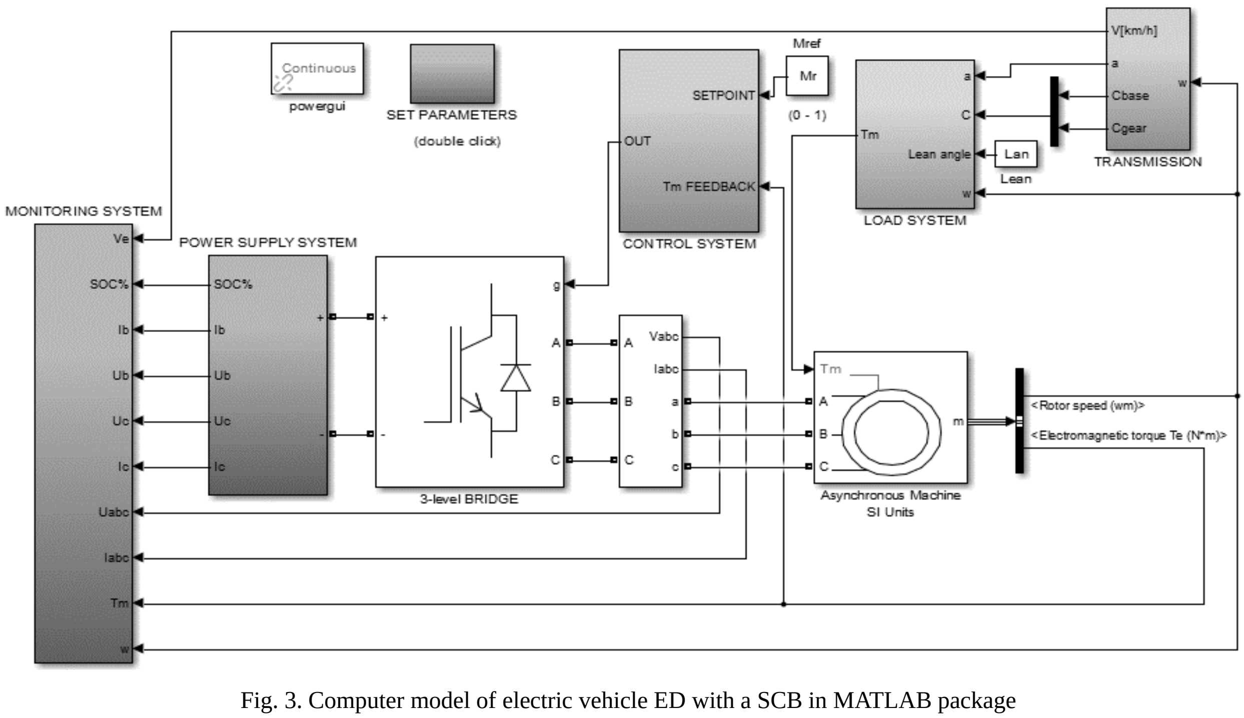

Fig. 3. Computer model of electric vehicle ED with a SCB in MATLAB package

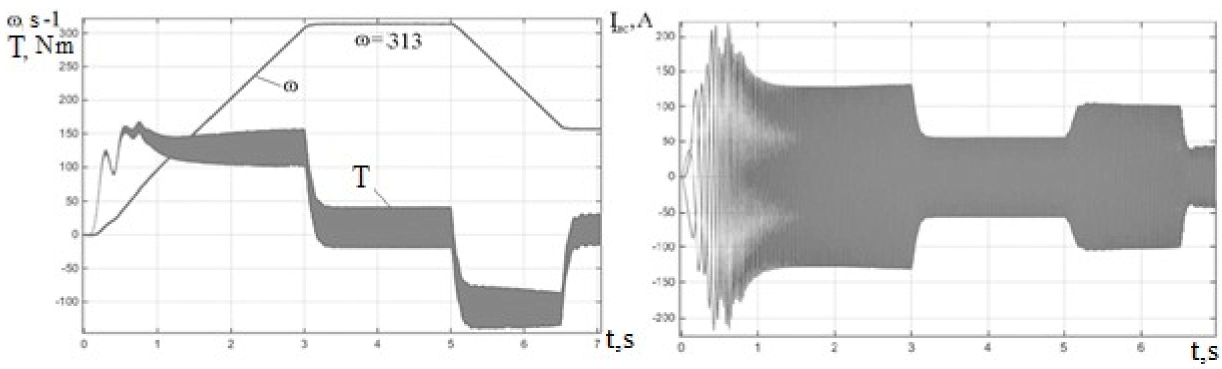

Fig. 4. Acceleration and regenerative braking of an electric vehicle at α = 0

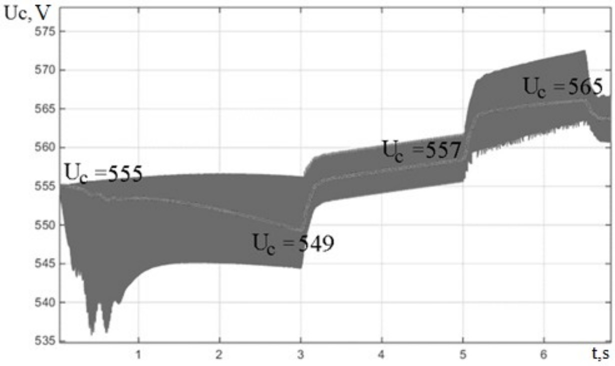

Fig. 5. Voltage at the SCB of an electric vehicle at α = 0

To enter the recuperative mode, the speed of the AM must exceed the idle speed. Frequency control, which is used in this system, allows to change the idle speed in the whole range of speed control, which allows to realize regenerative braking at any initial and final speeds.

The voltage on the SCB when moving with α = 0 is shown in Fig. 5

The results of simulation of acceleration, steady-state motion and regenerative braking of an electric vehicle when driving on an declined road (downward movement with α = -200) are shown in Fig. 6, 7.

In this mode, an additional force acts on the electromobile, proportional to the sine of the slope of the road and directed along the movement of the electric vehicle, which means that the torque formed by this force will be subtracted from the load torque. In steady-state motion, the value of this force exceeds the total load torque due to the fact that the dynamic component of the load torque is equal to zero. From the above, we can conclude that the energy will be recovered into the SCB, even during the steady-state traffic. Voltage on the SCB during descent (α = -20°) is shown in Fig. 7th

From the graphs of transient processes it is seen that during braking the voltage of the SCB on the corresponding section increases, which indicates the presence of energy recovery. When braking in a fixed transmission to half the rated speed of the engine, the saved energy is about 40 kJ (braking was carried out at the maximum speed of the electric vehicle in the first gear).

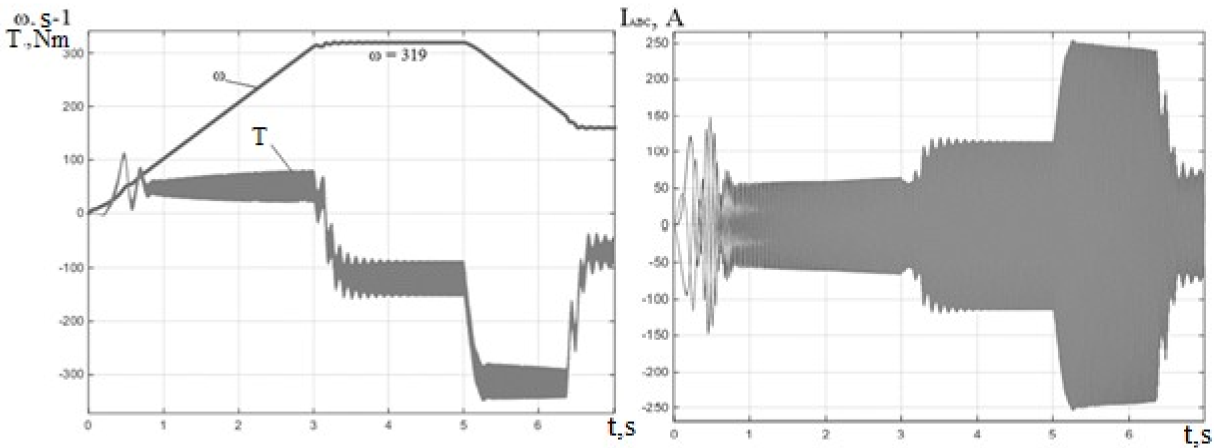

Fig. 6. Acceleration and regenerative braking of an electric vehicle at α = -20°

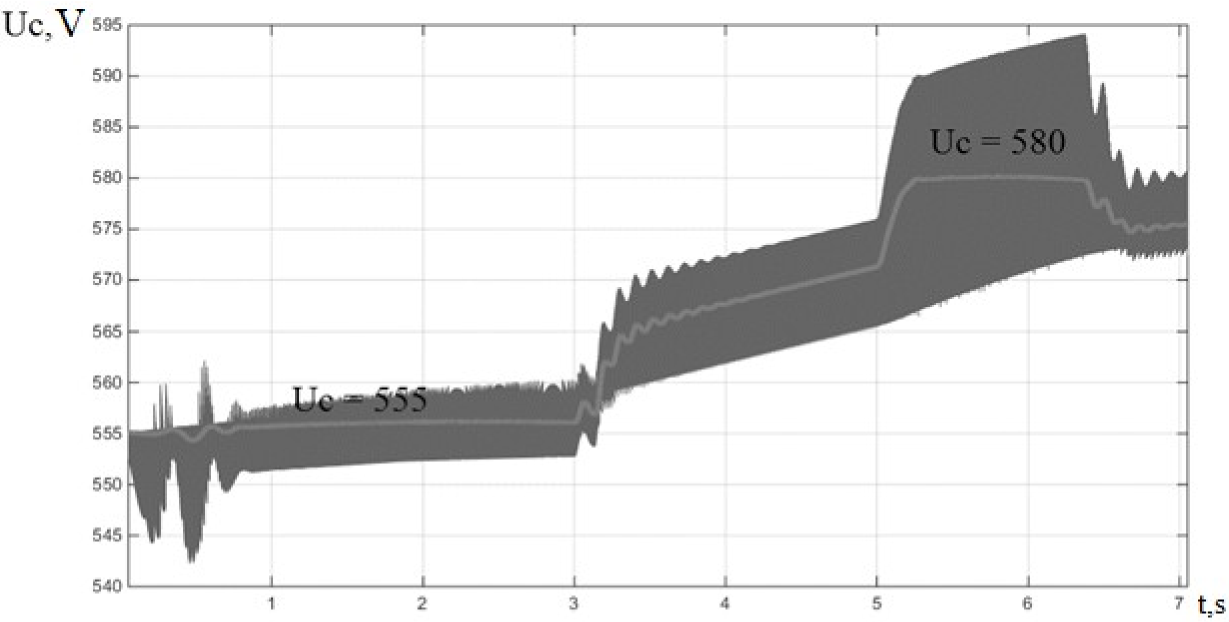

Fig. 7. Voltage at the SCB of an electric vehicle at α = -20°

Conclusions. The results of computer modeling showed the adequacy of the mathematical model to physical processes at various stages of the movement, confirmed the effect of energy recovery in brake modes, and also made it possible to draw a conclusion about the expediency of developing a power circuit of an electric drive using buffer energy storage devices in the form of supercapacitors. Numerical calculations of the energy saved by recuperative braking were also carried out.

As a result, a mathematical computer model is obtained that adequately reflects the nature of the processes in a real electric vehicle [5], [6], [7].

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Відомості про авторів / Сведения об авторах / About the Authors

Воробйов Богдан Віталійович (Воробьёв Богдан Витальевич, Vorobiov Bohdan Vitaliyovich) – Національний технічний університет «Харківський політехнічний інститут», аспірант кафедри автоматизованих електромеханічних систем; м. Харків, Україна; e-mail: volt.education@gmail.com