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STUDY INTO ENERGY EFFICIENCY OF THE DRIVE OF ELECTRIC VEHICLES WITH AN INDEPENDENT POWER SUPPLY DEPENDING ON THE CONFIGURATION OF THE POWER SOURCE

Об'єктом даного дослідження є електричний транспортний засіб з автономним джерелом живлення. На сьогодні подібні транспортні засоби займають все більшу нішу на автомобільному ринку, витісняючи своїх конкурентів з двигуном внутрішнього згорання за рахунок вищої енергетичної ефективності. І хоча ця перевага над транспортом з двигуном внутрішнього згорання є очевидною, з точки зору електричних систем ККД електромобілів залишається доволі невисоким. Проблемним місцем, яке накладає ці обмеження, є джерело живлення – літій-іонний акумулятор – який має значний внутрішній опір.

Для усунення цього недоліку на прикладі приводу електроскутера з асинхронним двигуном з короткозамкненим ротором досліджувалась схема з підключенням паралельно до акумулятора батареї суперконденсаторів. Суперконденсатори мають значно менший внутрішній опір і тому беруть на себе основне миттєве навантаження при перехідних процесах: розгоні та гальмуванні, коли через джерело протікають найбільші струми.

Дослідження показали, що подібна конфігурація покращує енергетичну ефективність транспортних засобів. Причому існує оптимальне значення необхідної ємності суперконденсатора для досягнення найбільшої ефективності (найменшого споживання енергії). Це пов'язано з тим, що батарея суперконденсаторів є доволі габаритним об'єктом і суттєве збільшення ємності призводить до збільшення маси транспортного засобу і відповідно до збільшення споживання енергії. Додатково була досліджена покращена система живлення, в якій суперконденсатор пришвидшено заряджається під час пауз руху транспортного засобу. Вона дозволила покращити вже отримані результати, ще зменшивши споживання електричної енергії.

У порівнянні з проведеними раніше дослідженням було показано важливість правильного вибору ємності суперконденсаторів та системи контролю живлення. Була доведена наявність точки оптимуму та чисельно продемонстрована різниця показників споживання енергії в цій та в інших точках.

Ключові слова: *система приводу електроскутера, літій-іонний акумулятор, паралельне з'єднання суперконденсатора та акумулятора, міський їздовий цикл.*

1. Introduction

Current trend in the transportation industry demonstrates that electric automobiles that have rapidly developed recently are gradually displacing their analogs driven by the internal combustion engine as they are more energy efficient and environmentally friendly. Economic approach when selecting a vehicle shows that the higher

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purchase price of electric cars will be justified by much less fuel cost. However, from the standpoint of electromechanical systems, the drive of electric cars is still rather low in terms of performance efficiency. This is linked to the fact that in addition to losses in the engine, there are also significant losses in the power source. Therefore, it is a relevant and promising task to study the improvement of energy conversion efficiency in the drive of electric transportation vehicles.

2. The object of research and its technological audit

The object of this research is the drive of electric vehicles with an autonomous power source.

A typical source of energy in electric vehicles is the lithium-ion or lithium-polymer batteries, which have high indicators of specific energy. There are several options when choosing an electromechanical converter for the drive; however, despite a number of proposals, the induction motor (IM) with a squirrel cage rotor has steadily occupied a top place among the manufacturers of electric cars. Control over such a drive is executed using a pulse width modulator (PWM) that operates on the system of vector control.

Such a configuration of the electric drive has significant drawbacks: the lithium-ion battery has a high internal resistance, which significantly limits the starting current, weakens the dynamics of transportation and increases energy loss. It is possible to solve these problems by connecting, in parallel to the accumulator, a battery of ultracapacitors, since the latter have a significantly less active resistance than the lithium-ion batteries and are less sensitive to shock currents. However, ultracapacitors bring along additional volume and weight that a vehicle has to carry, which would lead to additional energy consumption.

3. The aim and objectives of research

The aim of this study is to estimate the effectiveness of using parallel connection between a battery and an ultracapacitor to power the electric drive of a vehicle based on the induction motor with a squirrel cage rotor.

To accomplish the aim, the following tasks have been set:

1. To create a model to study the electric drive of vehicles and to choose an objective indicator for energy efficiency.

2. Based on the created model, examine the selected energy efficiency indicator for drive systems with a different capacity of ultracapacitor and without it at all. To analyze this study.

3. Based on the study analysis, determine whether it is possible, by changing only the configuration of a power supply system, to achieve additional improvement in energy efficiency.

4. Research of existing solutions of the problem

The idea of using ultracapacitors in parallel with batteries has been proposed in a number of studies. In paper [1], authors examined the effect which such a connection would exert on the battery when working for a standard load, not taking into account the peculiarities of the electromechanical energy transducer. Papers [2, 3] demonstrated the effectiveness of such a connection when operating in electric motors, but without indicating specific vehicles. More detailed study into such a system was reported in papers [4, 5]. These studies prove the effectiveness of a given connection in hybrid vehicles. However, the power system of hybrid vehicles is very different from that of electric ones with an independent supply, which is why the described benefits of using ultracapacitors in hybrids did not prove their presence when used in electric vehicles as shown in papers [6, 7]. However, only for the drives with DC engines that at present are rarer than the drives with induction engines as demonstrated in paper [8].

Articles [9, 10] reported studies into the system of independent power supply of electric vehicles with a ultracapacitor using a tram as an example, which has its own peculiarities compared to electric cars. In addition, these papers focused solely on the power source, while the electromechanical transducer of energy was disregarded.

The present paper estimates energy consumption efficiency by a vehicle, which employs as the electromechanical energy transducer the induction motor with a squirrel cage rotor, for different configurations of power source: with ultracapacitors of varying capacity and without them.

5. Methods of research

The study was carried out based the following parameters of the elements of a vehicle:

– electric scooter, type Genata Gtle 250 (China): maximum speed – 55 km/h, maximum travel distance – 80 km at a speed of 30 km/h, weight – 45 kg, maximum load – 150 kg;

– two induction motors with the squirrel cage rotor M2AA 080 C2 manufactured by ABB (Sweden), which operate in parallel with a rated power of 1.1 kW, a power voltage of 230/400 V, a frequency of rotation of 2,870 rpm, with performance efficiency of 80.6 % each;

– a battery of lithium-ion batteries Honcell HCP603650NZC (China): rated voltage – 370 V, capacity – 1.25 A·h, internal resistance 13 Ohms, weight – 2.1 kg;

– a battery of ultracapacitors Nesscap ESHSR-0100C0-002R7 (South Korea), composed of 136-consistently connected elements whose capacity varies for different study points within 25–200 F per one element.

To simulate the electric drive, we constructed a model in the software package Matlab/Simulink, shown in Fig. 1.

Some units and circuits aimed to display the calculated magnitudes are not indicated in Fig. 1 to improve its visibility.

To objectively assess energy efficiency of the circuit, we adopted the standard norms for the evaluation of energy efficiency of vehicles, specifically the UN/ECE Elementary Urban Cycle in line with the standards of the European Union (Fig. 2). This cycle reflects the character of motion of a vehicle in a city and best describes the load on the examined electric scooter.

The dependence of speed on time of the urban cycle is used to assign speed for the PWM vector control.

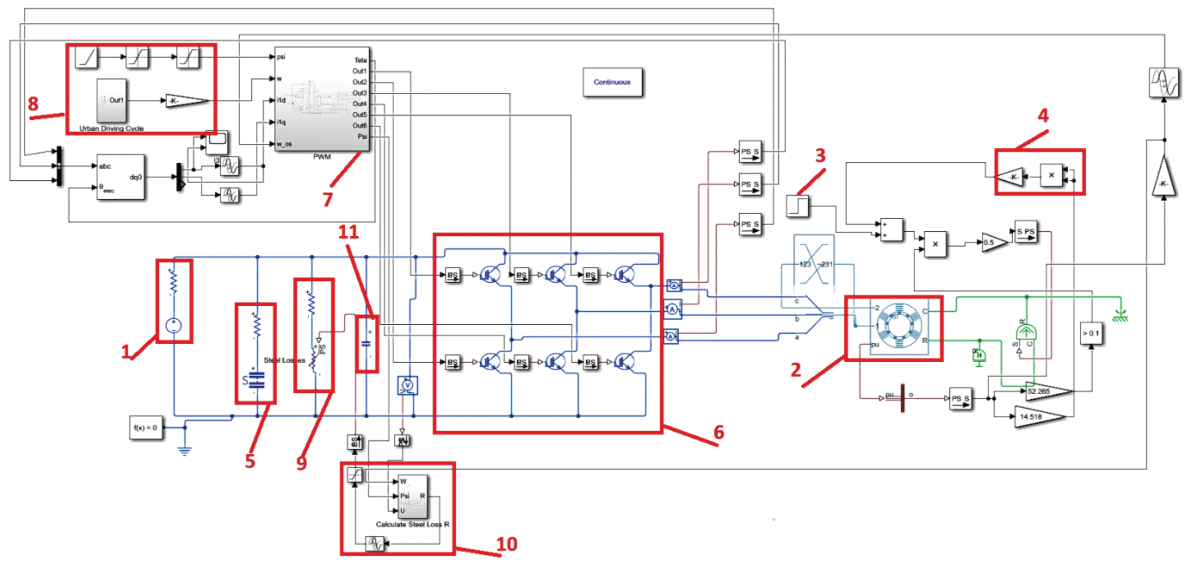

Fig. 1. Model of the electric scooter drive in the software package Matlab/Simulink:
1 – lithium-ion battery; 2 – induction motor (IM) with squirrel cage rotor; 3 – unit for setting the constant momentum of load (rolling friction force); 4 – circuit for calculating the resistance momentum, proportional to the square of speed (air resistance force); 5 – battery of ultracapacitors (can be disabled); 6 – electronic transducer based on IGBT-transistors; 7 – unit of vector control over converter; 8 – units for setting the speed and magnetic current for vector control; 9 – model to account for the magnetic losses in IM; 10 – unit for calculating magnetic losses in IM; 11 – capacitive filter of the converter from the source side

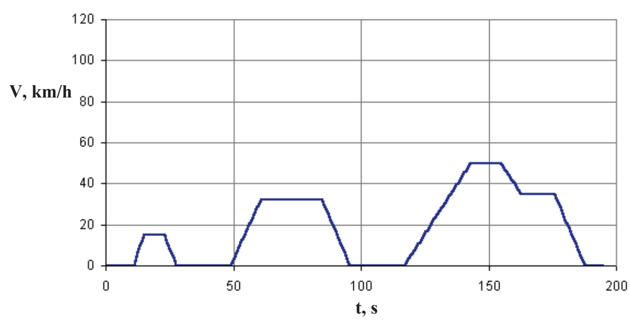

Fig. 2. The UN/ECE Elementary Urban Cycle

6. Research results

When performing an elementary urban cycle, the engine runs under a repeated-short-term mode. The specificity is the elevated load at acceleration and deceleration caused by a high reduced moment of inertia by the electric scooter. Fig. 3 shows a a dependence chart of the power consumed on time when the drive is operated under such a load without ultracapacitor.

Fig. 3 shows that the largest electric energy consumption and, accordingly, the largest losses, are observed during acceleration of the vehicle. Connecting a ultracapacitor would allow it to «take over» the load during acceleration and to perform more effective recuperative braking. It is obvious that it would improve the performance efficiency of the electric drive and reduce electric energy consumption.

The greater the capacity of an ultracapacitor, the more energy will remain in it upon engine acceleration, thus the efficiency of the electric drive must be greater. A study into performance efficiency was conducted for batteries of ultracapacitors with varying capacity. They all consisted of 136 elements, connected consistently, in order to establish the rated voltage of the battery of 370 V.

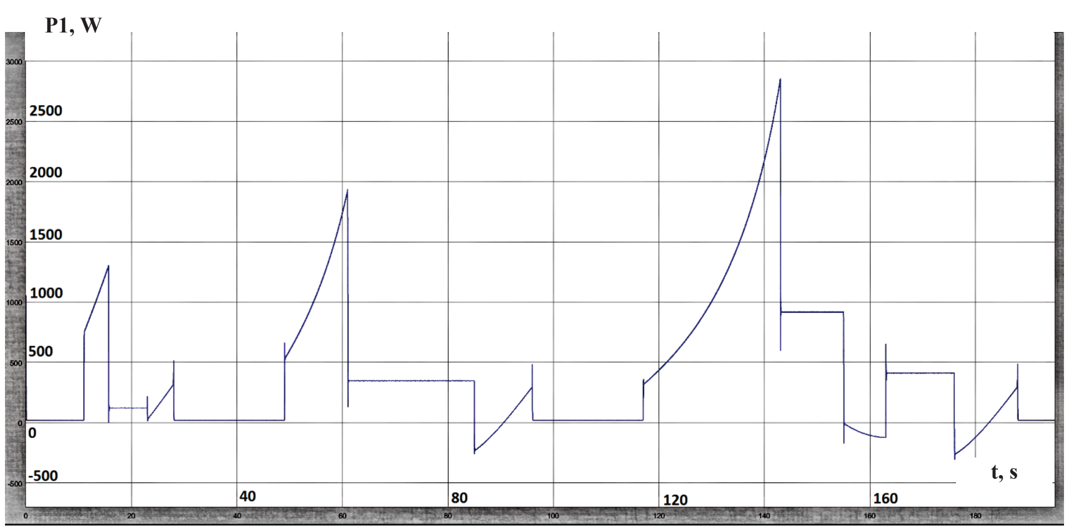

Fig. 3. Time dependence of power consumed by the electric scooter, powered by a source without ultracapacitor

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However, we changed the capacity (and together with it the active resistance and weight) of the separate item. Research results are given in Table 1 and Fig. 4.

Table 1

Dependence of the electric drive's performance efficiency on capacity of a single ultracapacitor

s, F	Efficiency
0	0.4004
50	0.4167
75	0.4203
100	0.4224
125	0.4231
150	0.4237
200	0.4237

Fig. 4 shows that the use of a ultracapacitor makes it possible to improve the averaged performance efficiency of the electric scooter from 40 % to 42.4 %. This result fully confirms the above assumptions. However, it is worth noting that performance efficiency is not a principal parameter when examining transportation vehicles. The point is that when calculating it, the «useful» load includes overcoming the resistance force of a vehicle. In this case, an increase in the mass of the vehicle leads to that this resistance grows, thereby increasing its «payload». Therefore, the energy consumed per cycle is a more objective indicator.

For the same parameters, we studied the energy consumed over an elementary urban cycle with respect to an increase in the mass of a vehicle due to the addition of a battery of ultracapacitors to it. The results are given in Table 2 and in Fig. 5.

Table 2

Dependence of the electric drive's consumed energy on capacity of a single ultracapacitor

S, F	W1, J
0	75.638
50	73.223
75	72.906
100	72.695
125	72.888
150	73.009
200	73.473

It follows from Fig. 5 that there is a certain value of capacity at which the consumption of electricity by a vehicle is minimal. For a given electric scooter, it is 100 F per one element, or 0.735 F per a battery. At a smaller capacity, the ultracapacitor is discharged too much when accelerating, thereby increasing the losses related to its recharging during further work of the electric drive. At a larger value, the effect of improved performance efficiency decreases with an increase in capacity, while the mass of a vehicle becomes larger; therefore, energy consumption grows.

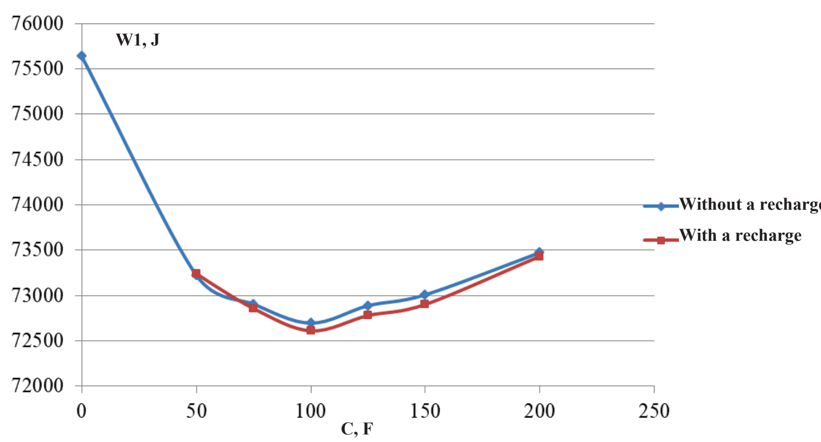

Fig. 5. Dependence of the electric drive's consumed energy on capacity of a single ultracapacitor

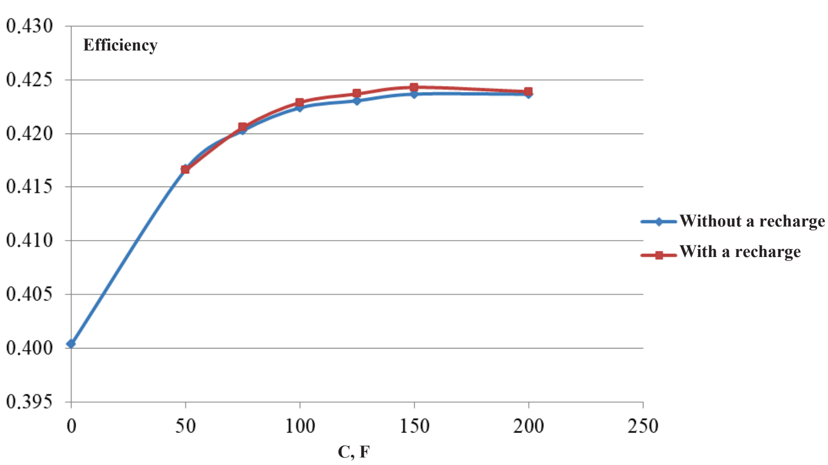

Fig. 4. Dependence of the electric drive's performance efficiency on capacity of a single ultracapacitor

Fig. 6 shows a change in voltage at ultracapacitor over time (when the capacity of the element is 100 F).

Fig. 6 shows that during pauses in motion the ultracapacitor does not have enough time to recharge to its starting value, which is why the subsequent acceleration occurs at the lowered value of the starting voltage. This leads to a reduction in the efficiency of the electric drive. To eliminate this drawback, we proposed a circuit that allows the ultracapacitor to evenly recharge during pauses lasting for 20 seconds (which corresponds to the averaged pauses during a vehicle motion in a city) until reaching its rated value. Fig. 7 shows the dynamics of voltage at a ultracapacitor for this case.

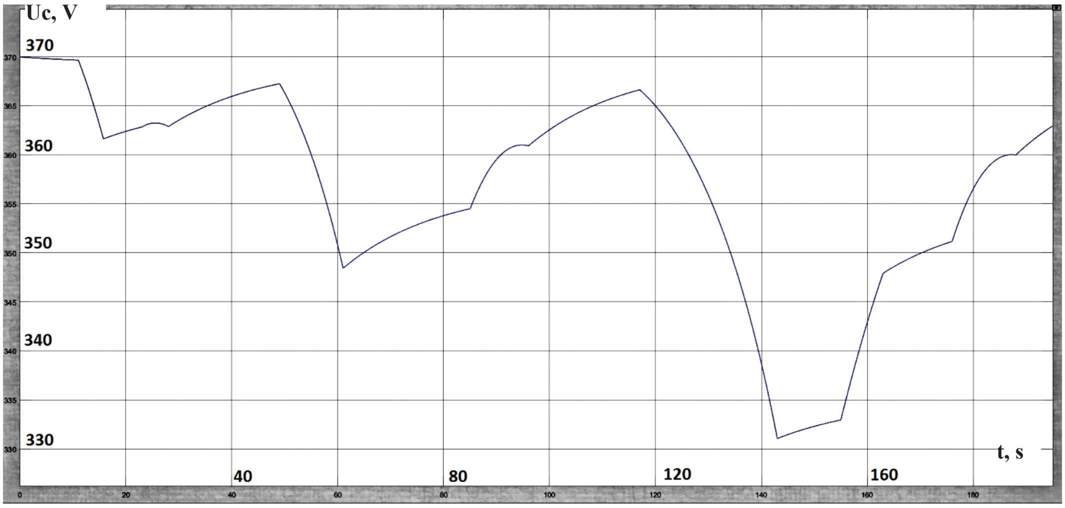

Fig. 6. Voltage dependence at ultracapacitor on time with a capacity of a single element of 100 F

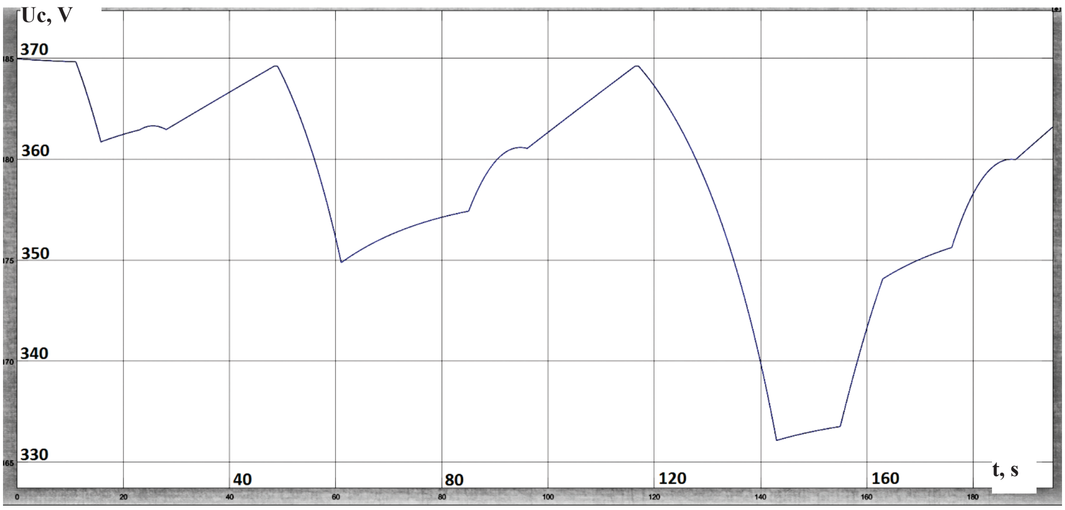

Fig. 7. Dependence of voltage at ultracapacitor on time with a capacity of a single element of 100 F when using a recharging system for the ultracapacitor during pauses in motion

To assess the effectiveness of a given system, we conducted a study with the results given in Table 3 and shown in Fig. 8.

Table 3

Dependence of consumed energy on capacity of the ultracapacitor element when using a recharge system and without it

s, F	W1, J		dW, %	
	Without a recharge	With a recharge	Without a recharge	With a recharge
0	75.638	–	–	–
50	73.223	73.239	3.19	3.17
75	72.906	72.856	3.61	3.68
100	72.695	72.610	3.89	4.00
125	72.888	72.779	3.64	3.78
150	73.009	72.902	3.48	3.62
200	73.473	73.432	2.86	2.92

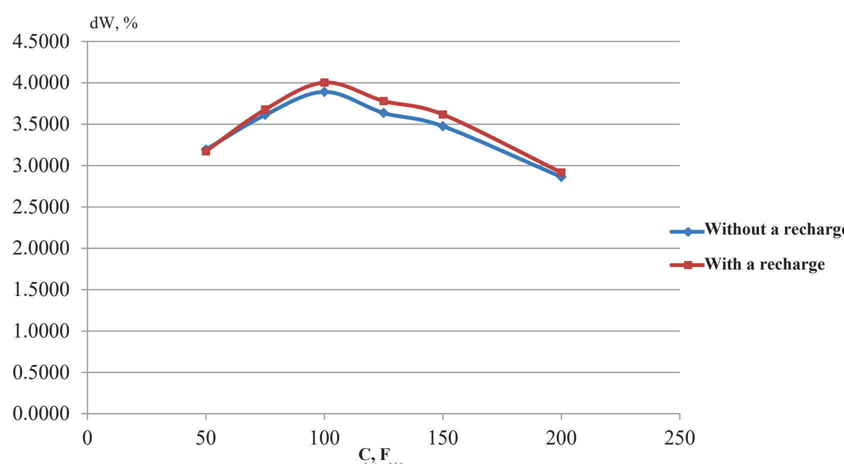

Fig. 8. Dependence of a decrease in the consumed energy compared with the case without the use of a ultracapacitor on capacity of the element using a recharge system and without it

The research results (Fig. 8) show that the use of a recharge system makes it possible to slightly reduce the consumption of electric energy by a vehicle when applying a ultracapacitor. Note that this system does not require the installation of additional large-scale force elements.

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7. SWOT analysis of research results

Strengths. Our study has shown that using the parallel connection of a ultracapacitor and a battery as a power source for electric vehicles makes it possible to reduce energy consumption by 4.0 % compared with power solely from a battery provided the right choice of the source configuration.

Weaknesses. Reducing energy consumption is not the only role taken by the ultracapacitor in the electric drive. Others include the improved vehicle dynamics and protection of the battery from overload currents. And although it only highlights the strengths of such a connection, multitasking complicates the choice of the optimal configuration, which in the present work has been studied exclusively from the energy point of view.

Opportunities. This study allows us to substantiate choosing the capacity of a ultracapacitor for electric vehicles and opens the way for the economic evaluation of a given system. In addition, it is promising to investigate the optimum when taking into account the additional tasks for the ultracapacitor mentioned above: the improvement of vehicle dynamics and protecting the battery from overload.

Threats. Even though that from the point of view of energy efficiency this system is absolutely necessary, there is no guarantee that it would be strong enough to convince an average consumer since most of the vehicles are driven by private owners. The availability of an additional system to control distributed power is an additional consistent element in the chain of reliability. And while on the one hand a ultracapacitor improves the reliability of the source by prolonging the lifecycle of a battery, the additional system that might fail could possibly be disliked by potential consumers.

8. Conclusions

1. In the course of this study we applied the software package Matlab/Simulink to create a model of the electric scooter based on the induction motor with a squirrel cage rotor, powered by a parallel connection between a lithium-ion battery and a ultracapacitor, with the possibility to adjust capacity or disable the ultracapacitor. To assess energy efficiency of such a system, we tested the model according to the UN/ECE Elementary Urban Cycle; the indicator of energy efficiency was the energy consumed per a cycle.

2. An analysis of the computer model that we performed has revealed that the use of a ultracapacitor by itself reduces the consumption of electric energy by the magnitude above 2.9 %. Moreover, to improve energy efficiency there is the optimal capacity of a ultracapacitor at which energy consumption is reduced by 3.9 %. Study has shown that it is not always that an increase in capacity leads to the improvement of efficiency, since, along with capacity, there is a growth in the mass of a vehicle. Thus, we have demonstrated the importance of a correct choice of the required source configuration.

3. We have proposed a power distribution system, in which a ultracapacitor is charged faster during pauses in motion. This system has helped improve energy savings of up to 4.0 %.

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