


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

Ob’ektom danyh doslidzhennia є електричний транспортний засіб з автономним джерелом живлення. На сьогодні подібні транспортні засоби займають все більшу нішу на автомобільному ринку, витіснюючи своїх конкурентів з двигуном внутрішнього згорання. І хоча ця перевага над транспортом з двигуном внутрішнього згорання є очевидною, з точки зору електричних 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 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 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 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 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 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 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 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 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 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 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 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 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 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 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 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 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 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 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 своїх конкурентів з двигуном внутрішнього згорання за рахунок вищої енергетичної ефективності.

**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
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 Gte 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.
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 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.
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.

![Fig. 4. Dependence of the electric drive’s performance efficiency on capacity of a single ultracapacitor](image1)

Fig. 4 shows that the use of an 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.

![Fig. 5. Dependence of the electric drive’s consumed energy on capacity of a single ultracapacitor](image2)

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. 6 shows a change in voltage at ultracapacitor over time (when the capacity of the element is 100 F).](image3)

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 an ultracapacitor for this case.
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

<table>
<thead>
<tr>
<th>C, F</th>
<th>W1, J Without recharge</th>
<th>dW, % Without recharge</th>
<th>With a recharge</th>
<th>dW, % With a recharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>75.658</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>50</td>
<td>73.223</td>
<td>73.239</td>
<td>3.19</td>
<td>3.17</td>
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<tr>
<td>75</td>
<td>72.916</td>
<td>72.858</td>
<td>3.61</td>
<td>3.68</td>
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<tr>
<td>100</td>
<td>72.695</td>
<td>72.610</td>
<td>3.89</td>
<td>4.00</td>
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<tr>
<td>125</td>
<td>72.858</td>
<td>72.779</td>
<td>3.64</td>
<td>3.78</td>
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<tr>
<td>150</td>
<td>73.009</td>
<td>72.902</td>
<td>3.48</td>
<td>3.62</td>
</tr>
<tr>
<td>200</td>
<td>73.473</td>
<td>73.452</td>
<td>2.86</td>
<td>2.92</td>
</tr>
</tbody>
</table>

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.
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 %.

References


Ostroverkhov Mykola, Doctor of Technical Sciences, Professor, Head of the Department of Theoretical Electrical Engineering, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: n.ostroverkhov@hotmail.com, ORCID: http://orcid.org/0000-0002-7322-8052

Trinchuk Danylo, Postgraduate Student, Department of Theoretical Electrical Engineering, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: d.trinchuk@gmail.com, ORCID: http://orcid.org/0000-0001-6022-9323