Development of a method for regenerative braking of an electric scooter

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ABSTRACT

In this work, a method of regenerative braking of an electric scooter was developed. Regenerative braking of electric vehicles is the basis for energy saving cars and environmental protection. A stand was made for the study of a magnets and an ionistor. In the proposed method, an ionistor is additionally connected in parallel to the battery, which charges faster than the battery, so the process of accelerating the electric vehicle after stopping also occurs faster. It should also be noted that if emergency braking is necessary to stop an electric vehicle, the driver can press the brake pedal and stop the car using brake pads. The paper investigates the method of the element base for the vehicle, as well as control. To develop this study, an electric scooter was chosen as an electric vehicle model. The dependences of the electric current on the operating time of the ionistor in three positions are determined. During the actual speed of the electric scooter corresponds to the controlled speed.

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1. INTRODUCTION

In recent years, conservation, and environmental protection, development of electric matter of serious. A clean electric car with four independent driving wheels, which thanks to four wheels can be controlled not only independently, but also accurately, is being studied especially extensively. Thus, regenerative braking has become a key technology of electric consumption increasing travel distance.

A regenerative braking system for a hybrid electric vehicle (HEV) based on an automatic transmission (AT) was developed and an algorithm for joint control of regenerative braking was proposed in [1]. A braking control scheme was developed using model predictive control (MPC) as shown in [2]. Various goals allow you to achieve maximum recovery during braking. The optimal control of the sliding coefficient is used, based on the sliding mode, which allows you to get the shortest braking distance. According to [3], methods for controlling the electric braking of the load are calculated, in which the occurrence of a slip lock in vehicles increases the time of pressing the brake. The article [4] explain special attention is paid to the creative adapted motor.

Figure 1 shows regenerative braking with one switch. The article [5], [6] provides basic solutions that have recently been influenced by electric vehicles with batteries and the type of traffic schedules encountered. The braking system of an electric vehicle using only electricity was investigated in [7]. Motors/generators are being investigated as drives in which energy can potentially increase. The article [8] presents an approach to modeling the efficiency of vehicles (EV) on the engine as shown in Figure 2.

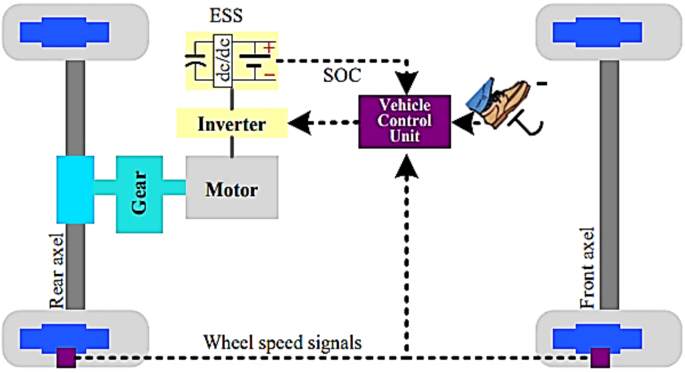

Figure 1. The braking system of an electric vehicle [7]

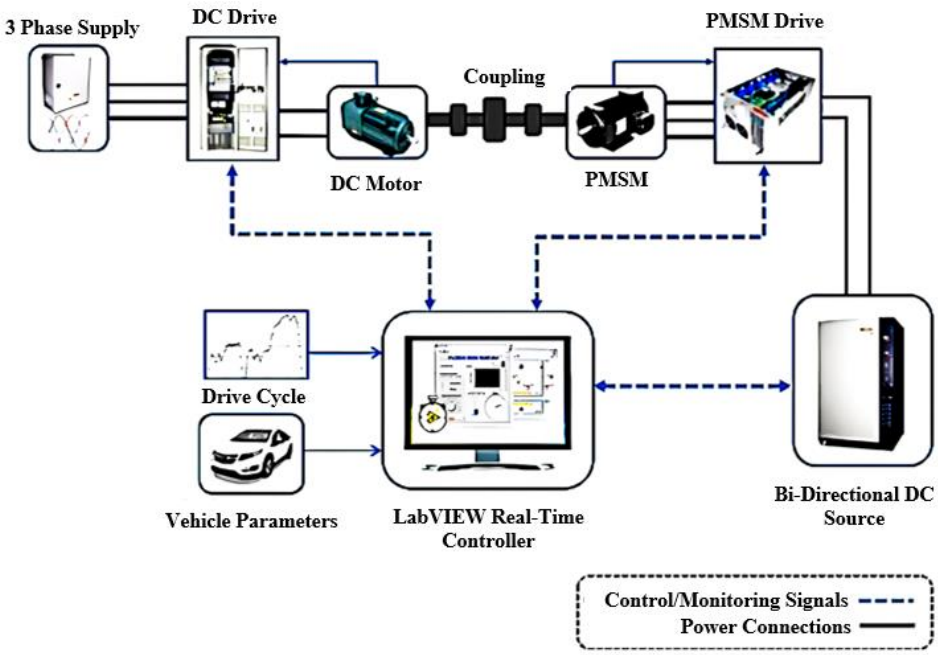

Figure 2. Block diagram of the braking efficiency of electric vehicles [8]

Figure 3 shows dynamic control during regenerative braking. The article [9] describes dynamic braking was determined to a minimum. Figure 4 shows dynamic control during regenerative braking. As we can see from this figure, dynamic control depends on the wheels of the car, as well as on the discs while driving. The article [10] describes the basic concepts of electrical and magnetic circuits that facilitate the use of input diode rectifiers and phase-controlled thyristor converters. The distribution of the driving force on four wheels was investigated on the basis of driving force control as shown in [11] and it is also proposed to preserve the operation of the law on separation. It was also tested using simulation and experiments Figure 4. According to the article [12], a new block diagram of an energy system for electric vehicles was created Figure 5.

A method of optimal sliding coefficient has been developed in [13], providing practically optimal characteristics of anti-slip braking. The article [14] a control engine on wheels has been created. The moments of energy recovery, the wheels from blocking, as well as the braking coefficient of the tire are calculated. The article [15] examined the study of the law of change in the energy of regeneration of brakes of clean electric vehicles exposed to normal and low-temperature environments, as well as various characteristics of the segment. The study shows that the characteristics of the segment strongly correlate with the regeneration energy of the brakes of the car. A during braking, there is an increase in brake regeneration energy. Figure 6 shows the configuration of improved regenerative braking. The control of the temperature in the cabin is the basis of regenerative braking by developing a strategy for predictive control of the hierarchical model (MPC) as shown in [16]. The displacement of the AC load and the heat load of the cab is caused by this fact.

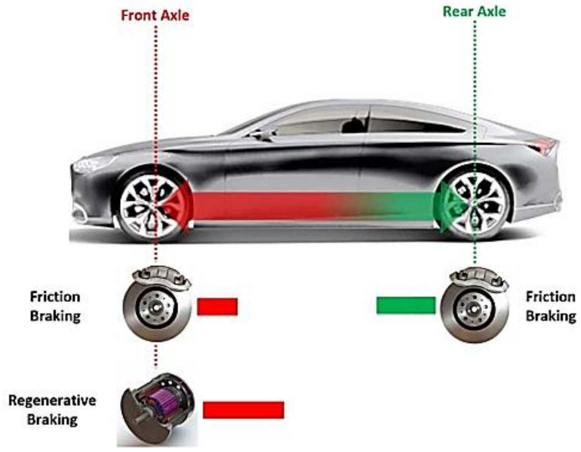

Figure 3. Dynamic control during regenerative braking [9]

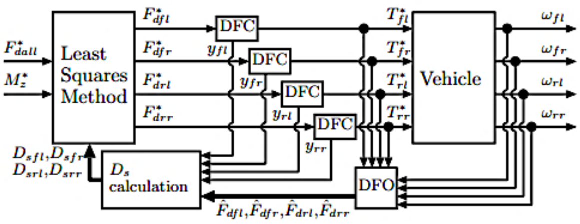

Figure 4. Method of distribution of driving force on four wheels [11]

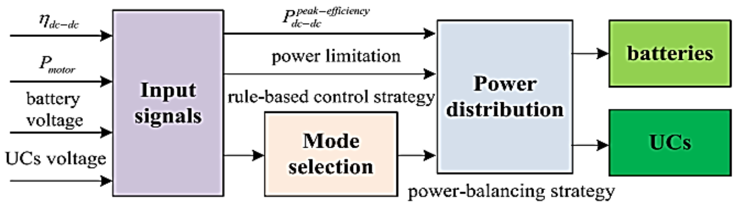

Figure 5. A new block diagram of an energy system for electric vehicles [12]

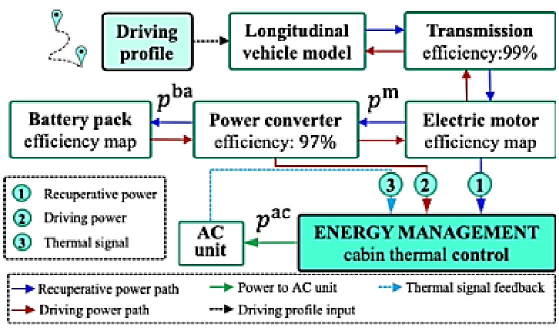

Figure 6. Configuration of an electric vehicle with improved regenerative braking [16]

Figure 7 shows the general scheme. The article [17] explains that a system was developed to increase the driving range of the car and the battery life, where the accumulation of recovery occurs. Cumulative recovery is an aid accumulation system that works in parallel with a car battery. The article [18] presents a new control scheme for regenerative braking. A method of current regulation and a strategy for controlling the use of braking torque was developed. The article [19] presents the development of an algorithm for regenerative braking. In the article [20], a system for the recovery of kinetic energy of vehicle braking was developed. The article [21] presents a new control system based on the field programmable gate array technology, designed to control the power units of multi-motor electric vehicles (EV). The article [22] developed a mathematical and computer model of tire and vehicle dynamics. The article [23] investigated a new motion control for an independent wheel drive. An integrated motion without sensors is being developed in [24], which is synchronized according to its purpose. In the article, an electric car was used, as well as a regenerative braking strategy using a capacitor is described in [25]. In this study, we studied and solved the problem of increasing the speed of regenerative braking and subsequent acceleration of an electric vehicle using the predictive control method for an electric vehicle with a four-wheeled engine.

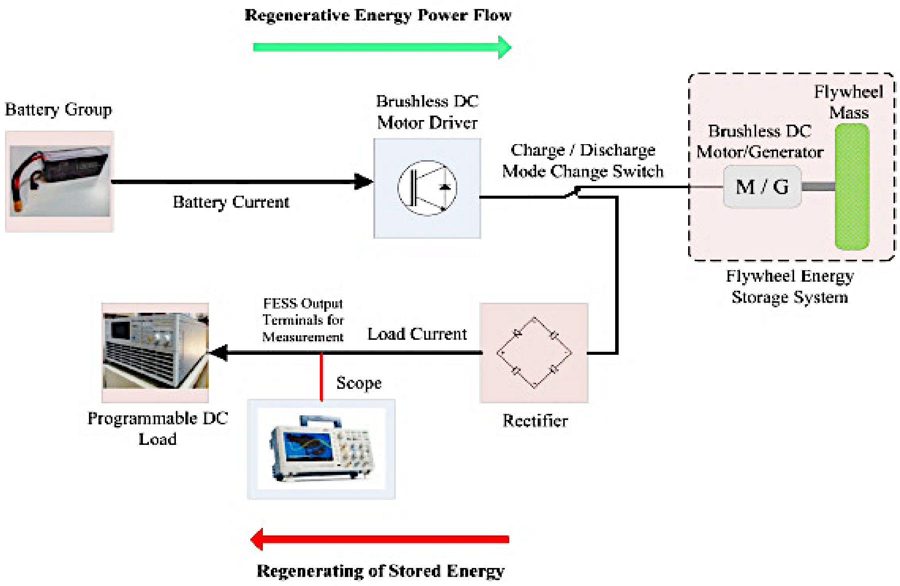

Figure 7. General scheme regenerative energy power flow [17]

2. METHOD

In 2020, a new method of regenerative braking of an electric vehicle was developed and investigated at the Kazakh National Technical University named after K. Satbayev. For the development of this study, an electric scooter was chosen as a model of an electric car. Figure 8 shows scheme of the method of regenerative braking of an electric vehicle. The novelty of this study lies in the fact that an ionistor is additionally connected in parallel to the battery, which charges faster than the battery, and the process of acceleration of the electric vehicle after stopping occurs faster. if emergency braking is necessary to stop the electric vehicle, the driver can press the brake pedal and stop the car using the brake pads. The idea of the proposed model can be understood from the figure shown in Figure 9, which shows the motor–electric motor 1, in which the stator windings during braking, i.e., when the electric motor is turned off, start working as a generator 2. Also shown is the brake 3, which is activated by pressing the brake pedal, the dashboard 4, the electronic contactless switch 5, the ionistor 6 and the battery 7. From Figure 1 it can be seen that the ionistor 6 and the battery 7 are connected to the generator-electric motor in parallel, and when the electric motor is turned off, they are charged from the generator, i.e. from the stator windings of the electric motor at the same time, but the ionistor charges faster due to the fact that its capacity is less than that of the battery and therefore the processes of braking and subsequent acceleration of the electric vehicle occur faster than in the prototype.

Thus, the proposed method of regenerative braking of an electric vehicle allows solving the problem of increasing the speed of regenerative braking and subsequent acceleration of an electric vehicle. The hypothesis is that there is a bank of supercapacitors. The supercapacitors were connected in series to absorb the maximum braking energy, which allows the supercapacitor to be used when the power generated by the engine is cut off, which is about 80% of the total energy. The supercapacitor unit consists of 20 2.7 V and 20 F supercapacitors. Serial connection of several supercapacitors is necessary to increase the operating voltage and decrease the charging and discharging current values. Therefore, the effective voltage is the number of capacitors multiplied by the voltage of one element 54 V and the capacitance 1F. However, the supercapacitor unit is charged from a 220 V battery and will have a battery voltage.

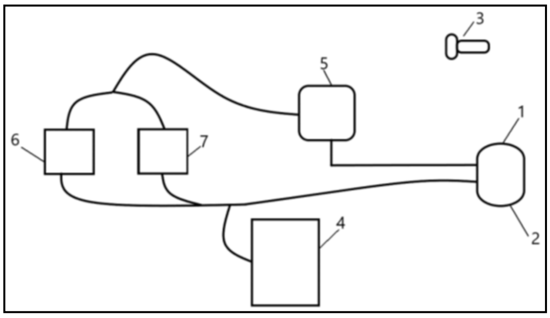

Figure 8. Scheme of the method of regenerative braking of an electric vehicle

Figure 9 shows the element base for the method of regenerative braking of an electric vehicle, where i) Li-on battery of the m365 scooter with a voltage of 36 V and a capacity of 7.8 Ah (ampere hours); ii) H-bridge of the scooter the device allows you to control a DC electric motor of the electric scooter; iii) Assembly of 20 cells of a 48V supercapacitor; iv) H-bridge for the stand; v) Shunt for reading the current consumed by the motor; vi) Constant meter allows you to measure current and voltage; and vii) Scooter control board.

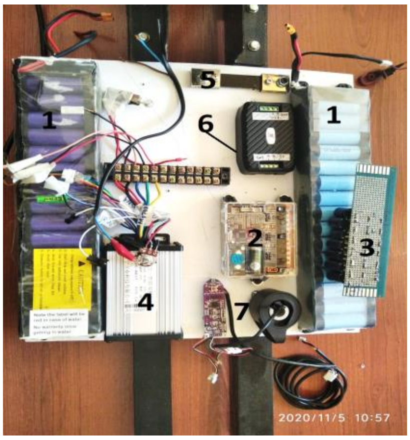

Figure 9. The element base for the method of regenerative braking of an electric vehicle

2.1. Vehicle dynamics model

To develop a method for regenerative braking of an electric vehicle, we will present a model of a control system that includes four main sections: a model of car dynamics, a tire model, an engine model and a battery. If we assume that the forces on the left and right tires are the same, then according to Newton's second law [21], the equations of dynamic behavior of the car during longitudinal and rotational movement of the direction can be expressed as (1) and (2).

$$M\dot{v} = -F_{xf} - F_{xr} - f_{air} - f_{roll} \tag{1}$$

$$J\dot{\omega}_{\omega i} = R_e F_{xi} - T_{bi}, i = f, r \tag{2}$$

Where M and v represent the mass of the vehicle and the longitudinal speed, F_{xi}, F_{xr} are the longitudinal friction force of the tire on the road with the front and rear wheels. Fairy and folk are, respectively, the air resistance and rolling resistance of an electric vehicle, which in this article are considered as zero. J is the inertia of the wheel rotation is the longitudinal rotation speed of the front and rear wheels in radians per second, R_e is the effective rolling radius of the tire in meters, T_{bi} is the front and rear braking torque of the wheels.

Figure 10 shows single-wheel braking model. The friction force of the tire on the road is related to the normal force F perceived by the wheel, which is described by the coefficient of friction μ indicated in (3). Whereas the coefficient of friction μ is a function of the sliding coefficient k.

$$F_{xi} = \mu_i(k)F_{zi} \tag{3}$$

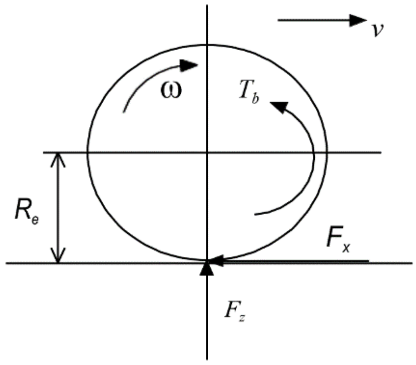

Figure 10. Single-wheel braking model

2.2. Tire model

As a link between the road and the car, tire characteristics directly affect the condition of the car. Packs [22] literature, which contains many parameters and accurately describes the characteristics of the tire [23]. In the magic formula model, the longitudinal front part of the tire non-linear function of the normal force F_{zi} and the sliding coefficient k_i, which is shown in (4):

$$F_{xi} = 2D_x \sin\{C_x \arctan[B_k k_i - E_x\ (B_x k_i - \arctan(B_x k_i))]\} \tag{4}$$

where $B_x, C_x, D_{x,} E_x$- corrodingly, they represent coefficient, their value using model parameters.

$$k_i = \frac{\omega_{\omega i} R_e - v}{v} \tag{5}$$

The normal force F_{zi} can be calculated from the deceleration a_x , as shown in (6) and (7),

$$F_{zf} = \frac{M(l_r g - h a_x)}{l_f + l_r} \tag{6}$$

$$F_{zf} = \frac{M(l_r g + h a_x)}{l_f + l_r} \tag{7}$$

where g: acceleration of free fall, h: distance from the center of mass of the car to the ground, l_f и l_r: the longitudinal distance from the center of gravity to the front and rear axles.

2.3. Engine and battery model

In this study, we assume that each motor-wheel has a torque regulator. The ability to recover maximum engine at the current rotational speed. In this study, the maximum engine speed can reach 1000 rpm, the maximum braking torque is 50 Nm, and the gear ratio g_0 is 2. The main element affecting the ability to recover energy is the efficiency of the engine to the battery η [6], which can be described by (8).

$$\eta = \frac{U_c I_c}{T_{mf}\omega_{mf} + T_{mr}\omega_{mr}} \tag{8}$$

Were U_c and I_c they represent the charging voltage and current of the battery during regenerative braking, and the charging power of the battery P_c can be described by (9), T_{mf} и T_{mr}: accordingly, the absolute value of the braking torque of the engine, ω_{mf} и ω_{mr} — the angular velocity of the electric motor of the front and rear wheels, which can be described by (10).

$$P_c = U_c I_c \tag{9}$$

$$\omega_{mi} = g_0 \omega_{\omega i} \tag{10}$$

Depending on the characteristics of ratio between the motor current I_a and the torque T_m can be described as (11).

$$I_a = \frac{T_m}{C_T\phi} = \alpha T_m \tag{11}$$

Where C_T: engine torque constant, φ: the magnetic flux at the pole of the motor, which in this study is assumed to be constant. Then the energy consumption by the resistance of the motor R, i.e., losses in copper, can be described as (12).

$$P_{loss} = \alpha^2 R T_m^2 \tag{12}$$

In (13) of normal force have the form

$$\frac{F_{zf}}{F_{zr}} = \frac{l_r g - h a_x}{l_f g + h a_x} \tag{13}$$

The braking torque coefficient has the form.

$$K = \frac{F_{zf}}{F_{zr}} = \frac{T_{mf}}{T_{mr}} = \frac{T_{hf}}{T_{hr}} \tag{14}$$

2.4. Dynamic EM model

The total resistance of the vehicle when moving can be expressed by (1):

$$\sum F = F_f + F_w + F_i + F_j \tag{15}$$

where F_f : rolling friction force of wheels, F_w: air resistance force, F_i : lifting resistance force, F_j : acceleration resistance force (inertia force). In (1), the rolling friction force of the wheels and the air resistance force can only affect the lifting force.

2.5. EM braking model

Assumption: the resistance to EM movement is equal to f, and the energy of regenerative braking for recycling can be expressed by (2):

$$E = \frac{1}{2} m V_1^2 - \frac{1}{2} m V_2^2 - f * s \tag{16}$$

where *E*: processed energy (J), V_1: the initial speed of the vehicle (m/s), V_2: the final speed of the vehicle, *s*: braking distance (m), *f*: the force of resistance to the movement of the vehicle (N). According to the equation of motion of the vehicle:

$$m\ddot{x} = (-B - f) \tag{17}$$

where $\ddot{x}$: vehicle acceleration (m/s^2), B: braking force (N), assuming that the body slows down on a flat moving point, the equation of its motion can be expressed as (18):

$$m\ddot{x} = \left(-\frac{P}{\dot{x}} - Gf - \frac{C_D A x^2}{21.25}\right) \tag{18}$$

G: electric vehicle weight, P: braking power. The body accelerates on a flat road, the equation of its motion can have:

$$m\ddot{x} = \left(-Kx - Gf - \frac{C_D A x^2}{21.25}\right) \tag{19}$$

K: the coefficient of resistance of the medium, C_D: air resistance coefficient.
Accordingly, the model of EM dynamics is obtained as (20):

$$\begin{cases} m\ddot{x} = -\frac{P}{\dot{x}} - Gf - \frac{C_D A x^2}{21.25} \\ m\ddot{x} = -Kx - Gf - \frac{C_D A x^2}{21.25} \end{cases} \tag{20}$$

2. RESULTS AND DISCUSSION

As mentioned earlier, the study was conducted in 2020 at the Kazakh National Technical University named after K. Satbayev on an assembled stand for ionistor research. Figure 11 shows a test bench for a drive magnet and an ionistor consists of the following elements; i) A 36 V 350 W permanent magnet synchronous motor, ii) a 36 V 4.4 Ah lithium-ion battery, iii) a driver, iv) an ionistor battery consisting of 20 supercapacitors with a total capacity of 1F and a maximum voltage of 54 V, and v) a data acquisition system. Figure 12 shows an electric scooter. For the development of this study, an electric scooter was selected as an electric vehicle model. This study uses a widely used electric scooter model manufactured by Xiaomi. It weighs 14 kilograms and is equipped with a 250 W BLDC (brushless DC motor) motor. The scooter is equipped with a BLDC motor speed controller with an operating voltage of 36 V and a protective current of up to 21 amperes. It provides direct charging and regenerative braking of the lithium-ion battery. The battery has a rated voltage from 42 V when it is fully charged to 32 V when it is discharged. The supercapacitors were connected in series. Serial connection of several supercapacitors is necessary to increase the operating voltage and decrease the charging and discharging current values. Therefore, the effective voltage is the number of capacitors multiplied by the voltage of one cell of 54 V and the capacity of 1F. However, the supercapacitor unit is charged from a 42 V battery and will have a battery voltage. The supercapacitor operates in the range from the rated voltage to half of this value. For a 42 V voltage source, 256 Ohms of the first resistor and 2200 Ohms of the second resistor were taken. The output voltage in this case will be 0.358 V. The output voltage must be lower than the measuring capabilities of the analog-to-digital converter. If the voltage is higher than 5 V, it can burn it.

The ADC 1015 analog-to-digital converter was used to convert the values of the ACS712 output voltage and the voltage divider circuit. This converter has a 12-bit resolution and 4 inputs, can measure voltage up to 5 V and has an I2C interface. Digital signals from the ADC 1015 were received by the ESP 32 microcontroller. ESP 32 is a 32-bit dual-core processor microcontroller. It has Bluetooth, Wi-Fi interfaces, so data can be received via the Internet or a Bluetooth phone app. Both methods of data acquisition were performed. In the course of experimental work, the characteristics of braking 1 of the IM and the results of the study of the battery current were revealed. Table 1 shows a list of characteristics of electromagnetic braking 1.

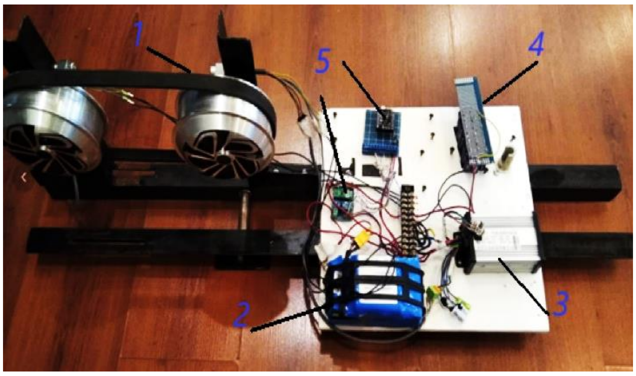

Figure 11. A test bench for a drive based on a synchronous motor with permanent magnets and an ionistor

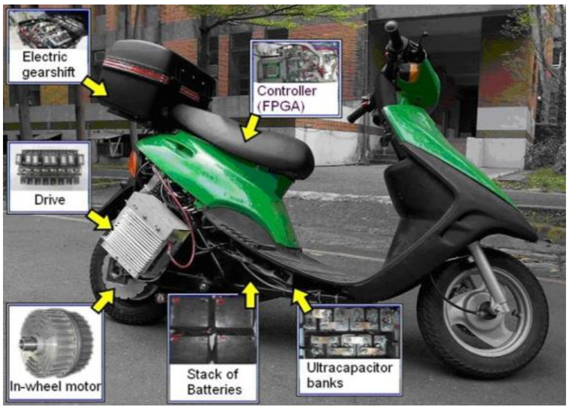

Figure 12. Electric scooter

According to the supercapacitor,

$$E = \frac{1}{2}C(U_1^2 - U_2^2) \tag{21}$$

where E: energy storage supercapacitors (J), C: supercapacitor capacity (F), U_1: supercapacitor voltage after charging (V), and U_2: the voltage of the supercapacitor before charging (V).

$$C = \frac{2E}{U_1^2 - U_2^2} \tag{22}$$

The values of the parameters of the supercapacitor can be taken as follows: $C \approx 0.5$, $U_2 = 75B$, $U_1 = 150B$. It follows from the calculation that the reference capacity of the supercapacitor is shown in Table 2.

Table 3 shows the results of the battery current study. Figure 13 shows the relationship between the capacitor voltage and the motor speed during acceleration. As can be seen from this figure, the relationship with the help of a supercapacitor has a sinusoidal shape.

Table 1. List of characteristics 1 of EM braking

Speed (km/h)	Braking time (s)	Braking distance (m)	Total energy (J)	Recovery energy (J)
30	17.26	38.23	104200	92150
40	18.92	54.7	185200	166800
50	20.88	80.28	289400	259400
60	23.38	117	416700	367400
70	26.06	165.5	567100	488100
80	28.95	225.8	740700	618200
90	31.99	297.4	937500	745600
100	35.09	379.3	1157000	894300
110	38.21	470.3	1400000	1035000
120	41.29	568.7	1667000	1373000

Table 2. List of capacities of supercapacitors

Braking speed (km/h)	Absorbed energy (J)	Capacitor Capacity (F)
30	73720	8.7372
40	133440	15.8151
50	207520	24.5950
60	293920	34.8350
70	390480	46.2791
80	494560	58.6145
90	596480	70.6939
100	715440	84.7929
110	828000	98.1333
120	1018400	120.6993

Table 3. Results of the battery current study

No	Battery current without ionistor	Battery current with ionistor	Ionistor current
1	-0.06	0.08	0.02
2	0.02	0.1	-0.02
3	0.04	0.02	0.02
4	0.06	0.06	0
5	0.04	0.08	0.02
6	1.8	0.94	1
7	0.92	0.84	0.16
8	0.92	0.78	0.16
9	0.92	0.82	0.14
10	0.96	0.84	0.1
11	0.86	0.9	0.1
12	0.02	0.78	-0.3
13	0.08	0.38	-0.24
14	0.02	0.24	-0.2
15	0.04	0.22	-0.18
16	0.1	0.18	-0.14
17	0.06	0.16	-0.08
18	0.02	0.16	-0.06
19	0.28	0.34	0.16
20	0.7	0.56	0.3

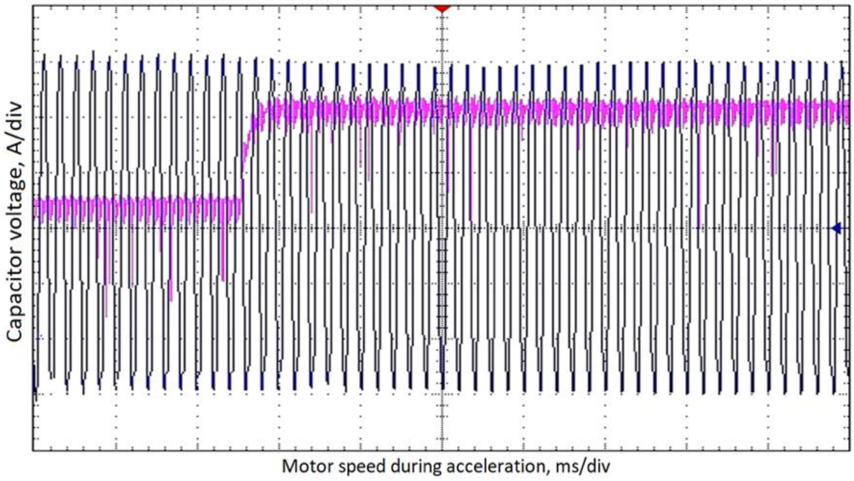

Figure 13. The relationship between the voltage of the capacitor and the speed of the motor during acceleration

Figure 14 shows the relationship between the voltage of the supercapacitor and the speed of the engine during deceleration. As can be seen from this figure, the relationship between the voltage of the supercapacitors and the engine speed during deceleration has the voltage of the supercapacitor close to the upper limit of protection. Figure 15 shows the dependence of the electric current on a battery without an ionistor. As can be seen from this figure, charging a capacitor without an ionistor is slower than a battery, which is why is slower, also process acceleration of an electric scooter (electric vehicle) after stopping is slower.

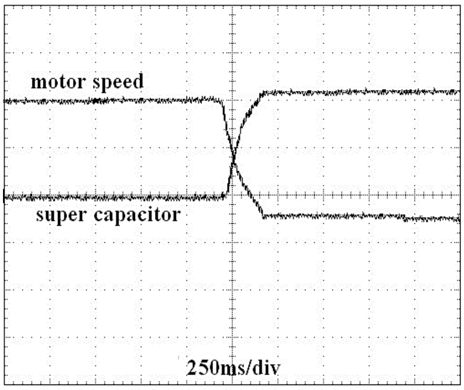

Figure 14. The relationship between the voltage of the supercapacitor and the speed of the engine during deceleration

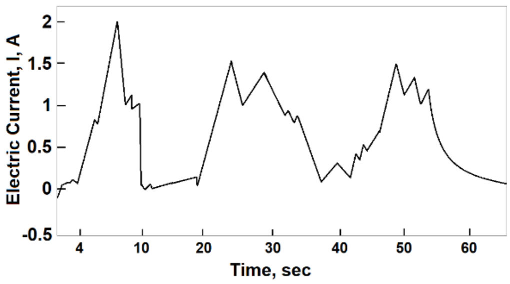

Figure 15. Dependence of electric current on a battery without an ionistor

Figure 16 shows the dependence of the electric current on a battery with an ionistor. As can be seen from this figure, the capacitor is recharged faster than the battery, which is why the process of regenerative braking is faster, and the process of acceleration of an electric scooter (electric car) after stopping is also faster. It can also be noted that if emergency braking of an electric scooter (electric vehicle) is necessary to stop it, the driver can press the brake pedal and stop the car using brake pads.

Figure 17 shows the dependence of the electric current on a battery with an ionistor. From ionistor increases over time, but there are decelerations that are associated with recharging the capacitor and the process of regenerative braking occurs faster. Figure 18 shows the dependence of the electric current on a battery with an ionistor. As this figure, a battery without an ionistor is recharged from a capacitor more slowly, a battery with an ionizer is recharged from a capacitor faster, and from the ionistor current by recharging the capacitor and the process of regenerative braking occurs faster.

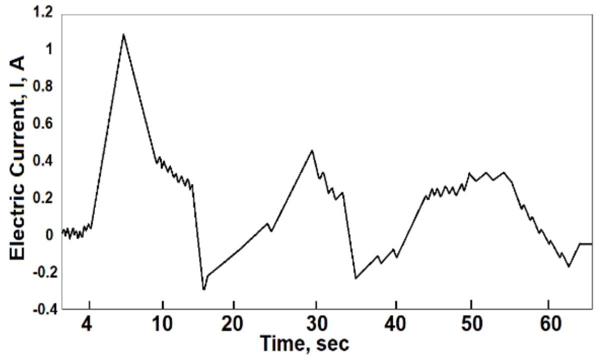

Figure 16. Dependence of electric current on a battery with an ionistor

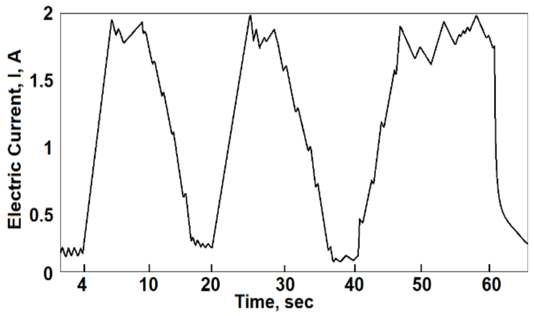

Figure 17. Dependence of the electric current on the ionistor current

Figure 19 shows the dependence on tracking the speed of an electric scooter (electric vehicle). Its actual speed of an electric scooter (electric vehicle) can well correspond to the controlled speed of the vehicle, and the average error between them is 0.03 m/s. This indicates that this method of regenerative braking can provide a vehicle in a stable condition that meets the expectations of the driver, not only in terms of driving characteristics, but also efficiency.

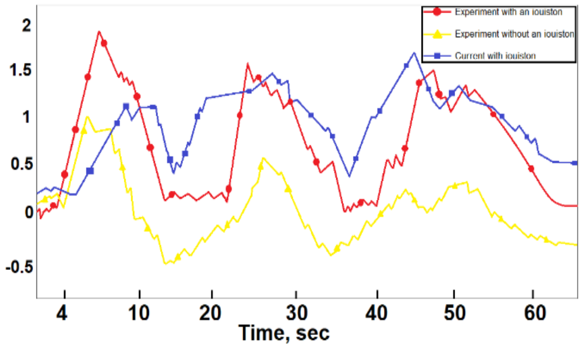

Figure 18. The dependence of the electric current on the ionistor time in three positions

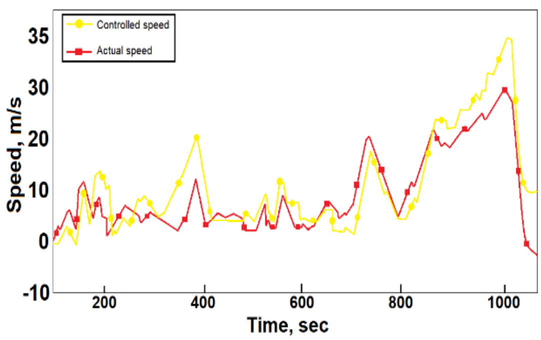

Figure 19. Dependence of electric scooter speed tracking

Figures 20 and 21, respectively, represent the braking torque on one front and rear wheel in electric and hydraulic braking modes. The figure shows that the braking torque of the left and right wheels in this study is the same. From these experimental results it can be seen that electric motor braking plays an important role in every braking process.

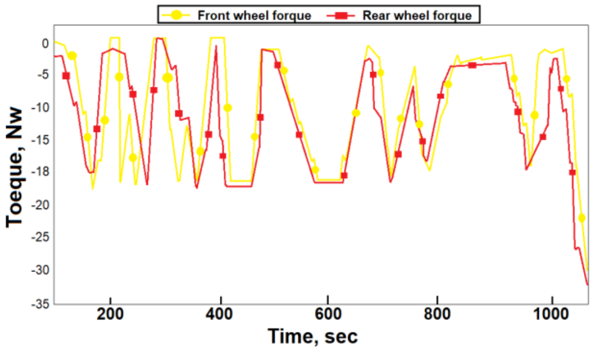

Figure 20. The dependence of the torque of the electric brake on one wheel

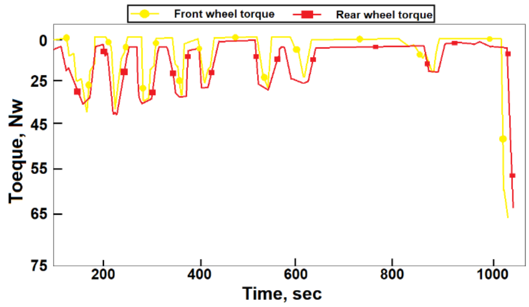

Figure 21. The dependence of the torque of the hydraulic brake on one wheel

Figure 22 shows a graph of the power of energy recovery. The figure shows that the efficiency of energy recovery varies depending on the speed of the vehicle. The total energy recovery eventually amounts to about 15%. Thus, experimental regenerative braking meets the expectations of the driver and is used effectively.

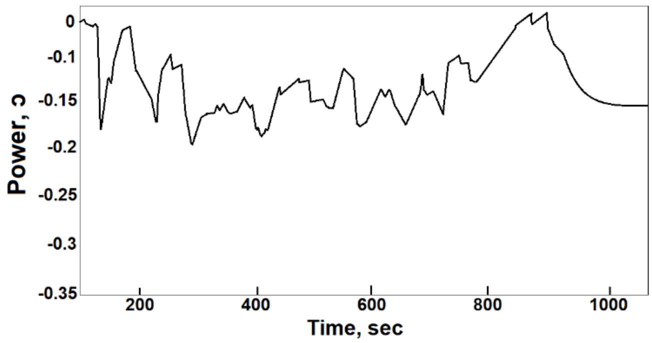

Figure 22. Energy recovery power graph

3. CONCLUSION

In this paper, a method of regenerative braking of an electric scooter (electric vehicle) is proposed. In the course of experimental work, it was shown that the presented approach to the method of regenerative braking has good efficiency both for tracking the expectations of the driver and for energy recovery. The engine speed should be reduced, the supercapacitor absorbs at this time the voltage of the supercapacitor close to the upper limit of protection, from these experimental results it can be seen that braking by an electric motor plays an important role in every braking process. During braking, it is triggered only when the vehicle speed is below a certain value, which in this simulation is about 1 m/s. The efficiency of energy recovery varies depending on the speed of the vehicle. The overall efficiency of energy recovery is eventually about 15%. Thus, the experimental results show that the proposed method of regenerative braking can meet the expectations of the driver, as well as use energy as efficiently as possible.

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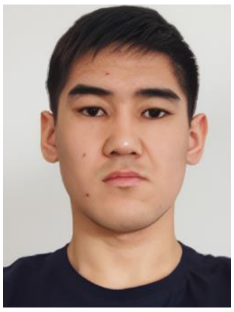

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