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Research of Regenerative Braking Strategy for Electric Vehicles

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Abstract. In the context of global energy instability caused by the transformation of global demand for energy and energy resources, one of the most important areas in the automotive industry is the development of electric vehicles. Serial production of high-tech electric vehicles with a long range contributes to the stabilization of the energy market and the sustainable development of the whole fuel-energy sector. To evaluate the possibility of optimizing the electric vehicles energy consumption, various regenerative braking strategies are discussed in the article based on the Nissan Leaf electric vehicle, which simulation model includes submodules of the traction electric motor, hybrid braking system, traction rechargeable battery and tires. In order to test the adequacy of the simulation model to reproduce the relationship between the operating parameters of electric vehicles various systems and evaluate their ability to regenerate energy during braking the simulation results were compared with the actual experimental data published by the Lab Avt research laboratory (USA). The relative error of the mathematical modeling results of the braking energy regeneration processes is 4.5 %, which indicates the adequacy of the electric vehicle simulation model and the possibility of its using as a base for research and comparison of the energy efficiency of various regenerative braking strategies. As the results of experiments have shown, the usage of the proposed control strategy of the regenerative braking maximum force allows increasing 2.14 times the energy recharging traffic to the battery as compared with the basic control strategy of fixed coefficient braking forces distribution with an increase in braking distance by 10 m. An alternative control strategy of regenerative braking optimal efficiency as compared to the basic control strategy provides a reduction in braking distance by 13.2 % at increasing by 84.4 % the amount of energy generated by the electric motor for recharging the batteries. The carried out investigations confirm the available significant potential for improving the efficiency of the electric vehicles usage by developing the control strategy and algorithms of the braking energy regeneration.

Keywords: electric vehicle, energy saving management, energy recovery, traction motor, traction batteries, simulation

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Исследование стратегии рекуперативного торможения электромобилей

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Реферат. В условиях энергетической нестабильности, вызванной трансформацией глобального спроса на энергию и энергоресурсы, одним из важнейших направлений в автомобилестроении является разработка транспортных средств на электрической тяге. Серийное производство высокотехнологичных электромобилей с большим запасом хода способствует стабилизации рынка энергоресурсов и устойчивому развитию всего топливно-энергетического сектора. Для оценки возможности оптимизации энергопотребления электромобилей в статье рассматриваются различные стратегии рекуперативного торможения на базе имитационной модели электромобиля Nissan Leaf, включающей субмодули тягового электродвигателя, гибридной тормозной системы, тяговой аккумуляторной батареи и шин. Результаты моделирования сопоставлялись с экспериментальными данными научно-исследовательской лаборатории Lab Avt (США), опубликованными для проверки адекватности имитационных моделей, воспроизводящих взаимосвязь между рабочими параметрами различных систем электромобиля и оценивающих их способность регенерировать энергию при торможении. Относительная погрешность результатов математического моделирования процессов рекуперации энергии составляет 4,5 %, что свидетельствует об адекватности имитационной модели электромобиля и возможности ее использования в качестве базовой для исследований и сопоставления энергоэффективности различных стратегий рекуперативного торможения. Как показали результаты экспериментов, использование предлагаемой стратегии управления максимальной силой рекуперативного торможения позволяет увеличить трафик энергии подзарядки в 2,14 раза по сравнению с базовой стратегией управления на основе фиксированного коэффициента распределения тормозных усилий по осям транспортного средства при увеличении тормозного пути на 10 м. Альтернативная стратегия управления оптимальной эффективностью рекуперативного торможения обеспечивает по сравнению с базовой стратегией уменьшение тормозного пути на 13,2 % при одновременном увеличении на 84,4 % количества вырабатываемой электродвигателем энергии для подзарядки тяговых аккумуляторных батарей. Проведенные исследования подтверждают имеющийся потенциал по повышению эффективности использования электромобилей за счет совершенствования стратегии и алгоритмов управления рекуперацией энергии торможения.

Ключевые слова: электромобиль, управление энергосбережением, рекуперация энергии, тяговый электродвигатель, тяговые аккумуляторные батареи, имитационное моделирование

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Introduction

The gradual transition of the automotive industry to the production of electric vehicles deals with the necessity of reducing the negative impact of traffic on the environment and, first of all, with the decreasing of the exhaust gases emission into the atmosphere, leading to climate change and global warming. A constraining factor in the launch of large-scale electric vehicles (EV) production is the relatively small driving range of the electric car on a single traction batteries charge. Brake energy recovery in EV is an ideal technical solution to this problem, because this process allows converting the vehicle’s kinetic energy into electrical energy for recharging the batteries during braking, forced deceleration or downhill movement. Regenerative braking increases the EV range about 16.3 %, at the same time reducing the total time of the braking process [1].

Another serious disadvantage of EV is the using of the batteries as the only source of energy, which requires a long charging time from an external electrical network in the optimal current mode. It should also be noted that traction batteries, having relatively low specific energy consumption and power, cannot fully satisfy the short-term needs of the traction motor for power consumption during acceleration or uphill movement, when the efficiency of electric motor energy recovery is significantly degraded [2, 3]. In addition, under various braking conditions, the feedback current generated by the generator can be quite significant [4]. At the same time, high levels of charging current negatively affect the operational life of the battery [5, 6], and the rate of energy recovery by the storage system may not reach the desired level due to the limitation caused by the characteristics of the traction motor and batteries. The disadvantages of electric vehicles include the high cost of traction batteries and the limitations of their usage in heavy vehicles [7]. However, it's also worth noting the fact that for heavy vehicles exploited in urban areas, this problem has been solved by using supercapacitors as an energy board storage device. Large urban passenger transport and delivery medium-duty trucks on electric traction are equipped with supercapacitors, which are charged both from stationary power sources at the final points of the route, and during movement around the city due to the regenerated kinetic energy during recuperation braking [8].

Nowadays, several control strategies of the regenerative braking process are used in world practice, among which one can note the sequential control strategy, the ECO strategy and the strategy of regenerative braking based on the fuzzy sets theory [9]. This paper has focused on the research of two control strategies for regeneration process, viz. a strategy for controlling the maximum force of regenerative braking and a control strategy for the optimal braking efficiency. In order to optimize energy management [10] the analysis of the complex parameters influence of the wheel electric drive, brake system, traction batteries and the chosen regenerative braking strategy on the EVs energy consumption was carried out on the basis of simulation modeling. The presented simulation model of the energy recovery system was developed on the technical and operational characteristics of the Nissan Leaf passenger car. The model allows simulating the process of braking energy regeneration at different EVs speeds and deceleration, taking into account the features of the chosen control strategy and the type of road surface. In addition, the mathematical model takes into account the level of the traction batteries charge and the tire slip coefficient in wheel contact with the road, which allows the possibility an in-depth research of the two proposed regenerative braking control strategies.

Regenerative braking principle

Regenerative braking is a high-tech, essentially energy-saving process, which consists in converting the kinetic energy of a vehicle moving in braking mode into electricity, and then using it to recharge traction batteries (or supercapacitors) and also the control system accumulator. The implementation of this process is technologically possible only on the board of the vehicles with electric drive wheels. Equipping a car with an electric drive by integrating traction motors into the front and rear drive wheel design has a number of undeniable advantages in comparing with a conventional vehicles using an internal combustion engine as the main source of driving force. Firstly, in addition to the internal combustion engine and a multi-stage gearbox, the transmitting and distributing torque mechanisms (dry friction clutch, inter-wheel and axle differentials, multiplate friction clutches, viscous couplings, etc.) are excluded from the vehicle design. Secondly, when power distribution between all vehicle wheels is required (for example, when driving on a snowy road, off-road or in icy conditions), there is a technical possibility of implementation the full-wheel drive. Finally, in the braking mode, forced deceleration or downhill movement, traction electric motors can be effectively used as a generator sets, realizing the process of regenerative braking [11], which saves energy consumption due to the regeneration of braking energy [12].

However, the implementation of the seemingly simple principle of braking energy recuperation requires full integration of the regenerative braking system with the EV regular braking system, which is the most important element of the driver, passengers and vehicle safety. To ensure reliable and efficient operation of the regenerative system, its integrated soft- and hardware platform must provide smooth and precise control of the combined mechanical and regenerative braking [13]. Therefore, the operation coordination of the regular hydraulic braking and the EV regenerative braking systems is an essential factor in developing a control strategy for the hybrid braking mode [14, 15]. Besides, in case of the regenerative braking system failure, safety requirements must be strictly observed. Braking torque distribution on the wheels should ensure the full usage of the EV grip weight during braking of any intensity, but at the same time, its value should have the minimum allowable value to maintain vehicle controllability during braking process.

Electric vehicle simulation model development. The EV simulation model [16], which includes submodels of traction electric motor, hybrid brake system, traction accumulator batteries, tires, driving cycle module, and the mathematical model of transient dynamics, is shown in Fig. 1.

The development of a complex EV simulation model was carried out in accordance with the practical recommendations for modeling vehicles on electric traction [10], which regulate the including tires models and the SOC percentage effect into the mathematical description of the EV dynamics and traction accumulator battery respectively.

Tire models. Tires are represented in the model by an elastic shell that deforms in the normal and tangential directions during operation. The corresponding forces F_{xf}, F_{xr} compatible with tire slip ratio can be calculated as [17]:

- front axle: $F_{xf} = \mu_f\left(s_f\right)F_{zf}$;
- rear axle: $F_{xr} = \mu_r\left(s_r\right)F_{zr}$, (1)

where F_{xf}, F_{xr} are traction forces respectively on the front and rear axles, N; μ_f, μ_r are traction coefficients of the front and rear axles, respectively; s_f, s_r are the front and rear tire slip ratio, respectively; F_{zf}, F_{zr} are vertical forces respectively on the front and rear axles, N.

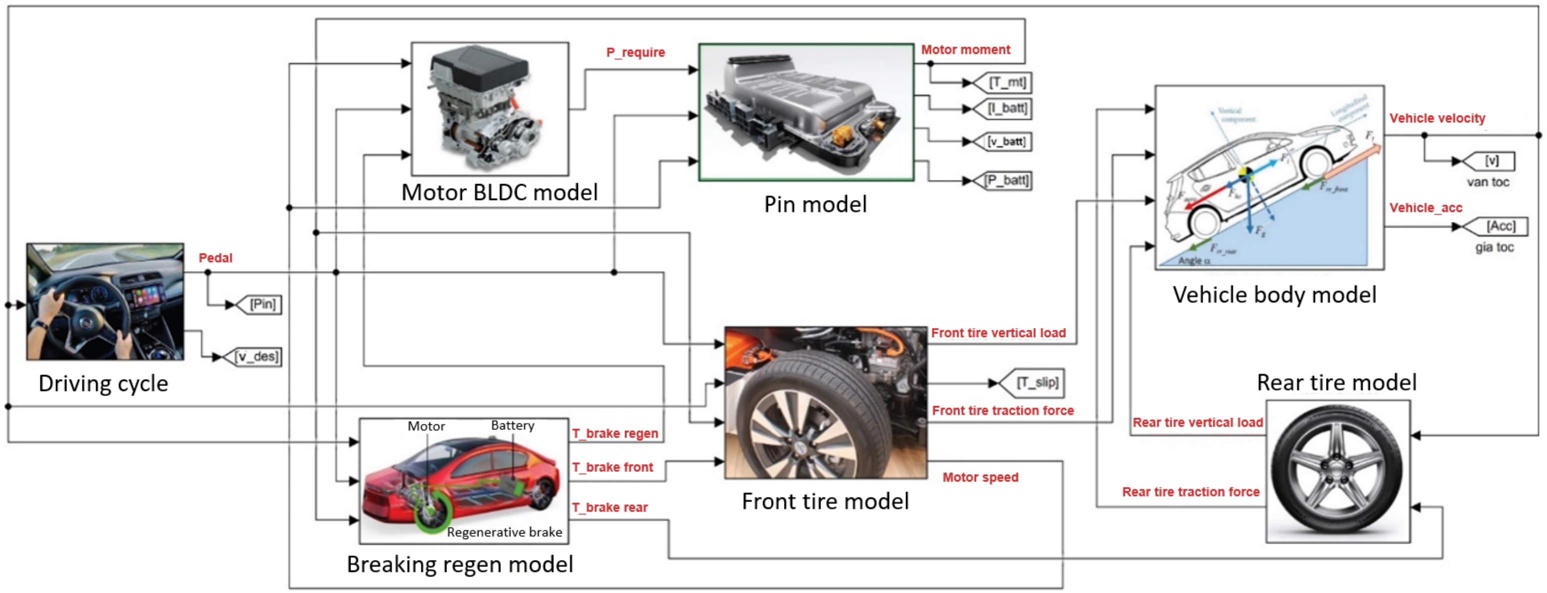

Fig. 1. Electric vehicle model

The slip ratio for each driving condition is calculated by the following equations [17]:

- acceleration: $s = \dfrac{v - \omega_{wh} r_{wh}}{\omega_{wh} r_{wh}} \left(-1 < s < 0\right)$;
- braking: $s = \dfrac{v - \omega_{wh} r_{wh}}{v} (0 \le s \le 1)$, (2)

where v is vehicle speed, m/s; ω_{wh} is wheel rotation speed, rad/s; r_{wh} is wheel dynamic radius, m.

The relationship between the coefficient of traction and the slip ratio of the tires, determined experimentally, is shown in Fig. 2.

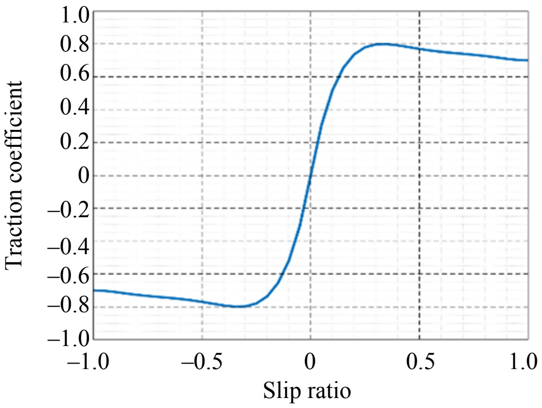

Fig. 2. The relationship between traction coefficient and tire slip ratio

Accumulator battery model. Accumulator battery equivalent circuit circuit (Fig. 3) does not directly simulate the flow of complex chemical processes inside the battery system, but allows approximating the output nonlinear characteristics and parameters of the traction accumulator battery in all EV operating modes, including the regenerative braking.

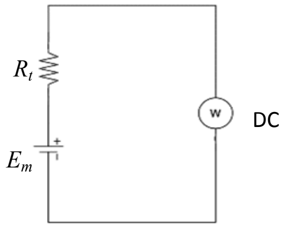

Fig. 3. Battery equivalent circuit

Each element of the equivalent circuit (internal resistance R_t, open circuit voltage E_m and direct current DC of the battery) is the basis for the construction of algebraic nonlinear equations, including constant parameters and variables. The internal resistance R_t parameters are presented in non-linear equations by constants obtained empirically using an interpolated data table.

From the equivalent circuit model, we have the output power of the battery

$$P_a = P_{yc} + P_r, \tag{3}$$

where P_a is battery output power, W; $P_a = UI$; P_{yc} is consumed power of the traction electric motor, W; P_r is capacity loss due to internal resistance R_t of the battery, W; $P_r = R_t I^2$; U, I are respectively operating voltage, V, and operating current, A, of the battery, respectively.

To calculate the current strength of the main branch, we substitute P_a, P_r into equation (3)

$$UI = P_{yc} + R_t I^2. \tag{4}$$

Equation (4) has two solutions $I_{1,2}$ as in the bellow formuler (5). The current value will be taken according to the solution that has an absolute value less than.

$$I_{1,2} = \frac{1}{2}\left(\frac{U}{R_t} \pm \sqrt{\left(\frac{U}{R_t}\right)^2 - 4\frac{P_{yc}}{R_t}}\right). \tag{5}$$

SOC battery capacity, as one of the main output parameters of the battery block, is calculated by

$$SOC_{(t)} = SOC_{(t_0)} - \frac{1}{C}\int_{t_0}^{t} I(t)\,dt, \tag{6}$$

where $SOC_{(t)}$ is the instant SOC at time *t*; $SOC_{(t_0)}$ is the original SOC at time t_0; *C* is battery capacity, A·h; *I*(*t*) is instantaneous discharge current strength, A.

In accordance with the equivalent calculation scheme the voltage on the battery terminals is determined from the equation

$$U - U_{in} = U_{dc}, \tag{7}$$

where U_{in} is voltage drop on the internal resistance, V; U_{dc} is the same on the load, V.

Regenerative braking models. During recuperative braking, the electric traction motor performs the function of a generator, converting the vehicle kinetic energy into electric energy, which is sent back to the accumulator battery for its recharging. It was experimentally established that the torque curves in the traction mode of the electric motor and in the generator mode are symmetrical (Fig. 4), i. e. the torque accepts negative values for regenerative braking [18, 19].

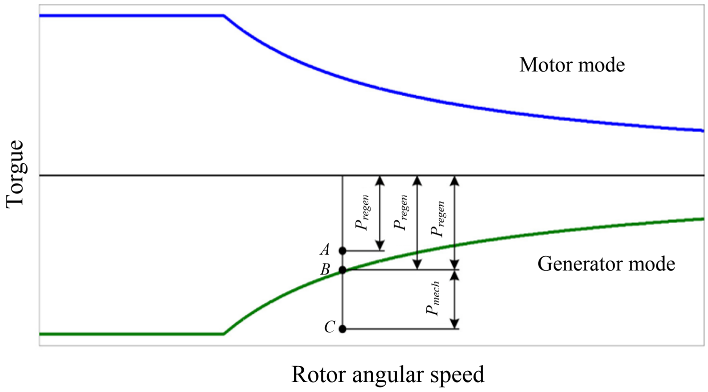

Fig. 4. Engine maximum braking curve

If required for EV deceleration the total braking moment on the front axle wheels is less than or equal to the maximum possible braking torque of the generator at a given speed (Fig. 4, points *A*, *B*), then only a recuperative brake is used for service braking. The EV regular hydraulic braking system is not activated. When the required brake moment exceeds the torque limit (Fig. 4, point *C*), the generator operates at the point of maximum torque (P_{regen}) and the rest of the power (P_{mech}) is wasted as heat on the brake discs surface due to mechanical braking. In addition, the regenerative braking system is not activated at low speeds due to low energy efficiency and therefore the required brake force on the front wheels during full vehicle stopping is created only by hydraulic actuators of the regular brake system.

To simulate this activity, the mathematical description of the transient process includes the speed-dependent recovery factor. The value of this indicator depends on the vehicle speed threshold v, m/s, during service braking. At initial braking speeds exceeding the upper threshold value v_2 of 12.0 m/s, the generator operates in the maximum renewable capacity, generating energy to recharge the batteries and participating, in parallel, in the formation of the total braking torque on the EV front axle drive wheels. If the actual vehicle speed falls below threshold v_1 in 4.47 m/s, the generator is deactivated and goes into “sleep” mode. For speeds between v_1 and v_2, it is assumed that the percentage of brake power that can be recovered increases linearly with vehicle speed up to the point of maximum resiliency, as shown in Fig. 5.

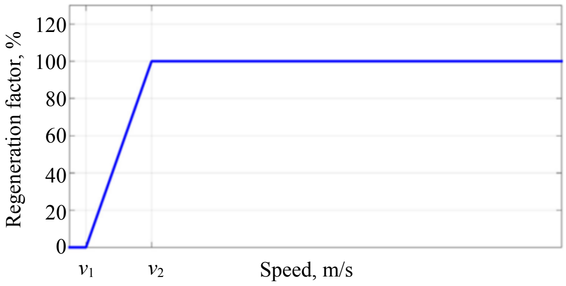

Fig. 5. Speed-dependent regeneration factor coefficient

Taking into account the dependence shown in Fig. 5, the $T(v)$ function of the electric motor braking torque T from the actual EV velocity v was built, which shows the influence of the EV speed mode on the electric motor regeneration coefficient during braking process.

Recharging the battery with regenerative energy while braking from 60 to 10 mph. The simulation results of the battery recharging with regenerative energy during braking from a speed of 60 mph (28.62 m/s) to 10 mph (4.47 m/s) were compared with the actual experiment results [20] to evaluate its validity. The main parameters and technical characteristics of the tested EV are presented in Tab. 1.

Table 1

Model parameters and EV technical characteristics

Parameters, dimensionalities	Values
Air density, kg/m^3	1.25
Battery energy, kW·h	24
Battery round trip efficiency	0.95
Drag coefficient	0.29
Frontal area, m^2	2.19
Gear efficiency	0.95
Gear ratio	8.2
Maximum motor power, kW	80 (2730–9800 rpm)
Maximum motor torque, Nm	280 (0–2730 rpm)
Tire radius, m	0.316
EV total mass, kg	1663

The transition to the regenerative braking mode was carried when the EV reached the set speed of 60 mph with activations at that very moment the traction electric motor as a generator to recharge the accumulator battery. The changing in the regenerative braking energy efficiency during EV deceleration in the above speed range is represented in Fig. 6.

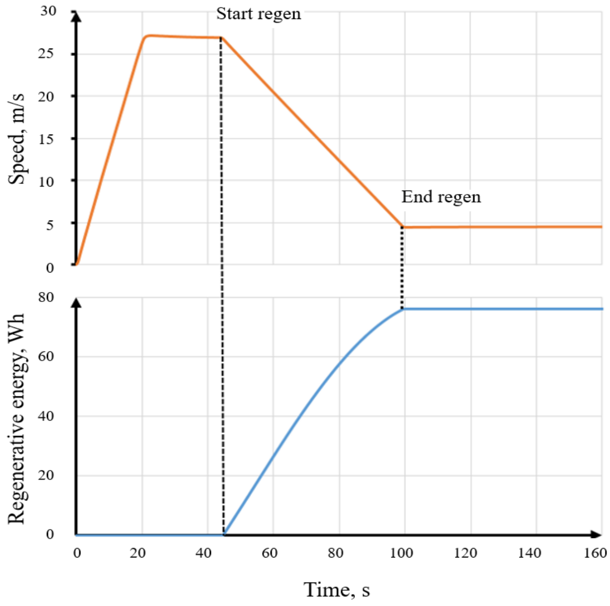

Fig. 6. Regenerative braking energy efficiency

As can be seen from modeling results the regenerative energy during EV braking from 60 to 10 mph is 76.19 W·h. According to the experimental results of Lab AVT (USA) [20], a similar indicator of the regenerative braking energy efficiency under the identical conditions of the transition process is 79.8 W·h. Thus, the error of the regenerative braking simulation is less than 5 %, which indicates the adequacy of the EV simulation model and the correctness of the developed mathematical description. The computer experiment error depends on the conditions of using the auxiliary load, environmental conditions, weather and the road surface grip.

The presented EV model is used as a basis for evaluating the effectiveness of the two proposed regenerative braking control strategies and developing the corresponding algorithms for the recuperation process control.

Proposed regenerative braking control strategies

Control strategy of the regenerative braking maximum force. The structure of the hybrid braking system control algorithm, developed on the basis of the proposed control strategy, allows realizing the law that ensures the redistribution of the maximum total braking forces to the front axle wheels. Braking forces distribution of the specified disproportion (the maximum possible braking force (according to the grid conditions), respectively, on the front wheels, the smallest one – on the rear axle wheels) is regulated by the Economic Commission for Europe (ECE) adjustment and described by the 0-*a*-*b*-*c* curve (Fig. 7).

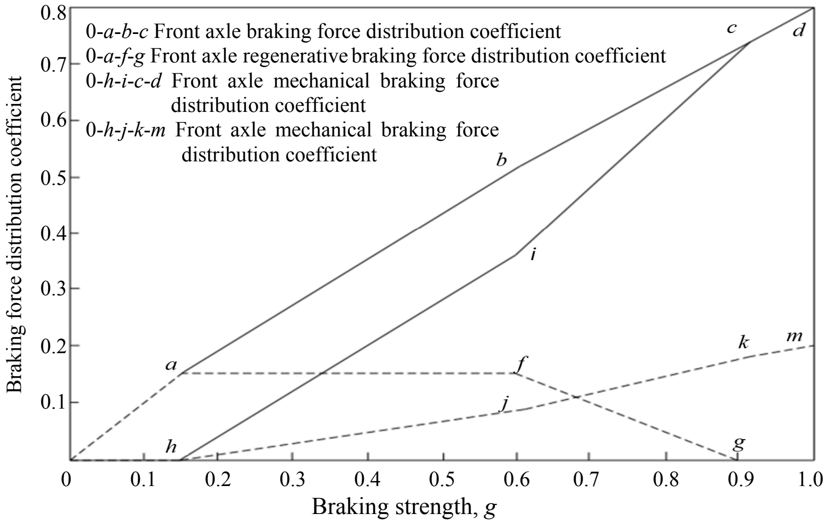

Fig. 7. The relationship between braking force distribution coefficient and braking strength

During braking with a deceleration of less than 0.2g, the hydraulic actuators of the regular brake system are not activated [21], and the required braking force on the front wheels is created only by traction electric motor due to the activation of the regenerative braking mode. In this case, the generator braking torque is regulated with ECU by signals processing from the EV brake pedal position and wheels speed sensors. When the deceleration exceeds 0.2g, the regular brake system begins to create pressure in the hydraulic actuators cylinders and the mechanical braking force on the front and rear wheels begins to increase in a linear relationship, shown in Fig. 8 by the β_m line.

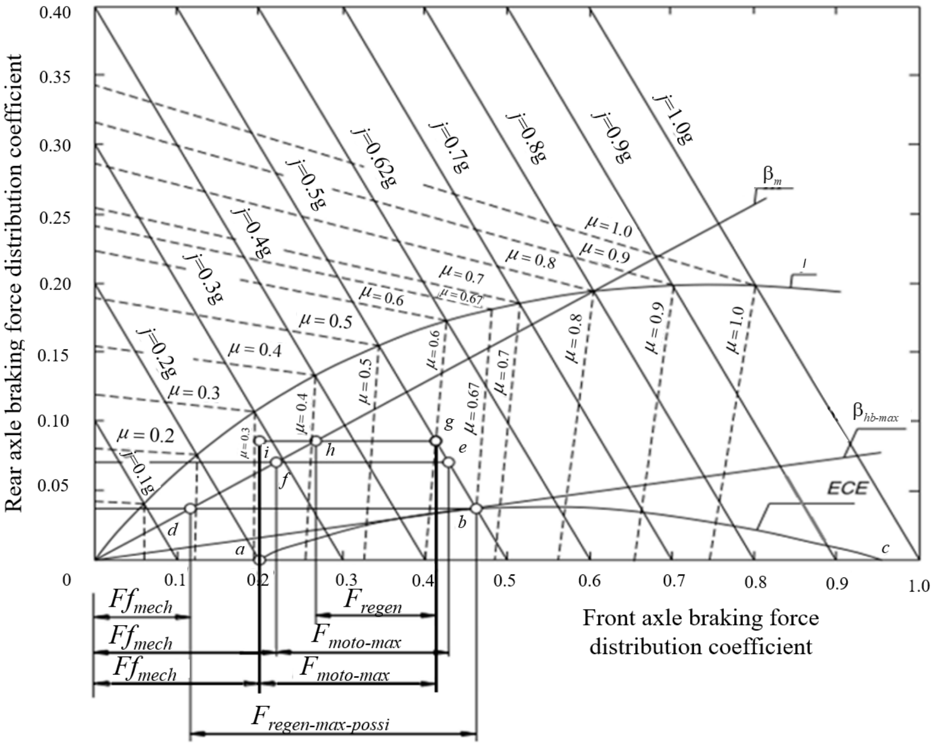

Fig. 8. Diagram of braking force distribution on the wheels

At this time, the traction motor continues to generate an electric braking torque on the front wheels, providing, together with the regular brake system, a total braking force corresponding to the distribution coefficient regulated by ECE. For example, when the EV deceleration is 0.5*g*, the total braking force is at point *b*, and the mechanical braking force on the front and rear wheels is at point *d*. In this case, the maximum possible braking force for regenerative braking is *d*-*b* line, marked $F_{regen-max-possi}$.

The battery recharge efficiency directly depends on the duration of the recuperation process in each braking cycle, i. e. the longer the regenerative brake takes part in the formation of the total braking torque on the front wheels, the more energy the battery will receive for recharging. However, for the greatest possible recovery of braking energy, the following two conditions must be satisfied.

The first condition is that the electric motor must be able to generate braking force. Assuming that at a deceleration of 0.5*g* the maximum braking force of the electric motor is limited in Fig. 8 by the *f*-*e* line, then the operating point of the total braking force should be at point *e*, and the mechanical braking force should be at point *f*. However, for producing a maximum of regenerative electrical energy per braking cycle, it is necessary to harmonize the generation of the maximum braking force by the electric motor with the ECE adjustment for the axle brake force distribution. The second condition is that the road surface grip coefficient μ must be greater than 0.67, otherwise the front axle wheels will be locked during braking. It is illustrated on Fig. 8, that in a case of deceleration j = 0.5g and μ = 0.6, the total braking force will be determined by the operating point *g*.

It should also be noted that for braking systems with ABS, the required total mechanical and regenerative braking force under identical braking conditions will differ from the operating values shown in Fig. 8. For vehicles equipped with an anti-lock braking system, the mechanical force generated by the hydraulic brake actuators when the front wheels are locked will be less than the potential values (Fig. 8, point *g*,) approximated by the line β_m, i. e. the value of the maximum mechanical braking force on the front axle will be determined by the operating point *i*. In this case, the motor can still provide the greatest braking torque (Fig. 8, braking force $F_{moto-\max}$) with the largest recovery energy for batteries recharging.

Thus, the ECE curve (Fig. 8), which illustrates the minimum allowable by ECE adjustment braking forces distribution along the vehicle axes, can be replaced by a simple straight line $\beta_{hb-\max}$ the coordinates of which can be used to form the required total braking torque depending on actual EV deceleration

$$\beta_{hb-\max} = \frac{2\sqrt{0.07 L_b h_g} + L_b + 0.07 h_g}{0.85 L}, \qquad (8)$$

where L is the EV wheelbase, m; h_g is the height of the EV's center of gravity, m; L_b is the distance from the EV's center of gravity to the rear axle, m.

Equation (8) shows that, in fact, the braking forces distribution coefficient is determined by the geometric parameters of the vehicle. Having calculated the total braking force $\beta_{hb-\max}$ from the hydraulic brake actuators and the regenerative braking, which is necessary for providing the required EV deceleration, it is possible to construct the braking forces distribution diagram on the front and rear axles wheels based on the straight line $\beta_{hb-\max}$, as shown in Fig. 8. At the same time, the control algorithm for the combined brake system is greatly simplified.

For simulation the proposed control strategy of the regenerative braking maximum force, the regenerative braking model represented by the function $T(v)$ was transformed. In particular, based on the diagram in Fig. 8, the line 0-*a*-*f*-*g* was built (Fig. 7), which allows creating the $T_1(\dot{v})$ function of the electric motor braking torque T_1 during the recovery process from the actual EV deceleration $\dot{v}$.

Optimal brake efficiency control strategy. The hybrid braking system (Fig. 9) allows to carrying out independent regulation of the total mechanical and regenerative braking forces on each wheel of an EV. During service braking, the torque generated by the hydraulic brake actuators on the front and rear wheels is H-EBS controlled by applying a PWM-signal to the appropriate proportional solenoid valve, taking into account the data processing from individual pressure feedback channels, the brake pedal position, the actual and required EV deceleration and the regenerative braking torque value transmitted to the front axle.

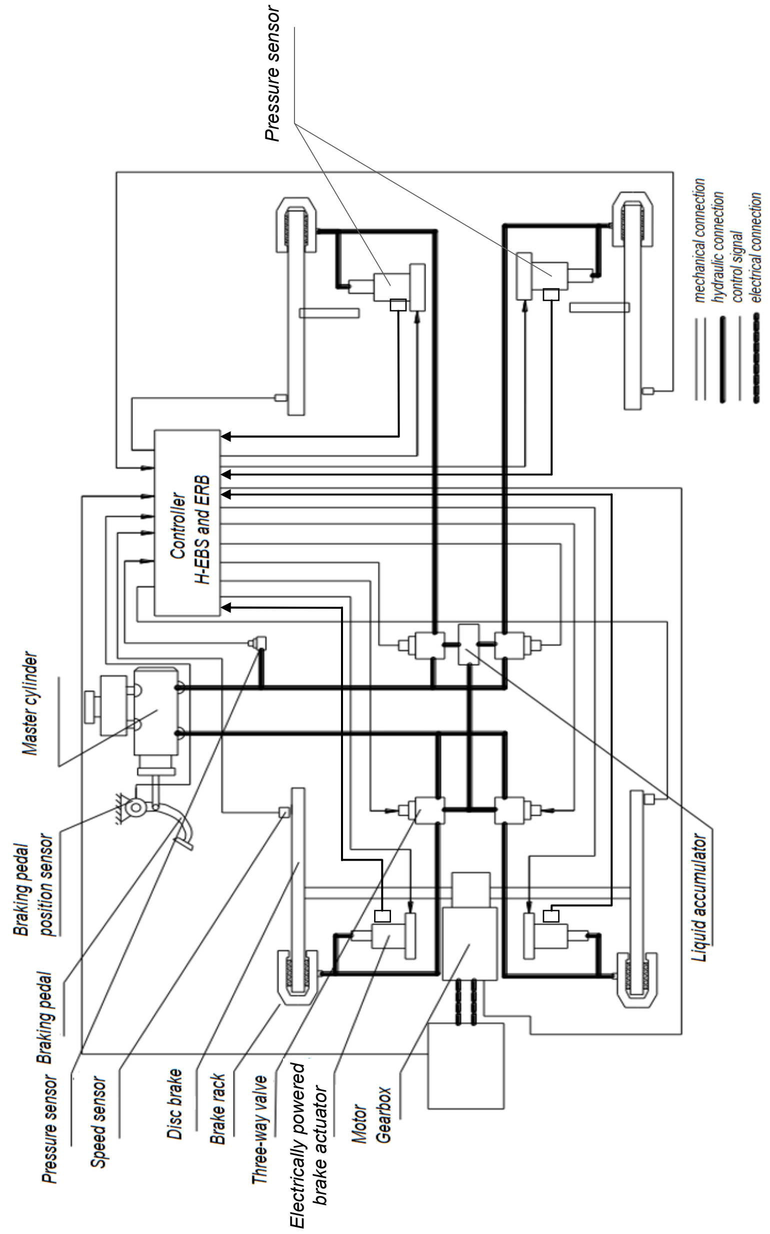

Fig. 9. Full control of hybrid braking system with H-EBS and regenerative braking

At the developing of control algorithm for the above-described combined braking system, the key point is the aspect of realizing the optimal control strategy for the total electrical and mechanical braking torque, which allows obtaining the required vehicle braking efficiency along with the maximum regenerative braking energy.

The concept realization of independent braking forces regulation on each wheel allows the hybrid braking system to precisely control the braking torque on the front and rear wheels according to the ideal brake forces distribution curve *I* (Fig. 8, 10). This control strategy can provide optimal braking efficiency.

When the required (on the condition of providing the necessary deceleration) total braking force on the front wheels is less than the potential capabilities of the electric motor, the braking torque on the front axle wheels is formed only by the regenerative brake without using of hydraulic brake actuators. In this case, the braking force on the rear axle wheels is created by the hydraulic actuators of the regular brake system in accordance with the distribution coefficient determined by curve *I* (Fig. 10). If the required total braking force on the front wheels is greater than the maximum braking force of generator, then both electric and hydraulic braking systems are used during service braking.

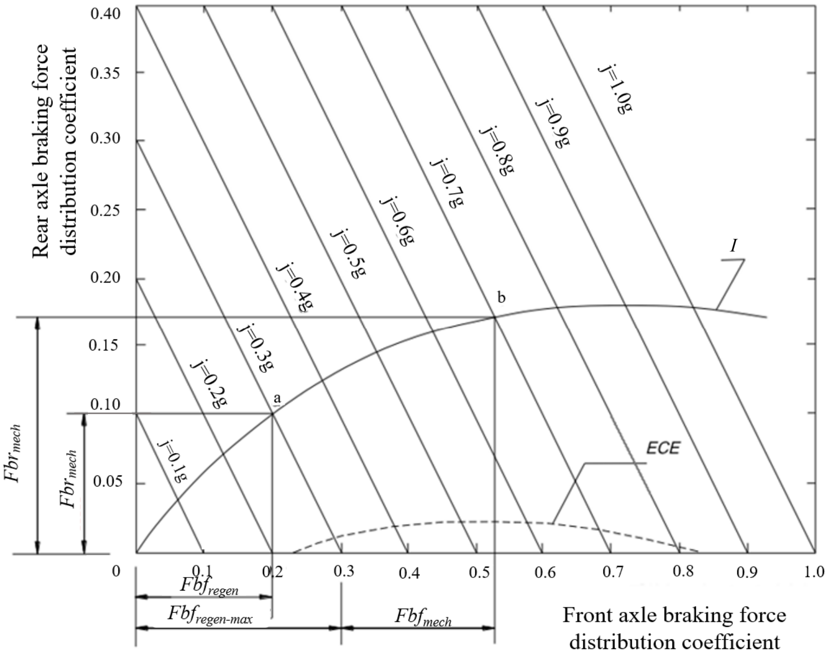

Fig. 10. Control strategy for the most optimal braking efficiency

For simulation the proposed control strategy of optimal brake efficiency, the regenerative braking model represented by the function *T(v)* was transformed. In particular, on the diagram of Fig. 10 reconstruction path 0-*a*-*b* was built, which allows creating the $T_2(\dot{v})$ alternative function of the electric motor braking torque T_2 in the recovery process from the actual EV deceleration $\dot{v}$.

Simulation results

In order to research the described above two regenerative braking strategies (Strategy 2 and 3), a scenario was developed to simulate the respective regenerative processes and calculate their effectiveness in terms of braking dynamics and the amount of renewable energy. The obtained results, namely the braking distance, the amount of regenerated energy for recharging per braking cycle and SOC battery capacity, were compared with similar indicators from the braking process simulation based on the basic control strategy with a fixed ratio of the braking forces distribution (Strategy 1). The transient processes simulation conditions are shown in Tab. 2.

Table 2

Scenario conditions

Condition	Value
Deceleration speed range, mph	From 60 to 10
Maximum grip coefficient $\varphi_{\max}$	0.7
SOC start at, %	50
Braking time, s	55.6 (from 100 to 155.6)

The simulation results of the regenerative braking process with display of the braking distance, the current vehicle speed and the brake pedal position are shown in Fig. 11. The braking distance comparison in the context of the three analyzed regenerative braking control strategies is shown in Fig. 12.

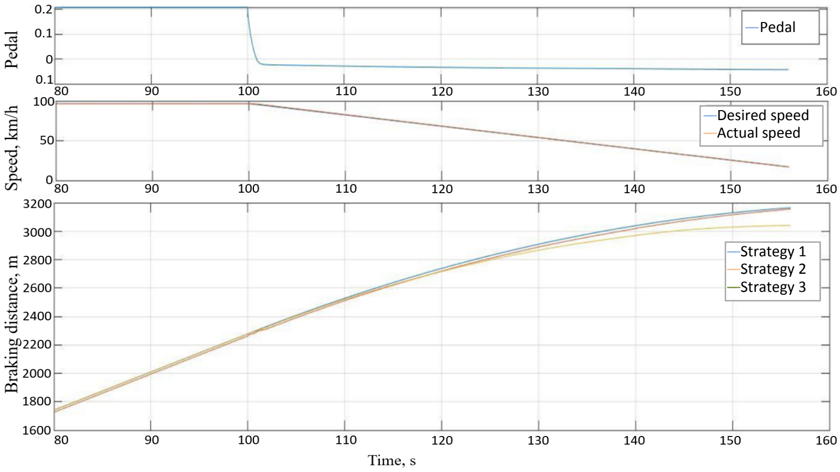

Fig. 11. Braking distance evaluation graph

As can be seen from the Fig. 12 diagrams, the usage of the optimal braking efficiency control strategy (Strategy 3) provides the shortest braking distance during transient process. Compared to Strategy 1 (fixed ratio of the braking forces distribution) and Strategy 2 (control strategy for the regenerative braking maximum force), the braking distance at applying Strategy 3 is reduced by an average of 13.7 % and its value is 768.2 m, thus confirming the braking process optimality in terms of braking efficiency.

Fig. 12. Braking distance graph

The simulation results of the regenerative braking process with the display of the total regenerated energy per time and the instantaneous values of the batteries recharging capacity are shown in Fig. 13. Graphical comparison of the most important energy efficiency characteristics of the researched regenerative braking control strategies is shown in Fig. 14.

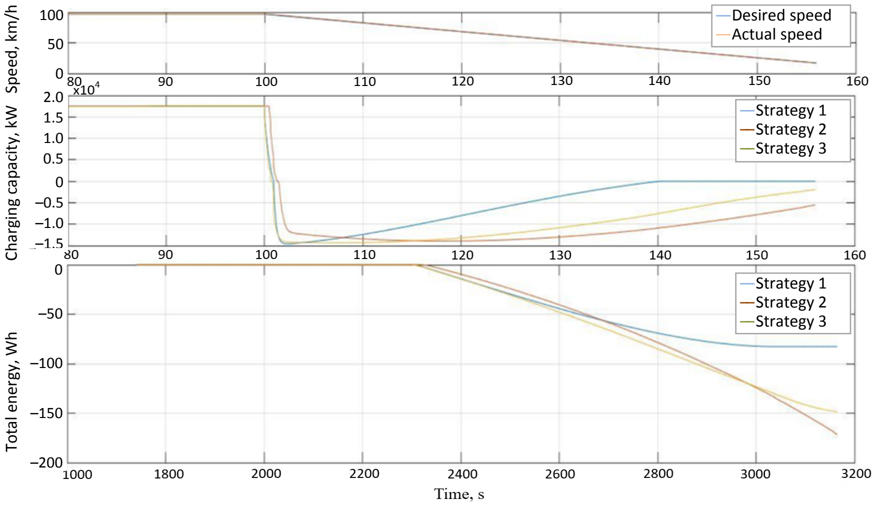

Fig. 13. Battery charging energy evaluation graph

As can be seen from Fig. 14, the peak batteries recharging capacities for various recovery braking control strategies are almost identical (deviation within 4.5 %). However, when using Strategy 2 and Strategy 3, the total energy generated by an electric motor for battery recharging is 2.14 and 1.84 times more, respectively, than when using Strategy 1.

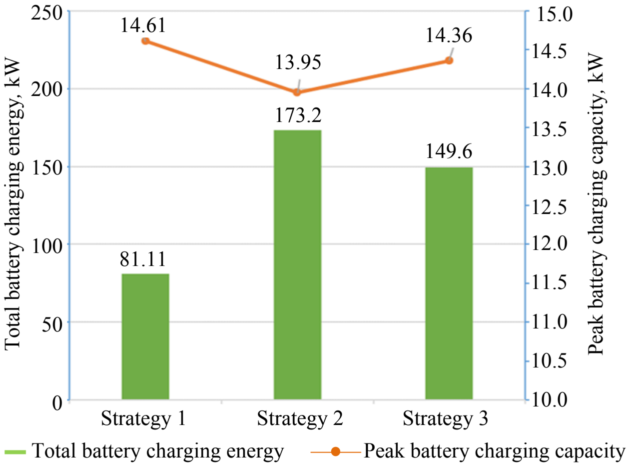

Fig. 14. Battery charging comparison results

The simulation results of the regenerative braking process with the display of SOC battery percentage and its ampere discharge are presented in Fig. 15. The graphic comparison of the indicated values in the context of three analyzed regenerative braking control strategies is presented in Fig. 16.

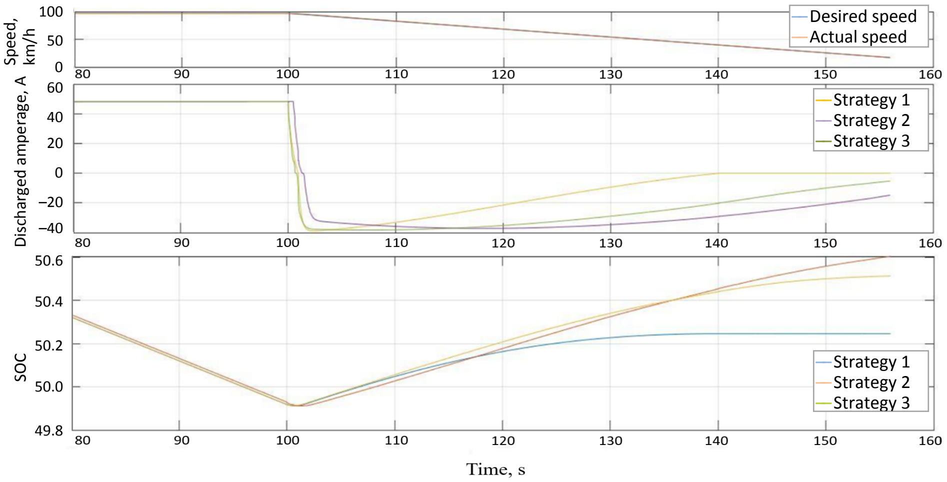

Fig. 15. The amount of SOC absorbed by the battery

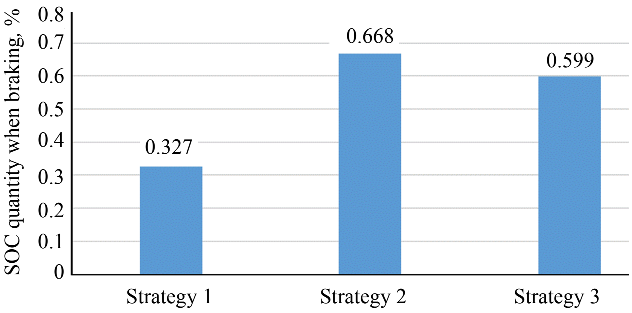

Fig. 16. SOC quantity comparison

After comparing the efficiency indicators of two proposed recovery braking control strategies (Strategy 2 and 3) with similar indicators of the Strategy 1, we can conclude that each strategy has its own advantages and disadvantages. When using the Strategy 2, the EV braking distance is the longest among the other ones, but instead, the battery receives maximum of recharging energy – 173.2 W per braking cycle. Strategy 3, on the contrary, provides the smallest braking distance, but, at the same time, the recharging energy transmitted by the generator to the battery is 13.6 % less compared to the Strategy 2 and 1.84 times more that of Strategy 1. Thus, Strategy 3 is the most optimal in terms of providing the smallest brake distance and minimal electric motor energy intake.

CONCLUSIONS

1. The relative error of the simulation results of the braking energy regeneration processes and the actual experimental data of the Lab Avt research laboratory (USA) is less than 5 %, which indicates the adequacy of the EV simulation model and the possibility of its using as a base for research and energy efficiency comparison of various regenerative braking strategies without conducting expensive bench and road tests.
2. As the simulation results shows, from two proposed regenerative braking strategies, the best one is the optimal brake efficiency control strategy, which provides a reduction in the brake distance by 13.2 % compared to the basic control strategy based on fixed ratio braking forces distribution with simultaneously increasing by 84.4 % of the total battery recharging energy produced by the electric motor in generator mode. The research confirms the existing significant potential to increase the efficiency of using electric vehicles by improving the control strategies and algorithms of the braking energy recovery.

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Оперативная идентификация сопротивлений проводов распределительных сетей 380 В автоматизированными системами учета

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Реферат. Рассматриваются четырехпроводные распределительные электрические сети 0,4 кВ, оснащенные автоматизированными системами учета электрической энергии. Решается задача идентификации сопротивлений проводов распределительной сети на основе действующих значений напряжений и токов, а также их углов сдвига фаз, получаемых системой учета в узле питания сети и у ее абонентов для выбранных интервалов наблюдения. Проводится краткий анализ известных методов и технологий, применяемых в указанном направлении исследований. Отмечается важность формулируемой проблемы для прикладных задач: контроля и диагностики потерь электрической энергии, а также технического состояния сети. Предлагается метод (алгоритм), позволяющий определять неизвестные, неодинаковые комплексные сопротивления межабонентских участков распределительной сети. В этих сопротивлениях реактивные составляющие считаются равными в пределах межабонентского участка, активные – отличаются вследствие воздействия неодинаковых протекающих токов и/или погодных факторов. При этом необходимы данные двух разных режимов работы сети, которые на основе анализа динамики изменения питающих токов и/или напряжений отбираются прибором системы учета, подключенным в узле питания. Учитывая, что активные сопротивления проводов должны оставаться неизменными, для расчетов используется режим до изменения энергопотребления в сети и следующий сразу (порядка 0,1 с) после него. Приведен пример расчета, демонстрирующий достоверность предлагаемых уравнений разработанного метода на моделируемой распределительной сети. Результаты исследований ориентированы на усовершенствование автоматизированных систем учета и реализацию их новых функций, повышающих надежность распределительных сетей, а также позволяющих организовать оперативное выявление нетехнических потерь электрической энергии.

Ключевые слова: распределительная сеть, параметры сети, метод идентификации сопротивлений, четырехпроводная трехфазная цепь, сопротивления проводов, решение нелинейных уравнений

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