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Creation of operation algorithms for combined operation of anti-lock braking system (ABS) and electric machine included in the combined power plant

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Abstract. The paper considers the Anti-lock Braking System (ABS) operation algorithm, which enables the implementation of hybrid braking, i.e. the braking process combining friction brake mechanisms and e-machine (electric machine), which operates in the energy recovery mode. The provided materials focus only on the rectilinear motion of the vehicle. That the ABS task consists in the maintenance of the target wheel slip ratio, which depends on the tyre-road adhesion coefficient. The tyre-road adhesion coefficient was defined based on the vehicle deceleration. In the course of calculated studies, the following operation algorithm of hybrid braking was determined. At adhesion coefficient ≤0.1, driving axle braking occurs only due to the e-machine operating in the energy recovery mode. In other cases, depending on adhesion coefficient, the e-machine provides the brake torque, which changes from 35 to 100% of the maximum available brake torque. Virtual tests showed that values of the wheel slip ratio are close to the required ones. Thus, this algorithm makes it possible to implement hybrid braking by means of the two sources creating the brake torque.

1. Introduction

In the modern automotive industry, sufficient attention is given to the study of the deceleration process of the hybrid vehicle using regenerative braking with combined operation of the anti-lock braking system and electric machine included in the combined power plant [1, 2, 3]. The justification to that is as follows:

- Growth of a share of electric vehicles and vehicles equipped with the combined power plants in the total number of sold vehicles. As a consequence, study and search for the optimum algorithms of the electric machine operation within the vehicle (V) transmission become more and more important for ensuring minimization of hazardous emissions and fuel consumption. [4].
- The ratio between the braking power and total power consumption of the vehicle varies from 34% to 82% depending on a driving cycle [5]. Thus, regenerative braking can be considered as one of the important factors, ensuring extension of distance on a single charge and reduction of

hazardous emissions from the internal combustion engine (ICE) as a result of reduction of its operation time.
- The analysis of the foreign works concerned with the studies of this subject has shown their significant growth [6-11].

The majority of works dedicated to the hybrid braking processes, i.e. braking at the same time by the means of friction brakes and regenerative braking using an electric machine, deal with the issues connected to the maximization of power gained from the electric machine during the service braking with a small wheel slip [6, 9-11]. At the same time, the attention given to the combined operation of electric machines and anti-lock braking systems is not enough.

Therefore, development of the anti-lock braking system (ABS), which will enable combined braking with the use of friction brakes and regenerative braking by one or several electric machines and will at the same time meet requirements of Annex 13 to UNECE Regulation No. 13, is currently a long-term and crucial task, solving which will allow improvement of fuel efficiency and ecological compatibility of the vehicles equipped with the combined power plants, and extension of their run distance on a single charge as well.

2. Development of operation algorithms for abs system with hybrid braking ability

For the development of algorithms of hybrid braking in question, N2 category electric vehicle has been chosen as a study subject, and its necessary specifications are shown in table 1.

Table 1. Specifications of N2 category vehicle.

Fully loaded weight	4200 kg
Weight on front axle	1653 kg
Weight on rear axle	2547 kg
Unladen weight	4060 kg
Weight on front axle	1555 kg
Weight on rear axle	2505 kg
Height of the center of mass	
unladen condition	998 mm
fully loaded weight	1001 mm
Tires	185/75R16C
Electric machine	Siemens 1PV5135-4WS14

The electric machine characteristics are shown in figure 1, [12].

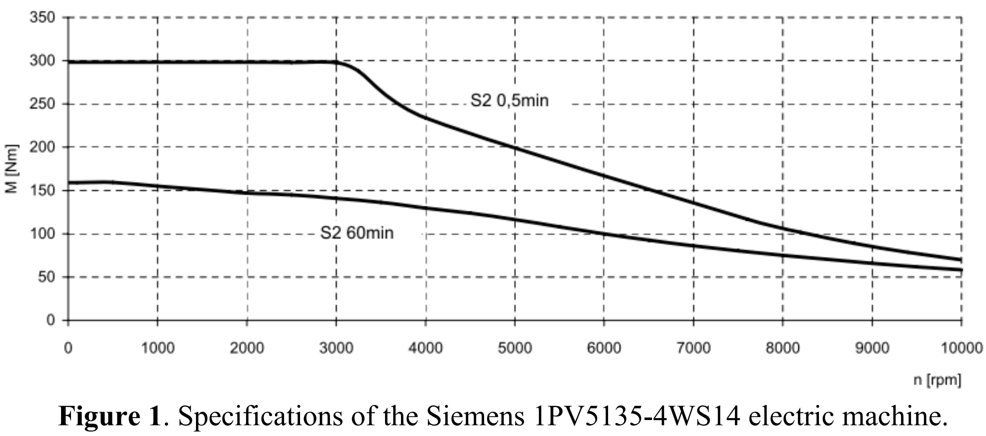

Figure 1. Specifications of the Siemens 1PV5135-4WS14 electric machine.

In order to define maximum longitudinal reaction of traction wheels, we shall examine forces acting on the vehicle at a linear motion (neglecting aerodynamic resistance forces), figure 2.

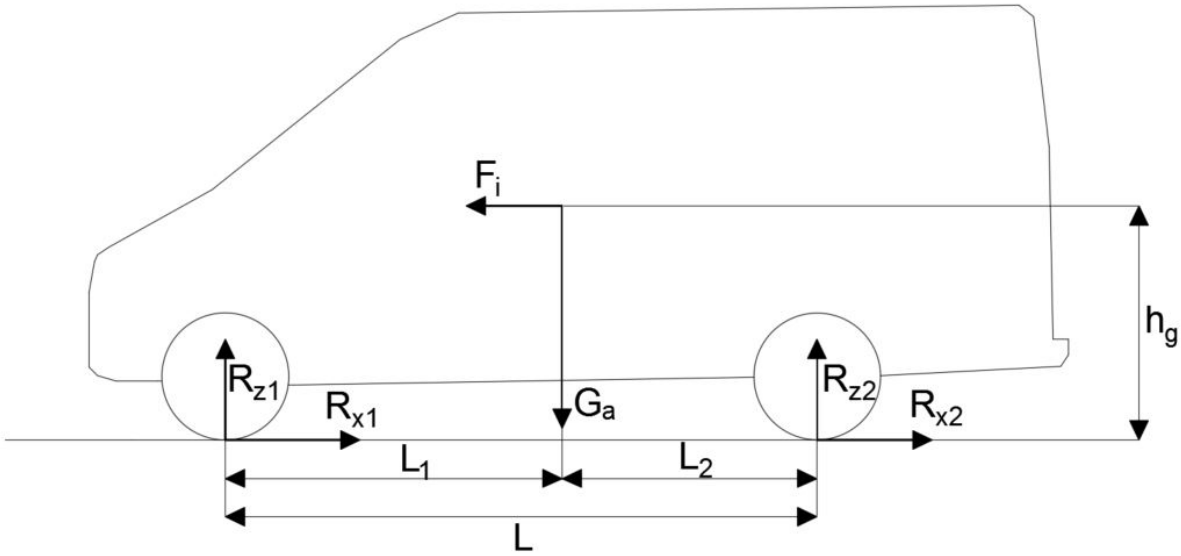

Figure 2. Distribution of forces during braking.

The maximum force acting on the rear axle wheels:

$$F_{x2} = R_{z2} \cdot \varphi_x, \tag{1}$$

where F_{x2} is axial or longitudinal (braking) force on the wheel, R_{z2} is vertical reaction of the rear wheels, andφ_x is the tire-road friction coefficient.

By setting the sum of moments (torques) relative to the front wheel contact equal to zero, we shall find the vertical reaction of the rear axle wheels:

$$R_{z2} = \frac{G_a}{L} \cdot (L_1 - \varphi_x \cdot h_g), \tag{2}$$

where G_a is the vehicle weight, L is the vehicle wheelbase, L_1 is the distance from the center of the front wheel to the center of mass, h_g is the height of the center of mass. By inserting (2) in (1), we shall obtain:

$$F_{x2} = \frac{G_a}{L} \cdot (L_1 - \varphi_x \cdot h_g) \cdot \varphi_x \tag{3}$$

The axial force on the vehicle traction wheels, which the electric machine operating in the energy recovery mode is capable to create:

$$F_{xel} = \frac{\mathrm{T}_{el} \cdot i_r \cdot i_{fd}}{r_d}, \tag{4}$$

where F_{xel} is the axial brake force transferred to the wheel from an electric machine, i_r is the reduction ratio, i_{fd} is the final (axle) drive ratio, and r_d is the effective radius. By equating the (1) expression to the (4) expression, we shall obtain:

$$\frac{G_a \cdot L_1 \cdot \varphi_x}{L} - \varphi_x^2 \cdot h_g = \frac{\mathrm{T}_{\mathrm{el}} \cdot i_r \cdot i_{\mathrm{fd}}}{r_d} \tag{5}$$

Taking into account that dependence between the electric machine braking torque and its speed (rpm) is decreasing (figure 1), we shall set $T_{el} = T_{elmax}$. By solving the equation for φ_x, we shall obtain that the maximum tire-road friction coefficient, which allows the electric machine to ensure enough braking torque without causing wheel lock-up within the whole variation range of the motor shaft rotation speed, is $\varphi_x = 0.1$. At the same time, we need to consider part load modes of the electric machine: since, on the one hand, the braking torque at high rpm of the electric machine shaft is not enough to ensure slip control without using friction brakes, and on the other hand, at low rpm of the electric machine shaft the braking torque excess can appear, which shall cause wheel lock-up. We shall accept the following hybrid operation strategy:

- for φ_x≤0.1, braking of the driving axle is only carried out with the use of the braking torque created by the electric machine. The wheel slip coefficient is adjusted by changing the braking torque created by the electric machine operating in the energy recovery mode;
- for 0.1<φ_x≤0.2, the electric machine shall work with 35% of the maximum torque. The wheel slip coefficient is adjusted by changing the braking torque created by the friction brakes.
- for 0.1<φ_x≤0.3, the electric machine shall work with 50% of the maximum torque. The wheel slip coefficient is adjusted by changing the braking torque created by the friction brakes.
- for φ_x>0.3, the electric machine and friction brakes shall jointly create braking torque and the electric machine shall operate at full capacity, and the wheel slip coefficient is adjusted by the friction brakes.

3. Definition of transfer function of abs hydraulic unit

In order to define the transfer function of the ABS hydraulic unit, an experiment has been conducted using the bench equipment of the Ilmenau Technical University, Germany. The experiment objective was to define characteristics of a commercial ABS hydraulic unit by sending a step signal to the module input and to construct a transfer function.

The bench represents a fragment of the vehicle braking system (figure 3), including the following components: brake pedal with control robot (1), vacuum booster (2), master brake cylinder (3), ABS hydraulic unit (4), four brakes and two braking discs (5). Since the bench imitates only the hydraulic module operation, the brakes are installed pairwise on two fixed brake discs. The bench is equipped with pressure sensors installed at all hydraulic inlet and outlets of the braking module.

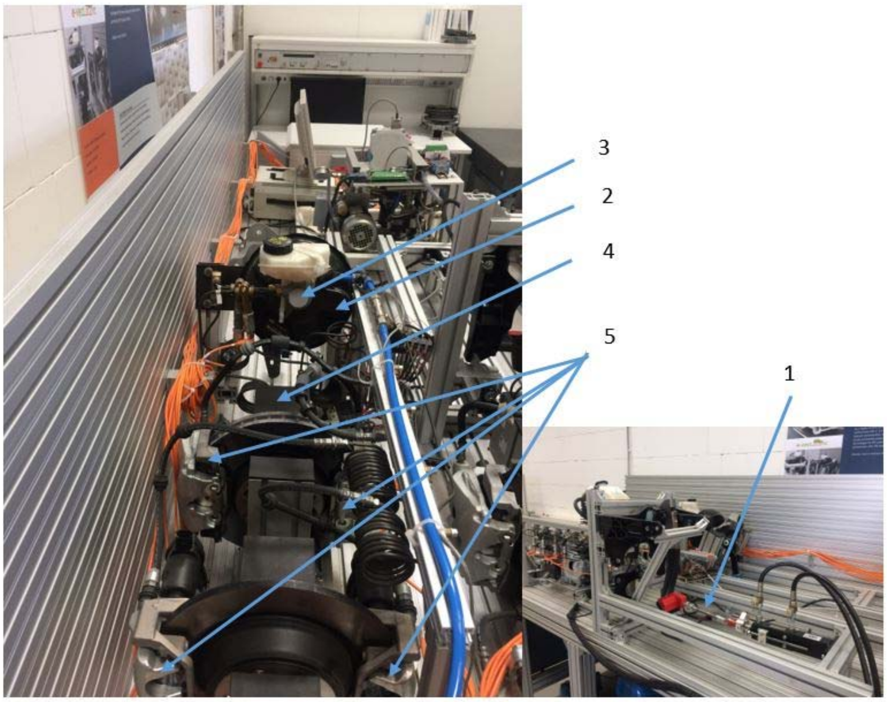

Figure 3. Test bench for ABS study.

The brake pedal is driven by the robotized drive connected to the real-time computer and controlled by Matlab State Flow. The valves and hydraulic module pump are controlled using the algorithms created in the Simulink environment. Information obtained from the pressure sensors is recorded by the computer.

Figure 4 shows pressure change in the brake line of the front right cylinder. Blue color shows change of the target pressure, black shows the real pressure measured on the front right wheel, and red shows the pressure measured using the transfer function.

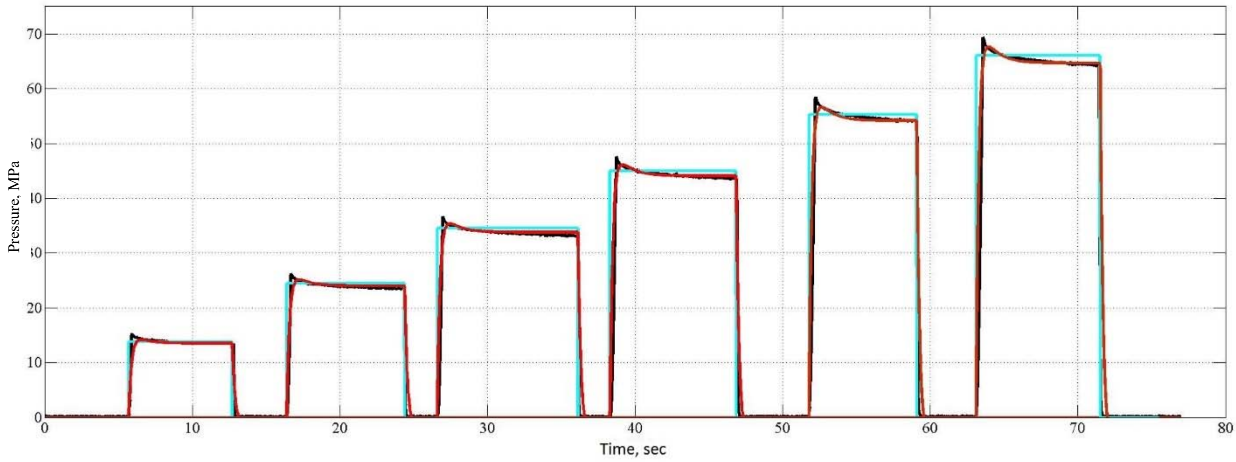

Figure 4. Pressure change in ABS hydraulic unit.

It may be noted that the transfer function describes real change of the pressure with high precision. That particular function is applied in the further work on the algorithm of the ABS module operation.

4. Development of ABS operation algorithms

One of the main purposes of the ABS system is to maintain necessary wheel slip coefficient. In this study, maintenance of the set slip is ensured by using a PID controller with an integral windup filter. As it is known, this controller is a control loop feedback mechanism. It produces the control signal using the sum of three components, which are proportional, integral and derivative components.

The control program, the diagram of which is shown in figure 5, adjusts the braking pressure in the ABS hydraulic module and controls the electric machine operation during braking. Input parameters for the system are pressure measured in the master brake cylinder, slip coefficient of each wheel, vehicle speed, its deceleration and rotation rate of the electric machine shaft.

In this system, search for the optimum value of the slip coefficient depending on the road condition is implemented. The tire-road friction coefficient is defined as a function of the maximum longitudinal deceleration of the vehicle. The decision to shut down the rear brakes is made based on the current tire-road friction coefficient.

The brake cylinder pressure is adjusted in the brake control units. The pressure is adjusted by the PID controller equipped with an integral windup filter. The feedback is performed by monitoring of the values of the wheels' slip coefficient. Control error is calculated as the difference between the target and current wheel slip coefficient.

The rotation and braking torque at the electric machine shaft are controlled by the electric machine control unit. Depending on the current tire-road friction coefficient, decision on the electric machine operation mode is made as follows: full load, part load or torque control using PI controller. In the latter case, the feedback and control error are set in the same way as for the brake control units.

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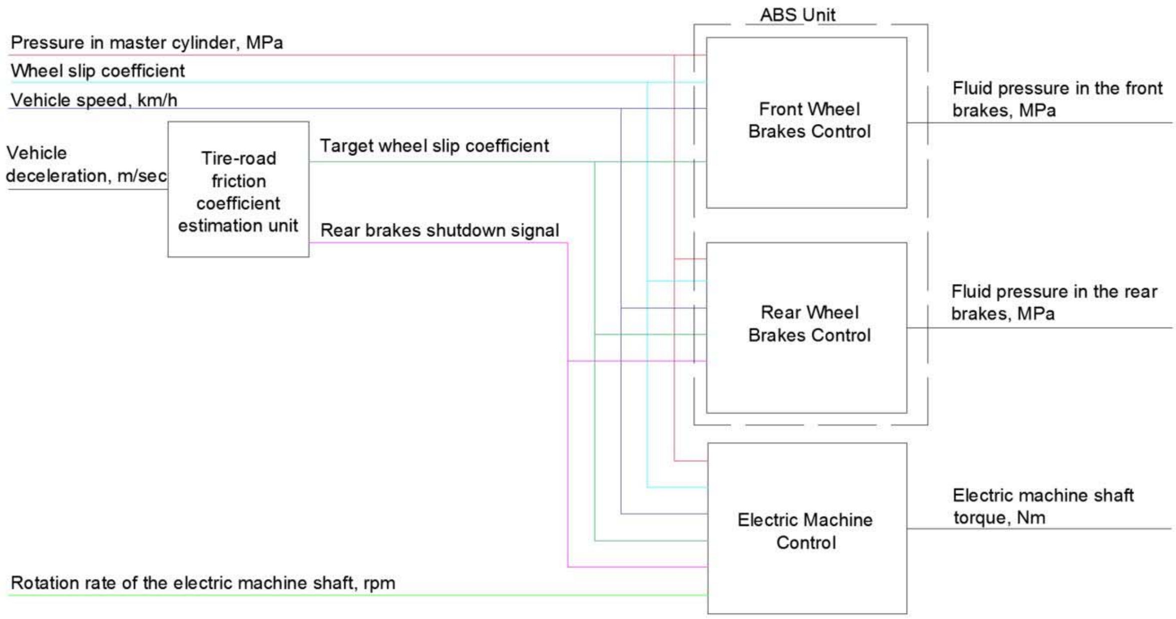

Figure 5. ABS Diagram.

The following virtual testing plan has been accepted for the system testing:

- Initial driving speed - 98 km/h, accelerator pedal travel - 100%.
- After reaching 100 km/h: accelerator pedal travel - 0%, brake pedal travel - 100%.
- Braking until complete stop.

The number of virtual tests were carried out on the road pavement with the tire-road friction coefficient varying from 0.8 to 0.1.

The system operation results for the front left and rear left wheels are shown in figure 6-9. Red shows the values of the wheel slip coefficient, blue shows the pressure change, and green shows the torque at the electric machine shaft.

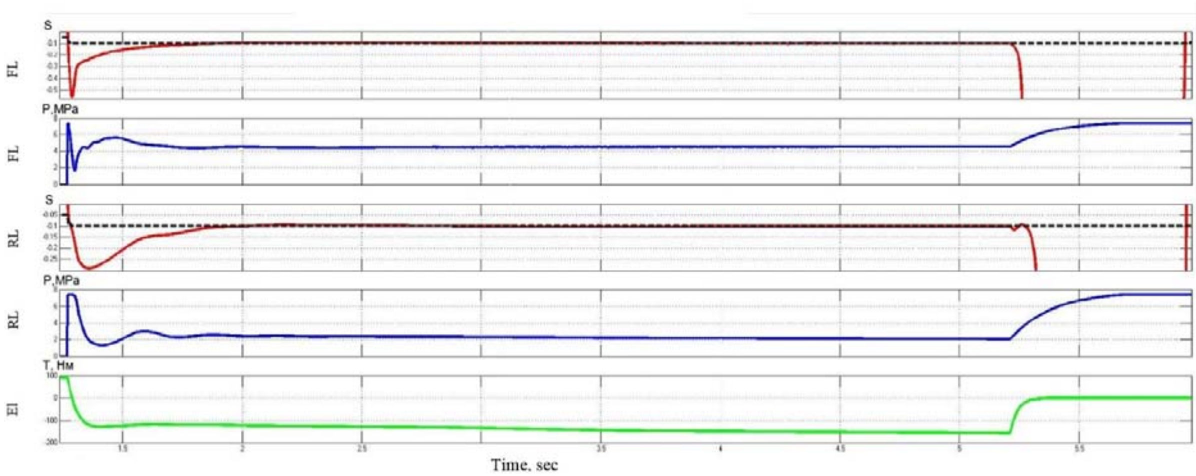

Figure 6. Slip coefficient and braking torque of the vehicle wheels when driving on the road with the friction coefficient of φ_x=0.8.

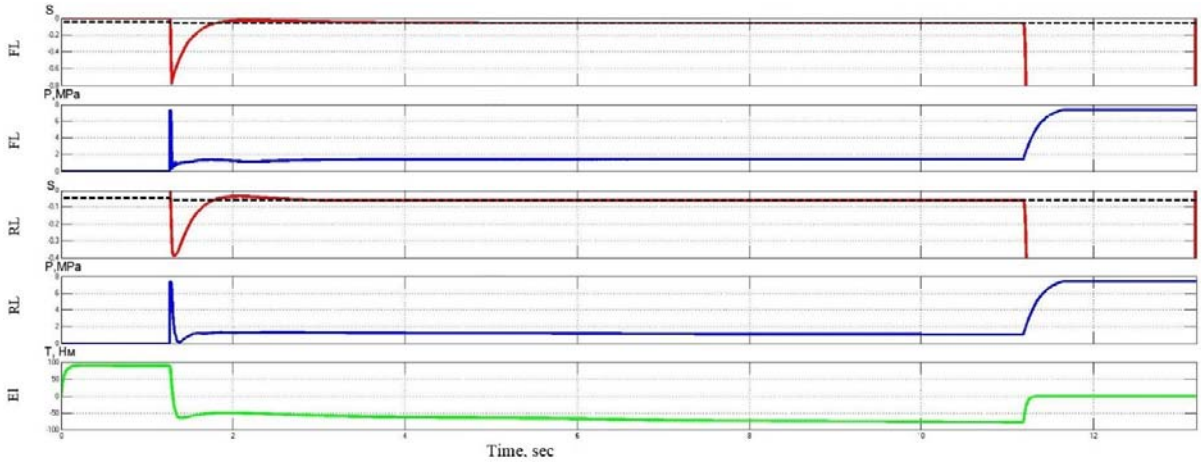

Figure 7. Slip coefficient and braking torque of the vehicle wheels when driving on the road with the friction coefficient of φ_x=0.3.

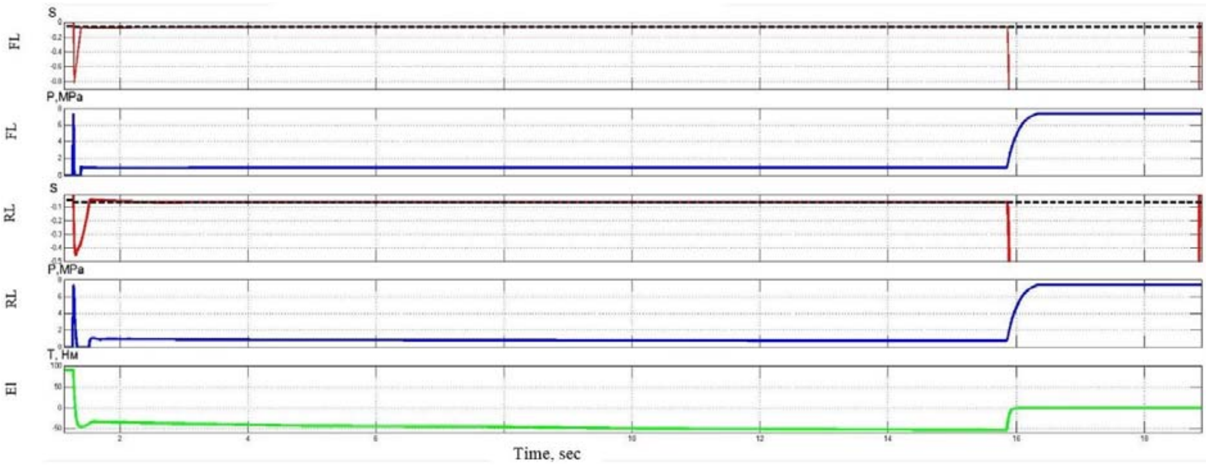

Figure 8. Slip coefficient and braking torque of the vehicle wheels during moving on the road with friction coefficient amounted to φ_x=0.2.

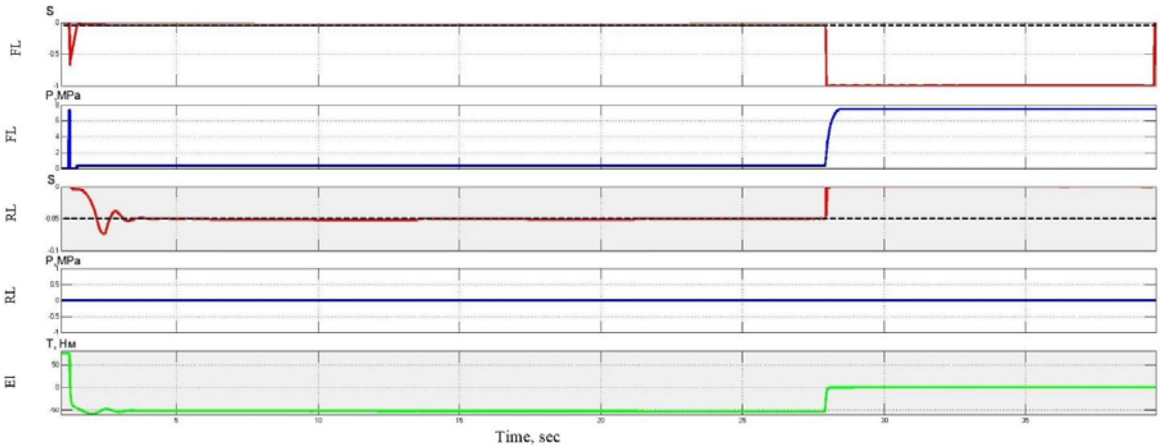

Figure 9. Slip coefficient and braking torque of the vehicle wheels when driving on the road with the friction coefficient of φ_x=0.1.

The virtual testing results showed that the system allows to combine braking using two different sources of the braking torque - friction brakes and electric machine operating in the energy recovery mode. At the same time, the wheel slip coefficient values are close to the target one.

At this stage, the wheel slip is set in an idealised way, and that leads to the smooth shape of the curve characterizing the wheel slip value. Further, it is planned to implement an energy storage device model and more detailed wheel model, and refuse from defining the pavement condition based on longitudinal deceleration of the vehicle.

5. Conclusion

This work allows us to make the following conclusions:

- For the system with hybrid braking, 3 operation options can be defined:
  a. Braking of vehicle driving axle using only electric machine.
  b. Braking of vehicle driving axle using friction brakes and electric machine operating with partial braking torque available when operating in energy recovery mode.
  c. Braking of vehicle driving axle using friction brakes and electric machine operating with full braking torque available when operating in energy recovery mode.
- The braking torque of the electric machine operating in the energy recovery mode can reach from 40% to 100% of the braking torque on the driving axle.
- The preset target value of the slip coefficient of the driving axle wheels is reached in 1.1 sec. when using only friction brakes and in 1.3 sec. when using hybrid braking. Thus, performance of the ABS when braking using the friction brake and the electric machine operating in the energy recovery mode is comparable to the "classical" ABS performance.
- The used approach for the tire-road friction coefficient definition based on the vehicle deceleration is low-efficient due to the high inertia of the vehicle. It is reasonable to study the mathematical model more deeply and to define the tire-road friction coefficient based on the dynamic parameters of the wheel motion.
- In order to get quantitative evaluation of the energy, which can be recovered by using the developed system, it is necessary to study the electric machine in more details and implement the model of the energy storage device.

References

[1] Savitski D, Ivanov V, Augsburg K, Pütz T and Barber P 2016 The new paradigm of an anti-lock braking system for a full electric vehicle: Experimental investigation and benchmarking *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* **230** pp 1364-77

[2] Kulikov I, Shorin A, Bakhmutov S, Terenchenko A and Karpukhin K 2016 A Method of Powertrain's Components Sizing for a Range Extended Electric Vehicle *SAE Technical Paper* 2016-01-8096

[3] Ivanov V, Augsburg K, Savitski D, Schreiber V, Els S and Dhaens M 2017 Collaborative engineering of integrated chassis control for ground vehicle: Case study of lifelong learning technologies in automotive mechatronics *IEEE International Conference on Mechatronics (ICM)* pp 449-54

[4] Panchishny V I, Luksho V A, Kozlov A V, Terenchenko A S and Karpukhinn K E 2015 The problem of toxicity of gas engines and their solutions *Biosciences Biotechnology Research Asia* **12** pp 217-24

[5] Ehsani M, Gao Y and Emadi A 2009 *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles* pp 109-16

[6] Gao Y, Chen L, and Ehsani M 1999 Investigation of the Effectiveness of Regenerative Braking for EV and HEV *SAE Technical Paper* 1999-01-2910

[7] Cikanek S R and Bailey K E 2002 Regenerative braking system for a hybrid electric vehicle

American Control Conference pp 3129-35
[8] Ahn J K, Jung K H, Kim D H, Jin H B, Kim H S and Hwang S H 2009 Analysis of a regenrative braking system for hybrid electric vehicles using an electro-mechanical brake *International Journal of Automotive Technology* **10,2** pp 229-34
[9] Wang F and Zhuo B 2008 Regenerative braking strategy for hybrid electric vehicles based on regenerative torque optimization control *Proceedings of the Institution of Mechanical Engineers Part D: Journal of Automobile Engineering* pp 499–513
[10] Chen Y and Wang J 2012 Fast and global optimal energy-efficient control allocation with applications to over-actuated electric ground vehicles *IEEE Transactions on Control Systems Technology* **20** pp 1202–11
[11] Zijian Zhang Weimin Li Guoqing Xu Liang Zheng 2010 Regenerative Braking for Electric Vehicle based on Fuzzy Logic Control Strategy *2010 2nd International Conference on Mechanical and Electronics Engineering* (Kyoto) pp V1-319-V1-323
[12] http://media3.ev-tv.me/Azure300VDC-400Acurve.pdf
[13] Singh K B and Taheri S 2015 Estimation of tire–road friction coefficient and its application in chassis control systems *Systems Science & Control Engineering* **3** pp 39-61