SIMULATION OF THE HYBRID VEHICLE'S RECUPERATION BRAKING MODE.

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Abstract. The paper considers the synthesis of mathematical model of recuperation braking mode for hybrid vehicle as a complex control object. The results of computer simulation as diagrams of transients of different operating parameters of hybrid vehicle power system are obtained on the basis of developed model. The analysis of simulation results confirms the adequacy of the mathematic model of the recuperation braking mode of hybrid vehicle to real processes. The developed model can be used for synthesis of automatic control systems of the electric motors, power converters, power supplies and chargers for hybrid vehicles.

Keywords: hybrid vehicle, mathematic model, recuperation braking mode.

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Introduction.

In recent years, the issue of economic use of world fuel resources is becoming more acute. There are several ways to solve this issue. One of them is the creation of hybrid and electric cars [1-3].

The use of an electric drive with implementation of an energy recovery system makes it possible to replenish energy during the movement of the vehicle.

At present, the use of energy recovery systems has reached its greatest development in the field of urban electric and railway transport.

Modern research of hybrid cars is mainly related to the modeling of layout schemes, determination of traction and speed properties, energy reserve.

The issue of studying the braking properties of hybrid vehicles on which energy recovery and storage systems are applied remains open, as such work is still under development in different countries of the world [4-6].

Complexity of hybrid power systems of modern vehicles as technical objects causes necessity of complex control systems development, that are especially effective at

functioning in automatic mode [7-9].

Mathematical and computer modeling methods are appropriate to be used for the research of the efficiency of hybrid engines automatic control system (ACS) at the stage of its development [3, 10, 11].

Analytical mathematic and computer modeling are quite effective and cheap instruments, comparatively with experimental and the other ones. Thus, the development of mathematical model of hybrid engines' is quite necessary.

One of the interesting tasks in the study of hybrid vehicle engines, which deserves special attention, is the research of the recuperation braking mode of a hybrid vehicle [12-14].

Studies of this mode will allow the development of highly efficient energy systems, power converters, power supplies, chargers for hybrid vehicles, as well as their automatic control systems.

The purpose of this work is development and research of mathematical model of hybrid vehicle's recuperation braking mode.

Simulation of the hybrid vehicle's recuperation braking mode.

The initial simulation of the hybrid vehicle's recuperation braking mode is conducted at the initial speed of the vehicle before starting of the recuperation braking process $v_{v0} = 100$ km/h and to the complete stop, $v_v = 0$ km/h. The simulation results are presented in the form of graphs of transients of changing the main variables of the hybrid vehicle (hybrid vehicle current speed of linear movement

v_v , angular speed of rotation of the generator anchor ω_r , electromotive force E_r of the generator anchor, current of generator anchor I_r , electrical power N_E of the generator and electrical energy W_E generated during the recuperation braking process).

The transients of changing of the hybrid vehicle main variables (v_v , ω_r , E_r , I_r , N_E and W_E) during the recuperation braking process for the given above parameters are presented in Fig. 1 – Fig. 6.

Fig. 1. Transients of changing of the hybrid vehicle current speed of linear movement v_v (km/h)

Fig. 2. Transients of changing of the angular speed of rotation of the generator anchor ω_r (rad/s)

Fig. 3. Transients of changing of the electromotive force E_r of the generator anchor (V)

Fig. 4. Transients of changing of the current of generator anchor I_r (A)

Fig. 5. Transients of changing of the electrical power N_E of the generator (W)

Fig. 6. Transients of changing of the electrical energy W_E generated during the recuperation braking process (J)

As can be seen from Fig. 1 – Fig. 6, the developed mathematical and simulation models allow to study the recuperation braking mode of the hybrid vehicle under different conditions and parameters values.

In particular, the given models give the **opportunity** to calculate such main variables of the hybrid vehicle during the recuperation braking process as:

linear speed v_v , angular speed of rotation ω_r , electromotive force E_r , current I_r , electrical power N_E and electrical energy W_E .

The obtained results in the form of graphs of transients of changing the main variables of the hybrid vehicle confirm a sufficiently high adequacy of the designed models to real processes.

Further, it is advisable to study the recuperation braking process at different values of the initial speed of the vehicle.

In turn, further simulation of the hybrid vehicle's recuperation braking mode is conducted at 3 different values of the initial speed of the vehicle before starting of the recuperation braking process $v_{v01} = 80$ km/h, $v_{v02} = 100$ km/h and $v_{v03} = 120$ km/h.

The recuperation braking process ended in each case in the complete stop of the vehicle, at $v_v = 0$ km/h.

The simulation results at 3 different values of the initial speed of the vehicle are presented in the form of graphs of transients of changing the main variables of the hybrid vehicle (hybrid vehicle current speed of linear movement v_v , angular speed of rotation of the generator anchor ω_r , electromotive force E_r of the generator anchor, current of generator anchor I_r , electrical power N_E of the generator and electrical energy W_E generated during the recuperation braking process).

The transients of changing of the hybrid vehicle main variables at 3 different values of the initial speed of the vehicle (v_v , ω_r , E_r , I_r , N_E and W_E) during the recuperation braking process for the same values of the other parameters are presented in Fig. 7 – Fig. 12.

The yellow line corresponds to $v_{v01} = 80$ km/h, the blue line corresponds to $v_{v02} = 100$ km/h and the red line, in turn, corresponds to $v_{v03} = 120$ km/h.

Fig. 7. Transients of changing of the hybrid vehicle current speed of linear movement v_v (km/h)

Fig. 8. Transients of changing of the angular speed of rotation of the generator anchor ω_r (rad/s)

Fig. 9. Transients of changing of the electromotive force E_r of the generator anchor (V)

Fig. 10. Transients of changing of the current of generator anchor I_r (A)

Fig. 11. Transients of changing of the electrical power NE of the generator (W)

Fig. 12. Transients of changing of the electrical energy WE generated during the recuperation braking process (J)

At the next stage of research it is advisable to study the recuperation braking process at different values of the total resistance R_a of the anchor winding of the generator and battery charger. In turn, further simulation of the hybrid vehicle's recuperation braking mode is conducted at 3 different values of the total resistance $R_{a1} = 1.02$ ohm, $R_{a2} = 1.72$ ohm and $R_{a3} = 2.42$ ohm. The initial speed of the vehicle before starting of the recuperation braking process for all cases was the same $v_{v0} = 100$ km/h. Also, the recuperation braking process ended in each case in the complete stop of the vehicle, at $v_v = 0$ km/h.

The simulation results at 3 different values of the total resistance R_a of the anchor winding of the generator and battery charger are presented in the form of graphs of transients of changing the main variables of the hybrid vehicle (hybrid vehicle current speed of linear movement v_v , angular speed of rotation of the generator anchor ω_r , electromotive force E_r of the generator anchor, current of generator anchor I_r , electrical power N_E of the generator and electrical energy W_E generated during the recuperation braking process).

The transients of changing of the hybrid vehicle main variables at 3 different values of the total resistance R_a of the anchor winding of the generator and battery charger (v_v , ω_r , E_r , I_r , N_E and W_E) during the recuperation braking process for the same values of the other parameters are presented in Fig. 20 – Fig. 25. The yellow line corresponds to $R_{a1} = 1.02$ ohm, the blue line corresponds $R_{a2} = 1.72$ ohm and the red line, in turn, corresponds to $R_{a3} = 2.42$ ohm.

As can be seen from the graphs of transients (Fig. 13 – Fig. 18) the decrease in resistance R_a can significantly speed up the whole braking process, increase the anchor current I_r and power N_E of generator, as well as slightly increase the released electrical energy W_E generated during the recuperation braking process.

Thus, the developed model can be successfully used at designing and efficiency researching of the automatic control systems of the generators, power converters, power supplies and chargers for hybrid vehicles of different types and different power [16-18].

Fig. 13. Transients of changing of the hybrid vehicle current speed of linear movement v_v (km/h)

Fig. 14. Transients of changing of the angular speed of rotation of the generator anchor ω_r (rad/s)

Fig. 15. Transients of changing of the electromotive force E_r of the generator anchor (V)

Fig. 16. Transients of changing of the current of generator anchor I_r (A)

Fig. 17. Transients of changing of the electrical power N_E of the generator (W)

Fig. 18. Transients of changing of the electrical energy W_e generated during the recuperation braking process (J)

Conclusions.

In this work the development and research of mathematical and simulation models of the hybrid vehicle's recuperation braking mode is carried out.

The presented models are based on equations of physics of processes and allow to study the recuperation braking mode of the different types hybrid vehicles under various conditions and parameters values (initial linear vehicle's speed, electrical power of generator, inclination angle and the quality of the road surface, etc.). The designed mathematical model has a rather high adequacy to the

real processes, which take place in the hybrid vehicles in the recuperation braking mode, that is confirmed by the obtained simulation results in the form of graphs of transients of the main variables changes.

Further research should be conducted towards the development of the functional structures, control devices as well as software and hardware for automatic control systems of the different types hybrid vehicles on the basis of the obtained mathematical and simulation models.