Research of control algorithm of traction drive of a mining dump truck using simulation models of motion

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Abstract. The paper describes control algorithms for a combined power plant made according to a sequential scheme for a 6x6 mining dump truck. The general approaches used in the development of control systems for similar power plants and transmissions are described. The methods of testing and simulation mathematical models used to analyze the operation of control systems for combined power plants are presented. As an example of control systems, the architecture of the developed system used for a mining dump truck is given. The developed control system and simulation model make it possible to analyze the behavior of the traction motor, energy storage device, transmission elements, and operational properties.

1 Introduction
Modern control systems for ground vehicles have a complex architecture, the elements of which directly and constantly interact to ensure a well-coordinated joint operation. The trend of robotization of trucks, in particular those used in quarries, obliges the use of similar control systems for dump trucks. One of the main elements around which all further control is built is the traction drive, since it is ensures the movement of the dump truck.

At present, when developing motor vehicles, manufacturers often give preference to electric power plants, but to ensure the required traction and speed characteristics, it remains necessary to use various transmission elements. In addition to the complexity of the control of electrical power plants, the problem of synchronization of control with transmission elements arises. To solve this problem, separate controllers are used that ensure the joint operation of several components, or all systems of the vehicle. Such controllers are called top-level, and the need for their use in modern vehicles and, in particular, on mining dump trucks is becoming more and more urgent [1-20].

Before testing algorithms for the described controllers, it is necessary to check their operability and adequacy using simulation models of motion; for these purposes, the MATLAB Simulink software package is used, which allows testing and designing these algorithms simultaneously.
2. Vehicle description
The vehicle under study is a 6x6 dump truck. Gross weight is 71000 kg, curb weight is 31000 kg. To ensure the movement of a mining dump truck, a combined power plant is used, made according to a sequential scheme.

The traction motor is equipped with a two-stage planetary gearbox, after which a transfer case is installed, which provides a permanent all-wheel drive of this vehicle.

The braking system is combined, hydraulic with the possibility of remote control, and recuperative.

3. Purpose of work
To ensure the operation of the traction drive of a dump truck in a quarry, it is necessary to implement control algorithms that will simultaneously provide both a reserve in the capacity of an energy storage device for regenerative braking on long descents, and a reserve of energy sufficient to maintain the required level of traction when driving on a long ascent, and will also allow operating vehicle on public roads without changing the overall control strategy.

The implementation of such control becomes possible through the use of a top-level controller, which combines the control of all elements of the power plant and traction drive, and is an intermediate link between the driver and the vehicle. The leading link in this control chain is the traction drive, for which the controller, first of all, forms control, according to the laid down strategy and the current state of the system components, and only then adjusts the operation of the remaining elements [10].

The algorithm is based on the strategy of maintaining the maximum charge level of the energy storage device, which is most often used for military vehicles. The use of this strategy, as a basic one, is due to the primary need to ensure the movement of the vehicle in a long ascent, and for the remaining modes of movement, various additions to the basic strategy are applied, correcting it depending on the current conditions [18].

4. General description of traction drive algorithm
Traction drive control is carried out on the basis of signals from the controls in close cooperation with the controllers of the generator set, the internal combustion engine, traction batteries and other additional components that ensure the joint operation of all systems [1-4, 9-20]. The general structure of the algorithm is shown in Figure 1.

![Figure 1. Block diagram of general structure of traction drive control algorithm.](image-url)
First of all, the controller selects the driving mode based on the command received from the gear selector. Since the command is transmitted via the CAN bus, and the algorithm is responsible for the safe operation of the system, then when determining the driving mode, additional checks are carried out on the state of the brake pedal, position of the parking brake, vehicle speed, transfer in the transfer case and the presence of diagnostic restrictions indicating the presence of a malfunction of the control organ directly or data bus.

After selecting the driving mode, the operating mode of the power plant and the traction drive is selected, which are also reference signals for controlling the internal combustion engine, generator set and traction batteries. The selection of the mode is based on the current state of the system components and external conditions.

The algorithm provides for operation in seven modes, two of which are auxiliary. Auxiliary modes include preparatory and neutral states and are used to ensure correct and consistent control of system elements. In the preparatory STOP_MODE (Figure 2), the procedures for enabling or disabling traction inverters, initial checks of the system state for inhibitions are carried out, and permissions are generated to activate the necessary systems involved in ensuring the movement of the vehicle. Neutral or free-running IDLE_MODE (Figure 2) is used as an intermediate mode for making safe transitions between operating states. In this mode, all systems are ready for operation, but there is no load on the traction drive.

The remaining five modes include three traction modes and two braking modes. Traction modes provide movement only due to the energy of the generator set (ENG_GEN_TRACTION_MODE), only due to battery power (BATTERY_TRACTION_MODE) or due to the joint use of energy from both sources (HYBRID_TRACTION_MODE) (Figure 2) [10]. Such a separation of these modes is necessary to organize the correct calculation of the available power.

Braking is possible in two modes: only due to energy recovery (RECUPERATION_BRK_MODE) or due to the combined use of regenerative energy and the service brake system (HYBRID_BRK_MODE) (Figure 2) [10]. The use of joint control mode during braking is one of the additions to the inherent control strategy. This allows metering the energy level entering the storage device and maintaining the optimal charge level for the current driving conditions. This functionality also protects the battery from overcharging and makes it possible not to lose braking efficiency on descents if the driver ignores the warning signal about a possible overcharge and continues braking using regenerative energy.

Figure 2. Machine of states of subsystem of mode selection of traction drive operation.

The torque on the traction motor is formed on the basis of the selected operating mode, which determines the list of checks and possible restrictions from the system components. Also, during torque determination, the target current on the traction battery and the target power on the generator set are generated. Obtaining these parameters occurs in two stages. At the first stage, according to the
signal from the accelerator pedal and the current rotational speed of the electric motor, a torque request is generated according to the inserted pedal map (Figure 3).

![Figure 3. Map of dependence of torque request on position of accelerator pedal and rotational speed of electric motor.](image)

At the second stage, the available power is checked depending on the driving mode and the current state of the components, in accordance with the inserted control strategy. For example, in the case of joint operation of energy sources, the maximum discharge current of the battery and the available power of the generator set are estimated and the amount of torque available for implementation is formed and, if it is greater than the demand from the driver, then the initial request is taken as the basis for further calculation, otherwise the valid value is taken.

As a result of these calculations, the target values are sent to the subsystem responsible for interaction with the inverters of the traction motor, and the algorithm proceeds to the formation of control for the planetary reducing gear. Then, the data will be processed taking into account the gearbox, and as a result, a control action will be generated on the inverter.

5. Planetary reducing gear control algorithm

The planetary reducing gear used has two stages, which allows focusing more attention on the quality of the switching process and lay ample opportunities for its adjustment on the vehicle.

In the control algorithm, two main components can be distinguished: a block for determining the target transmission and a block for generating control on the final elements.

In the block for determining the target transmission, the manual or automatic switching mode is selected. Also, the conditions for performing the switching are checked, and a request for switching is generated with the assignment of basic parameters for this process \[2, 5\]. When driving in regenerative braking mode, all shifts are blocked.

In the control formation unit on the final elements, the current level on the electro-hydraulic valve is determined to ensure movement in a given gear. Of greatest interest here is the transmission switching process, which is configurable and can carry out this process both with and without power flow interruption. This feature allows debugging the control at the stand and as part of the car using the same software, while minimizing possible damage to the transmission elements \[2, 5\].
Figure 4. Control laws of switching process with interrupted power flow.

During the gear shifting, traction motor torque is controlled to ensure smooth and shockless gear synchronization. In the case when a transmission shift with an interrupted power flow is used (Figure 4), torque control is carried out before the start of the synchronization stage and allows reducing the shift time and speed loss during this process [2]. In the case of gear shifting without interrupting the power flow, torque control allows compensating for control errors during the synchronization stage and ensures timely completion of the process without bumps or increased slipping of the friction element [2].

Also, in order for the friction element to be controllable at the synchronization stage, it is necessary to ensure high-quality filling of its piston cavity. The most stable control law to ensure filling is considered to be the law that uses the stepwise nature of the control action (Figure 5). The filling process with such an effect can be divided into two stages: starting and stabilizing the piston movement [13].

Figure 5 Control laws for piston chamber filling process using different control profiles.
At the stage of the piston moving away, the control action is formed in such a way as to ensure a large fluid flow through the electro-hydraulic valve, which in turn provides the impulse to the piston of the friction control element sufficient for its starting and further movement [13]. This stage, as a rule, does not exceed half of the entire process of filling the piston chamber.

During the stabilization stage, the control action is kept at a level corresponding to the point of contact of the piston with the friction element [13]. At this level, the piston slightly presses the set of friction discs, providing a sampling of the gaps between the discs. The torque transmitted to the friction control at the moment is rather negligible. Keeping the control action at this level allows for a smooth deceleration of the piston after it starts to move and does not allow it to stop prematurely.

6. Traction inverter control algorithm
Traction inverter control algorithm operates in three modes: stop, standby and operation. In stop mode, the activation signals of traction inverters are controlled and tested to ensure they are safely turned on or off. In standby mode, traction inverters are without load and wait for the necessary conditions to be met to ensure their further operation. In the operating mode, the formation of the load is carried out only under the condition that internal combustion engine, generator, traction batteries and planetary gearbox have carried out all the necessary operations and are ready to start moving. In addition, when the load is being formed, the presence of diagnostic restrictions and restrictions on the speed of movement with active differential locks is taken into account [10].

7. Model for evaluating operation of traction drive control algorithm
The model for evaluating the operation of the algorithm consists of three parts (Figure 6): the module for the formation of reference influences or the module for simulating the driver and controllers of auxiliary systems, the traction drive control algorithm [2, 5] and a simplified model of transmission dynamics [10].

![Figure 6. Simulation model structure.](image)

Equation of dynamics of input shaft of transmission is

\[ J_{e/m} \cdot \omega_{e/m} = T_{e/m}(\alpha_{ped}, \omega_{e/m}) - T_{in}, \]  

(1)

where \( J_{e/m} \) is moment of inertia of the electric motor, kg\( \cdot \)m\(^2\); \( \omega_{e/m} \) is angular speed of the electric motor, rad / s; \( T_{e/m}(\alpha_{ped}, \omega_{e/m}) \) is torque of the electric motor, N\( \cdot \)m; \( T_{in} \) is torque on the transmission input shaft, N\( \cdot \)m.

Equation for engine torque is
\[ T_{e/m} = \begin{cases} \min(T_{\text{request}}(\alpha_{\text{ped}}, \omega_{e/m}), T_{\text{cap}}) \alpha_{\text{acc}} > 0, \alpha_{\text{reg}} = 0; \\ 0 \text{ at } \alpha_{\text{acc}} > 0, \alpha_{\text{reg}} > 0 \text{ or } \alpha_{\text{acc}} = 0, \alpha_{\text{reg}} = 0; \\ T_{\text{reg}}(\alpha_{\text{reg}}) - T_{\text{brak}} \alpha_{\text{acc}} = 0, \alpha_{\text{reg}} > 0, \end{cases} \]

where \( T_{\text{request}}(\alpha_{\text{ped}}, \omega_{e/m}) \) is driver torque request, N·m; \( T_{\text{cap}} \) is available torque of the electric motor, limited by the capabilities of the power plant, N·m; \( T_{\text{reg}}(\alpha_{\text{reg}}) \) is regenerative braking torque, N·m; \( T_{\text{brak}} \) is braking torque, N·m.

\[ T_{\text{reg}} = \begin{cases} -T_{\text{reg}}^{\text{max}}(\alpha_{\text{reg}}) at \nu_{\text{veh}} > 3 \text{ km/h} \\ 0 \text{ at } -3 \text{ km/h} \leq \nu_{\text{veh}} \leq 3 \text{ km/h} \\ T_{\text{reg}}^{\text{max}}(\alpha_{\text{reg}}) at \nu_{\text{veh}} < 3 \text{ km/h} \end{cases} \]

where \( \nu_{\text{veh}} \) is vehicle speed, m/s.

Equation for dynamics of the transmission output shaft is

\[ J_{\text{veh}} \cdot \omega_{\text{out}} = T_{\text{out}} - T_{\text{res}} - T_{\text{brak}}, \]

where \( J_{\text{veh}} \) is reduced moment of inertia of the vehicle, kg·m²; \( \omega_{\text{out}} \) is angular speed at the transmission output shaft, rad/s; \( T_{\text{out}} \) is torque on the transmission output shaft, N·m; \( T_{\text{res}} \) is total moment of resistance to motion, N·m.

\[ T_{\text{out}} = i_{\text{pgr}} \cdot i_{\text{tc}} \cdot T_{\text{in}}, \]

where \( i_{\text{pgr}} \) is planetary gear ratio; \( i_{\text{tc}} \) is transfer ratio of the transfer case.

Equation for total moment of resistance is

\[ T_{\text{res}} = (P_{\text{aer}}(\nu_{\text{veh}}) + P_{\text{roll}}(\nu_{\text{veh}}) + P_{\text{road}}(\alpha_{\text{grad}})) \cdot r_{\text{rad}}, \]

where \( P_{\text{aer}}(\nu_{\text{veh}}) \) is aerodynamic drag force, N·m; \( P_{\text{roll}} \) is rolling resistance force, N·m; \( P_{\text{road}}(\alpha_{\text{grad}}) \) is road resistance force, N·m; \( r_{\text{rad}} \) is rolling radius, m.

Equation for aerodynamic drag force is

\[ P_{\text{aer}}(\nu_{\text{veh}}) = c_{\text{x}} \cdot F_{\text{front}} \cdot \rho_{\text{aer}} \cdot \nu_{\text{veh}}^{2}/2, \]

where \( c_{\text{x}} \) is drag coefficient; \( F_{\text{front}} \) is vehicle frontal projection area, m²; \( \rho_{\text{aer}} \) is air density, kg/m³.

Rolling resistance equation is

\[ P_{\text{roll}}(\nu_{\text{veh}}) = f(\nu_{\text{veh}}) \cdot M \cdot g, \]

where \( f(\nu_{\text{veh}}) \) is rolling resistance coefficient; \( M \) is vehicle weight, kg

\[ f(\nu_{\text{veh}}) = f_{\text{tire}} \cdot (1 + k_{\nu} \cdot \nu_{\text{veh}}), \]

where \( f_{\text{tire}} \) is tire rolling resistance coefficient; \( k_{\nu} \) is speed loss factor.

Equation for road resistance force is

\[ P_{\text{road}}(\alpha_{\text{grad}}) = M \cdot g \cdot \sin(\alpha_{\text{grad}}), \]

where \( \alpha_{\text{grad}} \) is road elevation.

Equation for reduced moment of inertia to transmission output shaft is

\[ J_{\text{veh}} = \frac{M \cdot r_{\text{wh}}^{2} + 6 \cdot J_{\text{wh}}}{(i_{\text{fdr}})^{2}}, \]

where \( J_{\text{wh}} \) is wheel moment of inertia, kg·m²; \( i_{\text{fdr}} \) is final drive ratio.

Equation of moment of working brake system is
8. Simulation results and algorithm evaluation

Motion simulation is carried out in two stages. At the first stage, a primary check of the algorithm’s operability is carried out according to the set test scenarios, which make it possible to check that the generated load, the processes of gear shifting and braking on descents reflect the set requirements. The second stage is the simulation of the movement in various cycles, which makes it possible to assess the performance of the set control strategy and confirm its performance.

Figure 7-11 shows simulation results using basic test scenarios. The graphs show the positions of the controls: the accelerator pedal and the regeneration pedal, the actual torque and the torque on the drive requested by the driver, the speed of the gearbox input shaft and the speed of the gearbox output shaft, as well as the currents on the electro-hydraulic control elements of the planetary gearbox.

\[ T_{brak} = \begin{cases} -T_{brak}^{max} & \text{at } v_{veh} > 0 \\ 0 & \text{at } v_{veh} = 0 \\ T_{brak}^{max} & \text{at } v_{veh} < 0 \end{cases} \]  

(12)

Figure 7. Vehicle acceleration from a standstill.

Figure 8. Vehicle acceleration while driving with downshifting.
Figure 9. Vehicle movement on a gradient of 12% with downshifting.

Figure 10. Movement of vehicle in regenerative braking mode with interception of control by service brake system.
Having confirmed the performance of the algorithm on test scenarios, we can consider the driving cycle in the quarry. To carry out this simulation, the authors of the work recorded the movement of a real dump truck along two routes, one of which reflects the movement of the dump truck into the face (Figure 12), and the other one reflects the movement along approach roads with slight gradients (Figure 13). Based on the results of these records, the initial data for motion simulation were generated.

During the simulation, a primary set of parameters was carried out, with which the algorithm ensures a sufficient level of battery charge and minimizes the likelihood of overcharging, and the dump truck is always provided with a sufficient level of traction and a reserve for recuperation.

**Figure 11.** Vehicle movement in mode of simultaneous pressing of accelerator and regenerative pedals.

**Figure 12.** Movement of vehicle into face.
9. Conclusion
The developed traction drive algorithm showed its efficiency based on the results of modeling the movement in the quarry. The battery charge level, at which it is possible to achieve a balance of energy reserve and recuperation, must be maintained within a narrow range of 50-70%. While maintaining this level of charge, a 12% uphill movement with a length of 270 meters at an average speed of 25 km/h can be provided, and the recuperation margin will be enough for a long descent of 320 meters while maintaining an average speed of 27 km/h. According to the measurements, the length of the descent is 190 meters, and the ascent is 105 meters, and the slope of the road does not exceed 6%, which makes it possible to assert that the algorithm provides the requirements for the traction drive.

Confirmation
The work was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation in the framework of Agreement No. 075-11-2020-031 of 12/14/2020, with PAO (Public Joint Stock Company) KAMAZ under the Creation of high-tech production of family of robotic mining dump trucks with carrying capacity of up to 90 tons with electromechanical transmission based on digital technologies complex Project, with the participation of FGBOU VO (Federal State Budgetary Educational Institution of Higher Education) T.F. Gorbachev Kuzbass State Technical University in terms of the implementation of research, development and technological work.

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