Investigation of traction balance and movement dynamics of a self-propelled mine car in complex mining and technical conditions

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Abstract. In the article, an analysis of the dynamics of a mine self-propelled wagon (MSPW) while moving along routes with different inclination angles is presented, taking into consideration the force distribution acting on the driving wheels. The article discusses the basic components of the tractive balance: tractive force, grade resistance, rolling resistance, and inertial resistance during acceleration. The tractive force acting on the driving wheels varies from 23 to 105 kN depending on the inclination angle and operating conditions. Grade resistance, rolling resistance, and inertial resistance are constant, while inertial resistance occurs during the initial phase of motion and disappears after achieving a steady-state velocity. It was determined that as the inclination angle increases, the velocity reduces, the time for the transient process increases, and simultaneously, the maximum starting tractive effort needed to overcome resistance increases.

INTRODUCTION

Mine self-propelled wagons (MSPWs) are dedicated vehicles for underground mines to transport mineral resources safely and efficiently through tunnels. MSPWs operate on electric drives, which enhance productivity and ensure the reliability of the mining process. Currently, MSPWs operating in our country have three-phase asynchronous (induction) AC electric motors as drives. The use of induction motors instead of DC motors has a number of advantages, including improved safety in explosive environments and simplified electrical equipment configuration [1,2].

In the electric drives of mine self-propelled cars, there are several approaches for controlling induction motors, namely stator voltage control (thyristor voltage regulator, TVR), frequency control, and stepwise variation of the number of poles of the winding. These approaches ensure the necessary traction and dynamic properties for complex mining and technological operating conditions [3]. TVR makes it possible to regulate the speed of an induction motor by varying the effective value of the stator voltage. It decreases the high starting current and, consequently, the surge of the starting torque; however, the electric drive with TVR is not economical for a long and deep speed regulation of the car [4]. Frequency control of induction motors is one of the most widely used approaches and is currently being widely implemented. This approach ensures smooth regulation of the speed within a wide range, and the resulting characteristics can have any desired stiffness. The disadvantages of frequency converters (FCs) for induction motors include high initial cost, as well as additional losses introduced by the converter into the overall power system [5, 6].

At present, one of the ways for managing mine self-propelled cars is the stepwise regulation of the engine rotational speed by means of changing the number of poles of the winding. For mines with complex technological conditions, the presence of curved tracks, numerous changes in gradients during movement, as well as low maneuverability during passing through curves and connections, does not allow using the high speed (1500 rpm) of the three-speed electric motor of the AVTM15-4/6/12 type (1500/1000/500 rpm), specifically designed for the running gear of the 5VS-15M self-propelled wagon [7].

Considering the operational requirements of mine self-propelled wagons designed for mines with complicated mining and technical conditions, the electric drive of the running gear was improved. Taking as a basis the three-speed induction motor AVTM15-4/6/12, used earlier in standard operation conditions, a two-speed stator winding with a 6/12 pole ratio with high electromagnetic properties and the ability to switch the number of poles was developed to enhance the dynamic and tractive properties of the motor [8].

One of the important tasks of modern mining mechanics and underground transport operation is the investigation of forces influencing a mine self-propelled wagon. The forces have a direct impact on the motion dynamics, stability, and efficiency of the electric drive of the vehicle.

EXPERIMENTAL RESEARCH

The relationship between the tractive effort developed at the driving wheels and the forces resisting motion determines the efficiency of motion of mine self-propelled wagon used in underground mine workings.

In addition to being a fundamental tool for evaluating the dynamics of MSPWs, choosing electric drive parameters, and verifying operating modes under challenging mining and technical conditions, the idea of the traction balance enables a thorough description of the distribution of mechanical energy produced by the electric drive to overcome various types of resistance.

During the motion of an MSPW, the tractive effort at the driving wheels is expended to overcome grade resistance, rolling resistance, inertial resistance during acceleration, and, in some cases, other external factors. In general form, the traction balance equation can be written as:

$$P_{wheel} = P_f \pm P_s \pm P_{air} \pm P_j . \tag{1}$$

Since the resistance to motion is P_{Σ}(neglecting air resistance P_h), the tractive force can be written as:

$$\frac{M_m i_{tr} \eta_{tr} n}{r_w} = G_w \psi \pm \frac{G_w \delta_r}{g} j_w , \tag{2}$$

where: M_{m} – torque of the traction motor, kgf·m;
n – number of traction motors;
r – wheel radius, m.

Equation (2) is referred to as the MSPWs traction balance equation. It is convenient to express this equation in the form of the relationship P_{whell} (v_w), which shows the required traction force P_{whell} to overcome static resistances or to ensure steady motion of the MSPWs at different speeds.

In this case, the acceleration of the MSPW is taken as $J_v = 0$. Thus, the traction force on the wheels can be determined using the following formula:

$$P_{whell} = \frac{M_m i_{tr} \eta_{tr} n}{r_w} , \tag{3}$$

Here: M_m – torque of the traction motor, kgf·m;
n – number of traction motors.
Actual speed of the MSPWs.

$$v_w = \frac{2\pi\, r_w n_m 60}{i_{tr} \cdot 1000} , \qquad \text{km/h} \tag{4}$$

The traction characteristic of the MSPW is constructed for all transmission stages and speed modes and reflects the dependence of the tractive effort developed at the driving wheels on the vehicle speed under various operating conditions. Analysis of these characteristics makes it possible to determine the limiting motion modes, as well as the conditions for stable and safe operation of the MSPW.

Two squirrel-cage two-speed asynchronous electric motors with a power rating of 55/26 kW are used as the traction drive of the MSPW. The motor speed is controlled using two switching keys.

Torque from the shaft of the asynchronous electric motor is transmitted through a distribution gearbox that includes a three-stage gear train with five gears. This gearbox is the main kinematic element of the transmission and ensures torque distribution between the front and rear axles. The number of teeth of the first and second stages is 22 and 31, respectively, and of the second and third stages 31 and 38.

A bevel gear transmission with mutually perpendicular shafts is used to drive the wheels, with the number of teeth equal to 11 and 25. In order to increase the torque in the transmission, a planetary gear with a gear ratio of 8.25 is additionally used, which makes it possible to significantly increase the tractive capability of the MSPW when moving on steep inclines.

RESEARCH RESULTS

To study the tractive performance developed at the wheels by the newly designed motor in the MSPW running gear, a simulation model based on the kinematic scheme of the running gear was developed using the SimulationX software. Figure 1 shows the MSPW running gear model created in SimulationX.

The MSPC electric drive is driven by two asynchronous traction motors with pole-changing windings rated at 55/26 kW for each speed, respectively. Using this model, the maximum inclination angle was determined: for the lower rotational speed of the asynchronous motor (500 rpm) – 16°, and for the higher rotational speed (1000 rpm) – 9°.

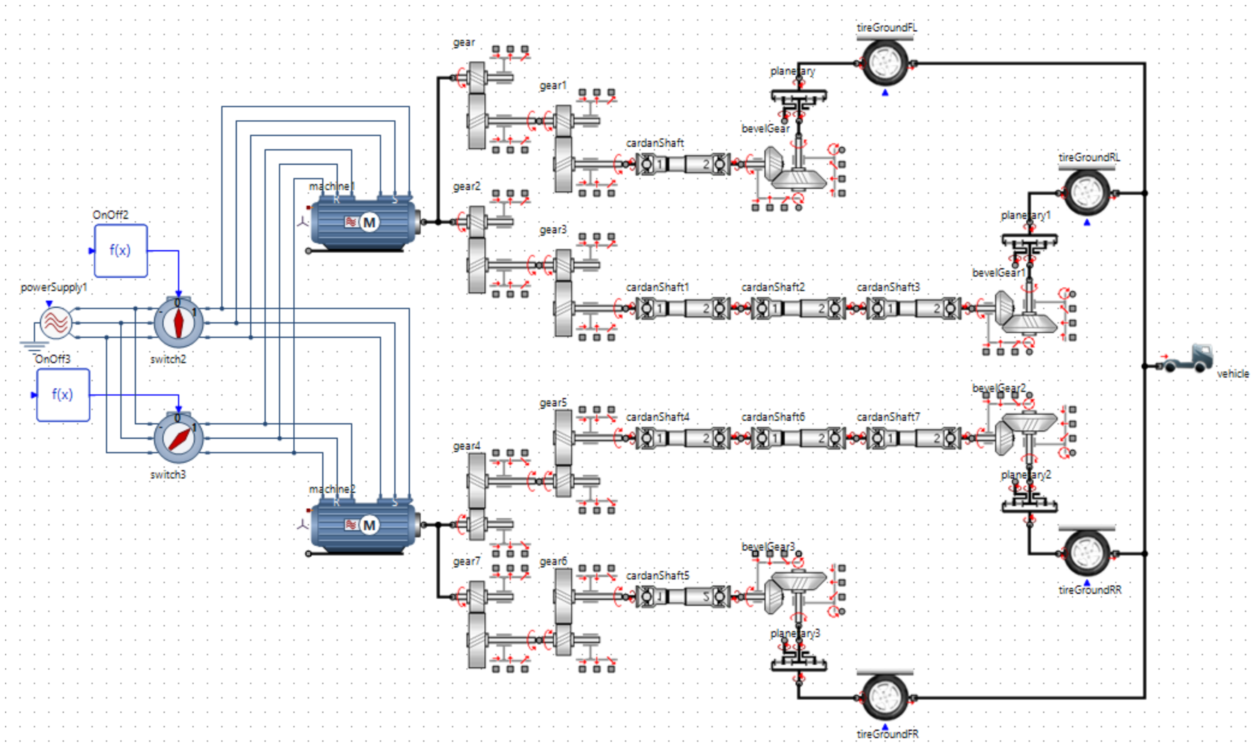


FIGURE 1. Simulation model of the MSPC kinematic scheme

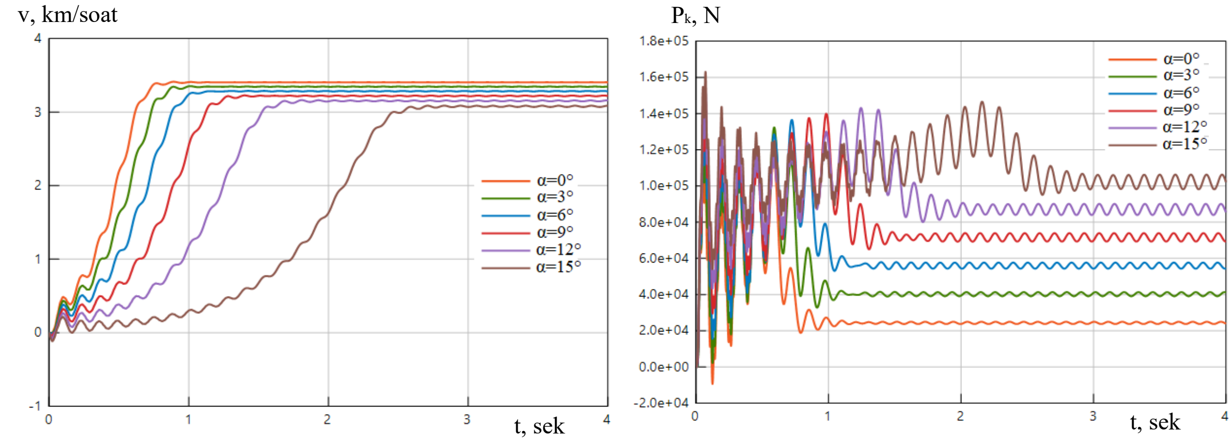
Using the simulation model, the speeds and tractive forces of an MSPW with a total weight of 31 tons were investigated on mine roads with inclinations of 0°, 3°, 6°, 9°, 12°, and 15° in a mine with complex mining and technological conditions. The results showed that the MSPC speed is in the range $v = 3–3.4$ km/h, and the time to reach steady speed, i.e., the duration of the transient process, is $t = 0.8–2.7$s.

During motion, the tractive force at the driving wheels varies within the range $P_k = 23–105$kN (Fig. 2). Analysis of the dependences of speed and tractive force on the inclination angle showed that an increase in the angle αhas a negative effect on the dynamic characteristics of motion. As the incline increases, a decrease in speed and an increase in the time required to reach the operating mode are observed. At the same time, during start-up, an increase in the maximum tractive force is observed, which is associated with the need to overcome greater grade resistance.

When the MSPW is moving, several resisitance forces act on it, including grade resistance (P_h), rolling resistance (P_f), inertial resistance (P_j), and air resistance (P_v). Air resistance is neglected, since it is very small compared to the other resistance forces.

As a result of the conducted studies, the influence of the mine road inclination on the resistance forces acting on the self-propelled car was comprehensively investigated. Figure 3 shows the variation of resistance forces acting on the MSPW at mine road inclinations of $\alpha = 10°$and $\alpha = 15°$, respectively. Figure 3a presents an analysis of the dynamic behavior of the forces acting on the self-propelled car at an inclination of $\alpha = 10°$and a transient duration of $t = 1.5$s. The graph clearly highlights four main components of the force interaction: tractive force P_k, grade resistance P_h, rolling resistance P_f, and inertial resistance P_j, each indicated by its own color for clarity.

The tractive force (red) is characterized by rapid growth at the initial moment of time, reflecting the dynamic acceleration of the car during start-up. After completion of the transient process, the force stabilizes at a constant level of about 76.8 kN, which corresponds to steady-state motion of the car on the given incline. The grade resistance (blue) maintains a constant value of 52.8 kN throughout the entire observation period, demonstrating that the effect of the incline on motion remains unchanged over time and does not depend on dynamic fluctuations.

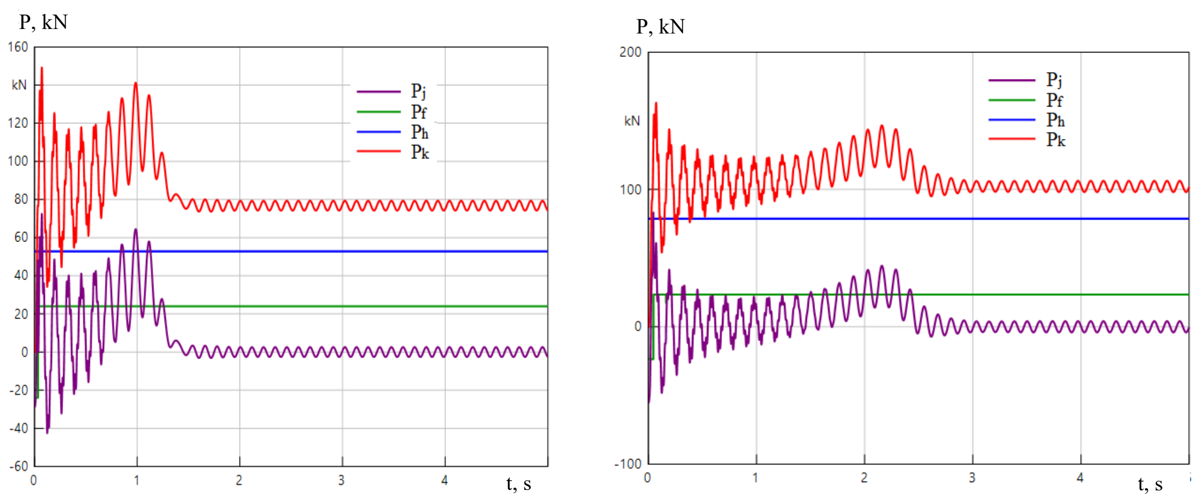


a) b)

FIGURE 2. MSPC running gear characteristics: a) speed, b) tractive force

The rolling resistance (green) also remains constant and is approximately 24 kN, reflecting the stability of internal mechanical losses in the wheel–axle system of the car. Of particular importance is the inertial resistance (purple), which manifests itself at the initial stage of motion, counteracting the instantaneous acceleration of the car. After the end of the transient process, this component pracitcally disappears and stabilizes at about 0 kN, which corresponds to the transition of the car to uniform motion without additional acceleration.

Figure 3b shows the variation of resistance forces acting on the MSPW at a mine road inclination of $\alpha = 15°$. The duration of the transient process is $t = 2.7$s, while the grade resistance force is $P_h = 78.7$kN, the rolling resistance force is $P_f = 23.5$kN, and the tractive force is $P_k = 102.2$kN.

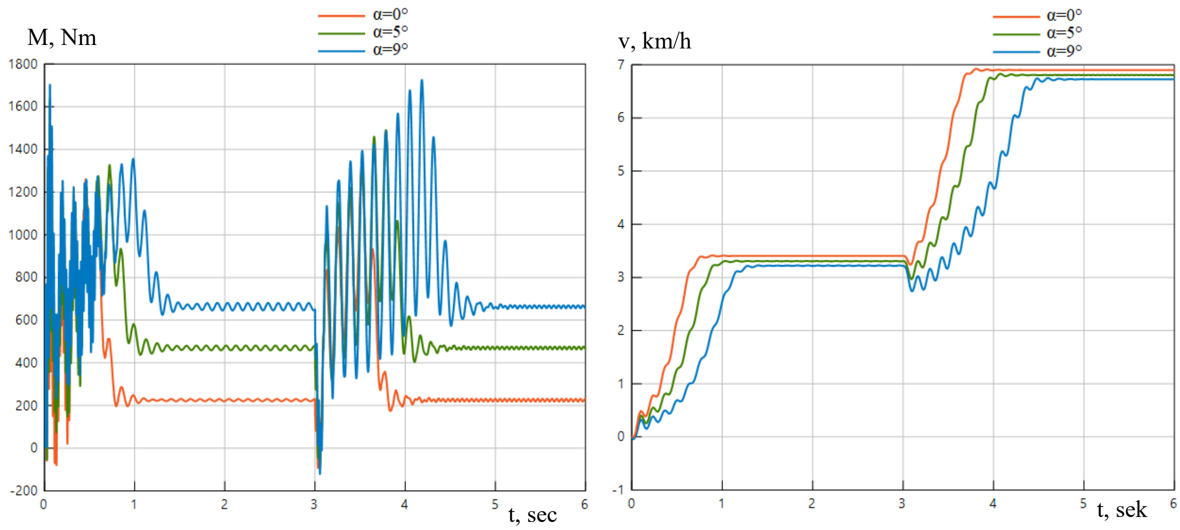


a) b)

FIGURE 3. Variation of resistance forces: a) at an inclination of $\alpha = 10°$, b) at an inclination of $\alpha = 15°$

Figure 4 presents graphs of the change in the drive motor torque (Fig. 4a) and the MSPW speed (Fig. 4b) when switching the motion mode from higher speed to lower speed for mine road inclinations of 0°, 5°, and 9°. The presented dependences make it possible to analyze the dynamic processes that occur when changing the motion mode under different longitudinal slopes.

Analysis of the graphs shows that with an incraese in the mine road inclination angle, the torque developed by the drive motor increases significantly. Thus, at an inclination of 0°, the torque value is about 230 N·m; at an inclination of 5°, it increases to 470 N·m; and at an inclination of 9°, it reaches 660 N·m. The increase in torque is due to the growth of resistance forces to motion, primarily the grade resistance force, which requires additional energy input from the electric drive to maintain the specified motion mode.



a) b)

FIGURE 4. Change in torque (a) and speed (b) during start-up of the MSPW electric motor from side $p_2 = 6$ and switching to side $p_1 = 3$

The MSPW speed in steady-state modes changes insignificantly and retains stable values. At the lower speed, it is 3.2, 3.3, and 3.4 km/h for inclinations of 0°, 5°, and 9°, respectively, whereas at the higher speed the values are 6.7, 6.8, and 6.9 km/h. This indicates sufficient stiffness of the mechanical characteristics of the drive and the effectiveness of the speed control system.

The temporal parameters of transient processes show that when starting the MSPW at the lower speed, the duration of the transient process is in the range of 0.7–1.2 s, whereas when starting at the higher speed, this interval increases to 0.8–1.5 s. The lengthening of the transient process at higher speed is explained by the increase in inertial loads and dynamic effects in the electric drive system.

CONCLUSIONS

As a result of the analysis of the traction balance of the mine self-propelled car, it was established that the use of a two-speed asynchronous electric drive in combination with a multi-stage mechanical transmission provides the required reserve of tractive effort for operation under complex mining and technical conditions. The constructed traction characteristics showed that at a low rotational speed of the electric motor, the MSPW is capable of confidently overrcoming inclines of up to 16°, which corresponds to real operating conditions in potash mines. With an increase in the inclination angle, the required torque increases, as well as the duration of transient processes, especially when operating at higher speeds. At the same time, the control system ensures stability of speed modes and reliable switching between them.

Analysis of the force characteristics showed that during motion, the tractive force at the driving wheels of the MSPW varies over a wide range of values -from 23 to 105 kN. The analysis confirmed that an increase in the inclination angle of the mine road generally has a negative effect on the running characteristics of the MSPW.

The obtained results confirm the correctness of the selected parameters of the electric drive and transmission, as well as the expediency of using two-speed asynchronous motors to improve the tractive capabilities and operational reliability of MSPWs.

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