Simulation Modeling of the Electric Drive System of a Mine Self-Propelled Wagon Using SimulationX

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Abstract: This paper presents a simulation model of the electric drive of the running gear of a 5VS-15M mine self-propelled wagon (MSPW), developed using the SimulationX software package. The model employs two pole-changing induction motors rated at 55/26 kW. A three-stage distributing gearbox with five gear pairs is connected to the shaft of the induction motor. This unit serves as the main transmission system, distributing the torque to two axles (front and rear wheels). The numbers of teeth in the first and second stage gear pairs of the distributing gearbox are 22 and 31, respectively, while the second and third stage gear pairs have 31 and 38 teeth, respectively. To drive the wheels, a bevel gear set arranged perpendicularly is used. In the bevel gearbox, the numbers of teeth are 11 and 25. A planetary gear train is employed to transmit and modify the torque, with its primary function being torque amplification. The transmission ratio of the planetary gear is 8.25. Using the simulation model, the MSPW with a total mass of 31 tons was investigated under severe mining conditions at mine road slope angles of 0°, 3°, 6°, 9°, 12°, and 15°. It was determined that at these slope angles, the motor torque varies correspondingly as 240, 380, 510, 650, 800, and 950 N·m. For the above-mentioned slope angles, the vehicle speed and tractive force characteristics were analyzed. The MSPW speed ranges from 3 to 3.4 km/h, and the time required to reach this speed (i.e., the transient process duration) is 0.8–2.7 s. During vehicle operation, the tractive force at the driving wheels varies within the range of 23–105 kN.

1 INTRODUCTION

Despite the fact that modern self-propelled mine wagons and dump trucks manufactured in the CIS countries still require improvements in maneuverability, the mass-to-payload ratio, and the refinement of certain structural components, they are widely used as the main means of transport in potash mines for hauling ore from the mining faces to main belt conveyors or ore passes [1].

At the same time, conveyor transport plays a particularly important role in delivering mineral resources to the surface in underground potash deposits, where high reliability and uninterrupted operation are required. Conveyors are characterized by high production capacity, a high level of automation, relatively low energy consumption, and reduced maintenance costs [2,3]. In main haulage sections, belt conveyors are the primary transport system ensuring the stability and continuity of the mining process.

The high maneuverability of self-propelled mine wagons in the mining face area, as well as their efficient operation under steep and inclined roadway conditions, allows them to be effectively used as a feeding and linking element within conveyor transport systems. In this arrangement, the ore extracted by self-propelled mine wagons is transferred to the main conveyors via reloading bunkers, thereby increasing the overall efficiency of the transport system [4,5,6,7].

Currently, self-propelled mine wagons are widely used in mines with steeply inclined ore bodies for material haulage. They are employed not only in underground mines with inclined deposits, but also in special operating conditions involving roadway inclinations of up to 15°.

The extensive use of self-propelled mine wagons in foreign mining operations, as well as the accumulated experience of their application in the CIS countries, demonstrates that this type of transport is highly promising. As a result, the number of ore transportation schemes based on the use of self-propelled mine wagons continues to increase. For induction motors of these drives, the use of a pole-changing winding is one of the most convenient and cost-effective means [8,9,10,11,12,13].

1.1 Research Background and Problem Statement

The operating range of electrically driven self-propelled mine wagons is limited by the capacity of the cable drum, which currently allows for a cable length of up to 200 m. However, if the mined material is transferred to another self-propelled mine car through a reloading bunker located at the beginning of the next section with a length of 400 m, the effective operating range of the self-propelled mine wagon can be significantly extended [1].

Although self-propelled mine wagons have been extensively applied in underground mining, further improvements are still required to increase their operational efficiency, reliability, and maneuverability under varying roadway conditions. Existing studies have mainly focused on mechanical design, drive systems, and transport organization, whereas considerably less attention has been devoted to integrated dynamic simulation of the running gear operating under realistic loading conditions. Such simulation models are essential for evaluating the dynamic behavior of the vehicle, predicting its performance under different operating scenarios, and supporting engineering optimization during the design stage. Therefore, the development of a comprehensive simulation model represents an important step toward improving the operational efficiency and reliability of self-propelled mine wagons.

1.2 Novel Methodological Contributions

A simulation model of the running gear of a self-propelled mine car (MSPW) was developed using the SimulationX software, based on its kinematic scheme. SimulationX, developed in 2000 by ESI ITI GmbH (Dresden), is a computer-aided engineering (CAE) software package designed for modeling technical objects and systems. It is widely used by researchers and engineers in both industry and academia for the design, modeling, simulation, analysis, and virtual testing of complex mechatronic systems.

Within a single integrated environment, SimulationX enables the modeling of the behavior and interaction of mechanical systems (1D and 3D), drive systems, electrical, hydraulic, pneumatic, and thermodynamic subsystems, as well as magnetic phenomena and analog and digital control systems.

The SimulationX software package supports the Windows operating system and includes predefined component libraries covering various branches of physics. These libraries classify model elements according to their physical properties and application domains. A complete simulation model can be created using both standard library components and user-defined elements.

Figure 1 shows the SimulationX simulation model of the MSPW running gear.

2 METHODS

In the developed model, the electric drive of the self-propelled mine wagon (MSPW) is powered by two two-speed induction motors with a rated power of 55/26 kW (see Sections 2 and 3). The rotational speed of the motors is controlled by two switching elements, which are actuated using a time-based control function.

A three-stage distribution gearbox with five gear pairs is connected to the shaft of each induction electric motor. This gearbox serves as the main transmission unit and distributes torque to two drive axes, supplying the front and rear wheels. The numbers of teeth in the first and second gear stages of the distribution gearbox are 22 and 31, respectively, while the second and third stages have 31 and 38 teeth, respectively (Fig. 2).

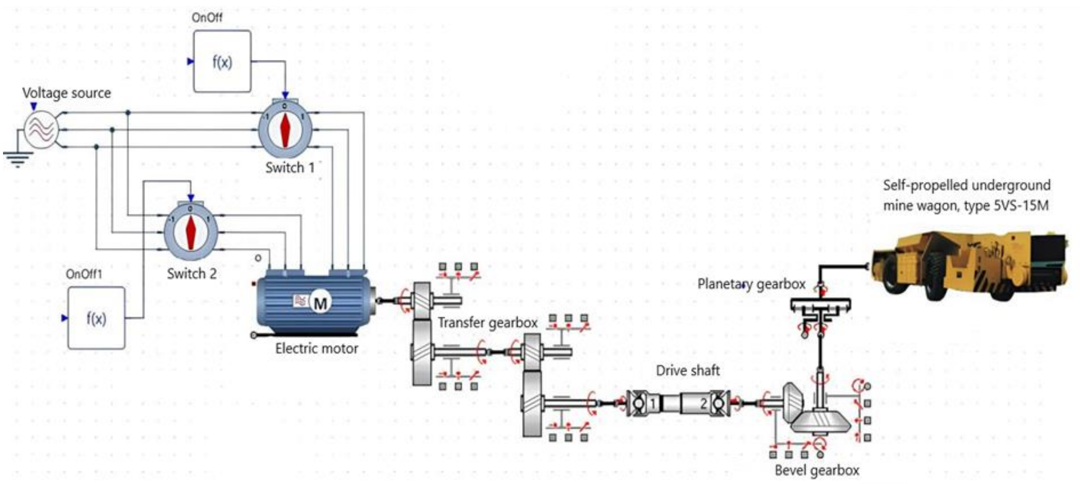


Figure 1: A simulation model of the 5VS-15M type MSPW kinematic scheme.

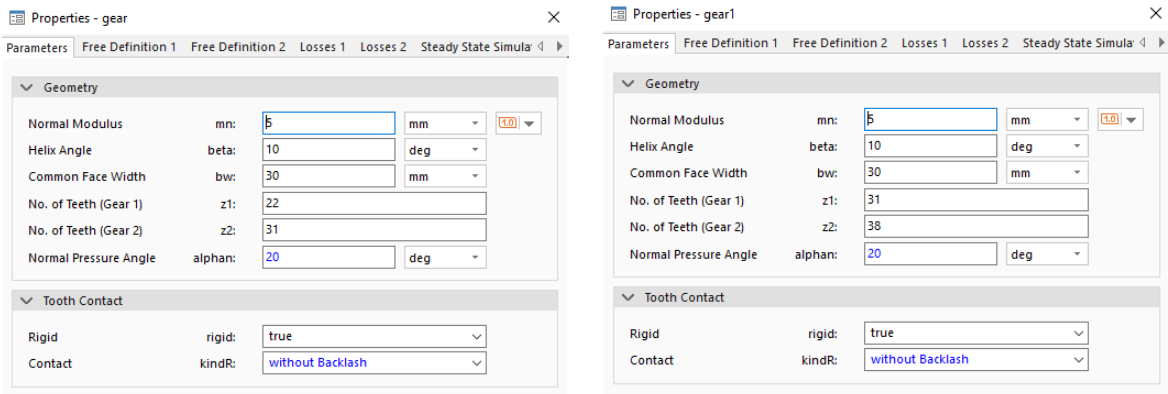


Figure 2: Adjustment window of the distribution gearbox.

Wheel drive is realized using a bevel gear set arranged with mutually perpendicular axes. The bevel gear set consists of gears with 11 and 25 teeth, respectively (Fig. 3).

A planetary gear set is used to transmit and transform torque, with its primary function being torque multiplication. The gear ratio of the planetary gear set is 8.25 (Fig. 4).

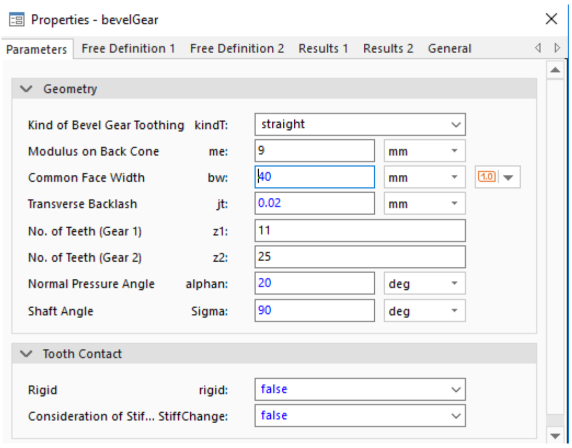


Figure 3: Bevel gear adjustment window.

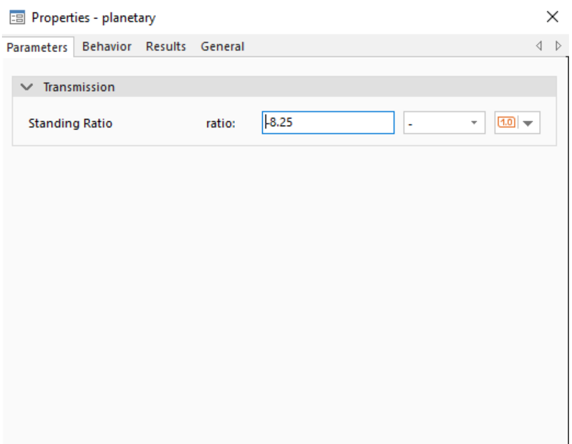


Figure 4: Planetary reducer adjustment window.

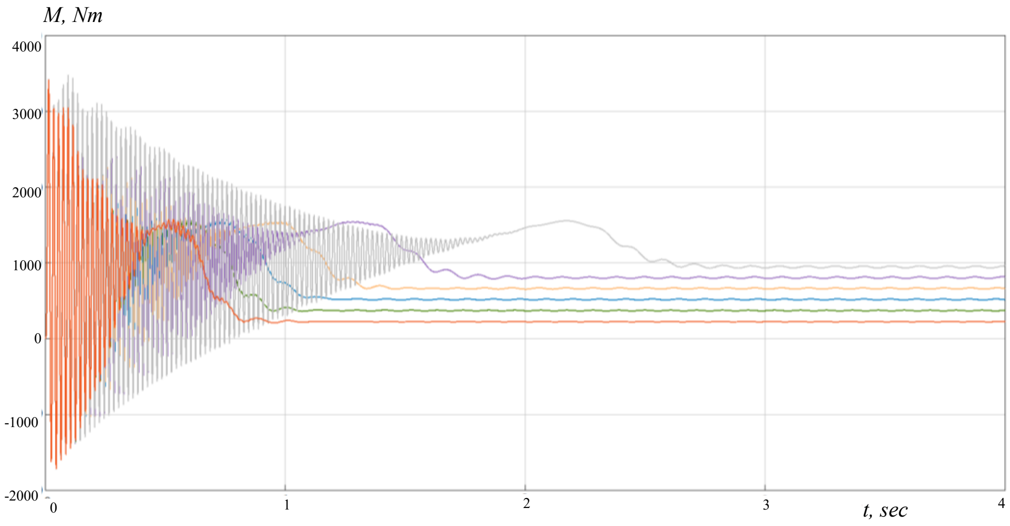


Figure 5: Variation of torques in an induction electric motor.

3 RESEARCH RESULTS

The Tyubegatan potash deposit is characterized by complex mining and technical conditions, with roadway inclinations for self-propelled mine wagons reaching 15–16°. Using the developed simulation model, the operation of the MSPW was investigated under various mining conditions, and the maximum allowable roadway inclination was determined for each operating speed of the new two-speed induction motor.

The maximum achievable slope angle at the low motor speed (500 rpm) was found to be 16°, while at the high motor speed (1000 rpm) the maximum slope angle was limited to 9°.

In addition, a MSPW with a total mass of 31 tons was analyzed using the simulation model under complex mining conditions with roadway inclinations of 0°, 3°, 6°, 9°, 12°, and 15°. For these slope angles, the corresponding electric motor torque values were 240, 380, 510, 650, 800, and 950 Nm, respectively (Figure 5).

The speed and tractive forces of the MSPW were analyzed for the above-mentioned roadway inclination angles. The operating speed of the MSPW was within the range of v = 3.0–3.4 km/h, while the time required to reach this speed (i.e., the transient response time) ranged from t = 0.8 to 2.7 s. During motion, the tractive force developed at the driving wheels varied within the range of P_k = 23–105 kN (Fig. 6).

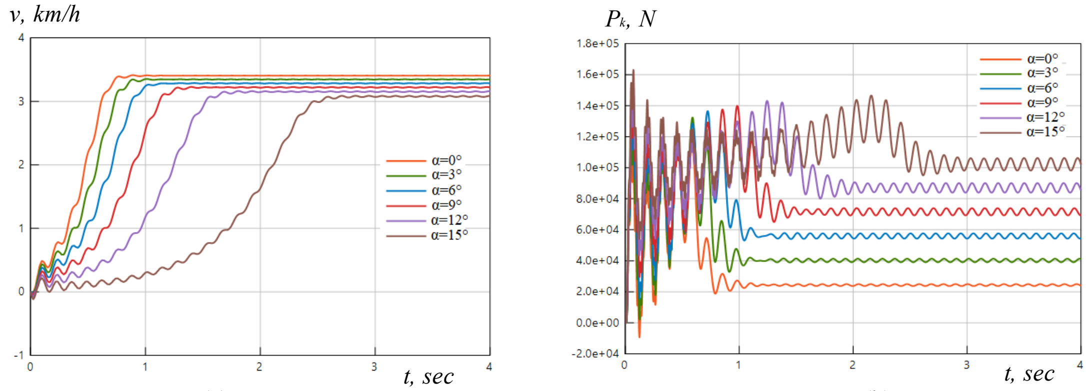
Several resistance forces act on the MSPW during motion, including grade resistance (P_h), rolling resistance (P_f), inertial resistance (P_j), and aerodynamic resistance (P_{air}). Aerodynamic resistance was neglected in the analysis due to its negligible magnitude compared to the other resistance components.

Using the simulation model, variations in the resistance forces acting on a 31-ton MSPW were investigated under complex mining conditions with roadway inclinations of 5°, 10°, and 15°.

Figure 7 illustrates the resistance forces acting on the MSPW when the roadway inclination is α = 5°. The transient response time was t = 1.1 s, during which the grade resistance was P_h = 26.5 kN, the rolling resistance was P_f = 24.3 kN, and the inertial resistance decreased to P_j = 0 after the transient process. The resulting tractive force was P_k = 50.8 kN.

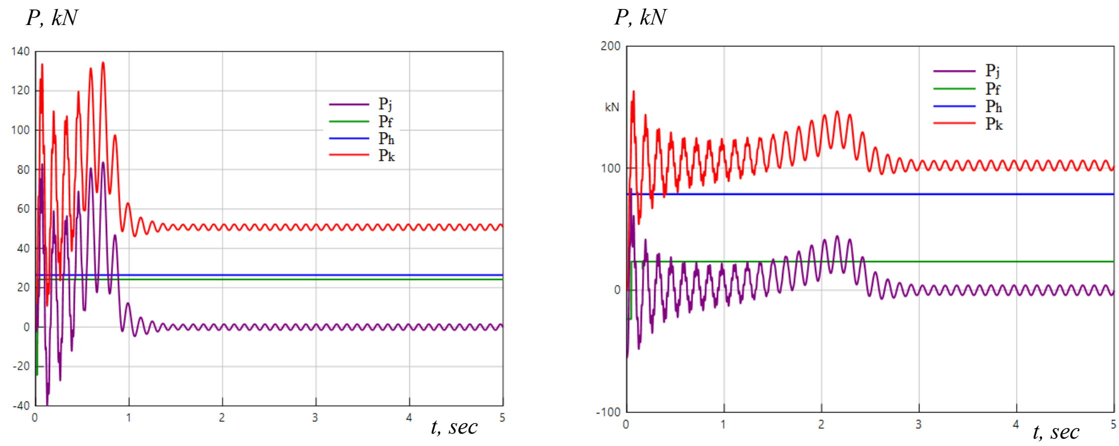
Figure 7 shows the variation of resistance forces when the roadway inclination increased to α = 15°. In this case, the transient response time increased to t = 2.7 s. The grade resistance was P_h = 78.7 kN, the rolling resistance was P_f = 23.5 kN, and the tractive force reached P_k = 102.2 kN.

Figure 8 presents the torque and speed curves of the electric motor when the two-speed induction motor with PCW windings in the MSPW electric drive was switched from low speed to high speed at roadway inclinations of 0°, 5°, and 9°. At low speed, the motor torque values were 230, 470, and 660 Nm, respectively, while the corresponding vehicle speeds were v = 3.2, 3.3, and 3.4 km/h. At high speed, the MSPW velocities increased to v = 6.7, 6.8, and 6.9 km/h. When starting at low speed, the transient response time ranged from t = 0.7 to 1.2 s, whereas at high speed it ranged from t = 0.8 to 1.5 s.



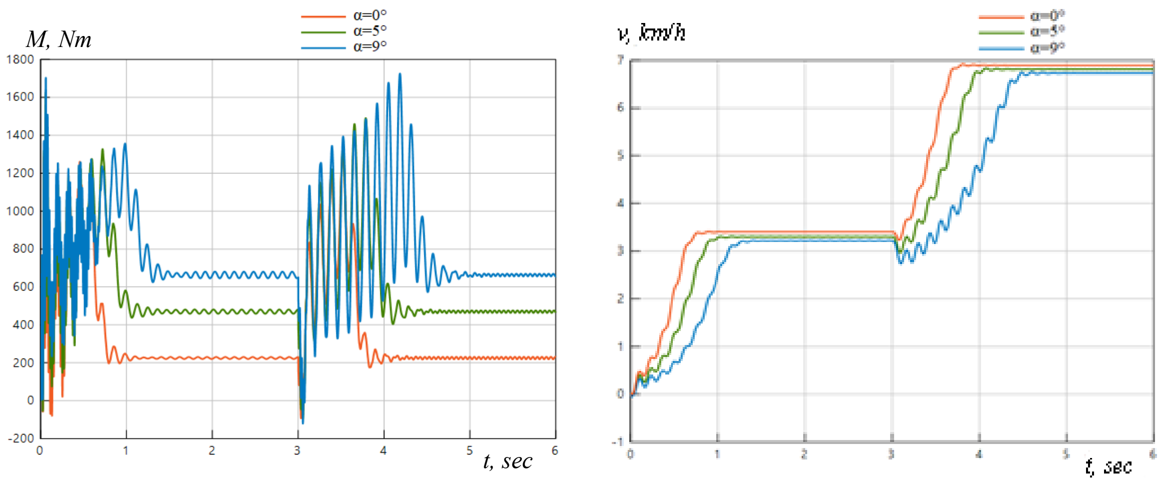
(a) (b)

Figure 6: Characteristics of the MSPW running gear: a) speed, b) gravitational force.



(a) (b)

Figure 7: Variation of the resistance forces of the self-propelled mine wagon (SPMW) under different roadway inclinations: a) α = 10°; b) α = 15°.



(a) (b)

Figure 8: Torque and rotational speed of the MSPW electric motor during start-up and gear switching: a) torque; b) rotational speed.

Figure 9 in this comparison, the nominal torque of the electric motor is 520 Nm. The currently used electric motor develops a torque of 1300 Nm at low speed and 1350 Nm at high speed, whereas the newly developed electric motor produces 1500 Nm at low speed and 1600 Nm at high speed.

Figure 10 presents the speed variation of the MSPW equipped with the existing electric motor and with the newly developed electric motor during operation. When starting at low speed, the MSPW equipped with the existing motor completed the transient process after 1.0 s and reached a speed of 3.05 km/h, while the MSPW equipped with the new motor reached a speed of 3.15 km/h after 0.9 s. After 3 s of operation, the drive was switched to high speed. In this case, the transient process of the MSPW with the existing motor lasted 1.3 s, reaching a speed of 6.3 km/h, whereas the MSPW with the new motor completed the transition in 1.0 s and reached a higher speed of 6.65 km/h.

Based on the analysis of the operating modes of the MSPW running gear, it can be concluded that the transient times during start-up and during switching between speed modes remained within permissible limits under all investigated conditions. Thus, the experimental results confirm that the MSPW electric drive based on a two-speed induction motor with a variable number of poles fully satisfies the operational requirements imposed on it.

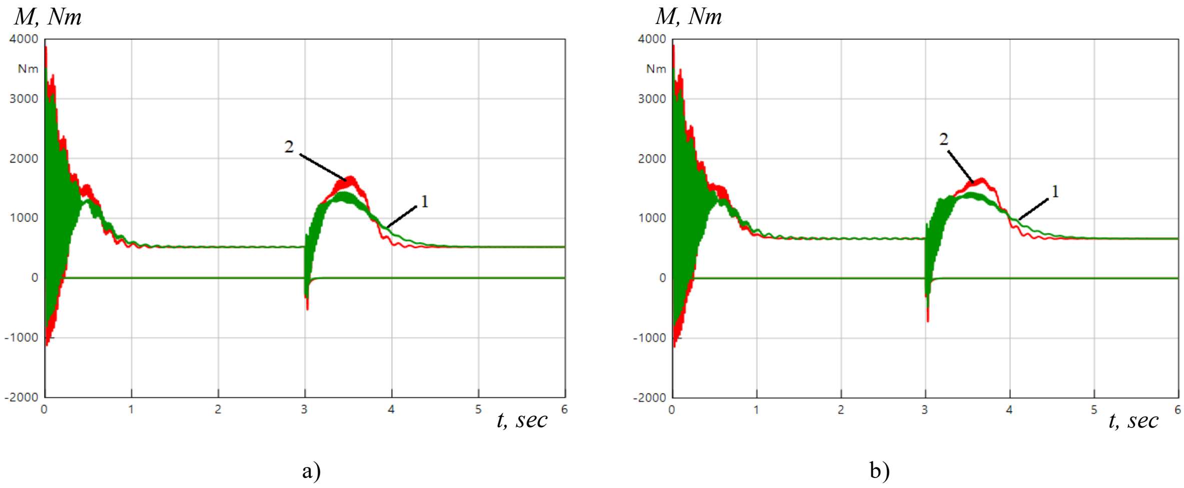


Figure 9: MSPW equipped with an existing electric motor (1) and a new electric motor (2) in operation electric motors moment change: a) for α=6°; b) for α=9°.

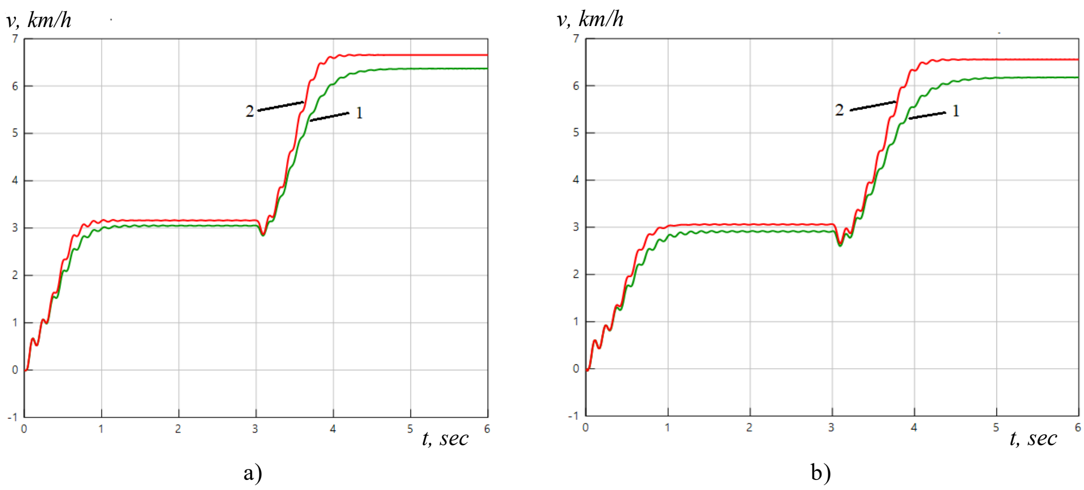


Figure 10: With existing electric motor (1) and new electric motor (2) Graph of speed changes during operation of the equipped MSPW: a) for α=6°; b) for α=9°.

4 CONCLUSIONS

A simulation model of the MSPW running gear was developed in the SimulationX environment based on its kinematic scheme. The proposed model enabled the analysis of vehicle operation under various underground mining conditions and provided a reproducible framework for evaluating the performance of the newly developed two-speed induction motor. Numerical simulations made it possible to determine the maximum allowable roadway inclination for different operating-speed modes and to assess the corresponding traction requirements.

The simulation results obtained for an MSPW with a total mass of 31 t demonstrated a progressive increase in the required motor torque as the roadway inclination increased from 0° to 15°. The calculated torque values reached approximately 240, 380, 510, 650, 800, and 950 N·m for roadway inclinations of 0°, 3°, 6°, 9°, 12°, and 15°, respectively. These findings confirm the suitability of the developed simulation model for evaluating the operating characteristics of self-propelled mine wagons and provide a practical engineering basis for optimizing electric-drive parameters and improving vehicle operation under varying underground mining conditions.

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