Simulation of drive power in mechatronic systems

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Abstract. The results of research on determining the parameters and circuit solutions of traction drives of funicular cars are presented in this paper. As a result of the research, it has been revealed that the funiculars, the bodies of which have an articulated joint, possess the greatest advantages. It is effectively to use three-phase AC machines with permanent magnets as traction electric motors. The mechanical part of the drive must contain a speed transformer with a gear rack-wheel type gearing. The wheels of the running gears perform the function of holding the car on the track structure. The traction force is performed in a gearing, the rack of which is placed between the rails of the track structure. The given method for calculating the power of the drive motor made it possible without question to determine its dependence on the angle of inclination of the railroad bed.

1. Introduction

The funicular is one of the types of rail transport with an electric traction drive. Compared to trams and electric trains, it is used on terrain where the slopes of the track structure reach values that do not allow the use of traditional vehicles for mass passenger transportation. When designing funiculars, one has to solve the same problems as when developing any vehicle: to determine the design of the car and the type of drive [1, 2].

2. Theory

Compared to tram and electric train cars, traction on a funicular car cannot be performed through the connection of wheels and railroad bed. This is due to the fact that the pressing force of the telecabin against the railroad bed decreases with increasing track steepness and may turn out to be insufficient to create the required tractive effort. In addition, a significant slope creates problems in generating the necessary braking force on the descent. Therefore, it is useful to implement the traction and braking forces not through the wheel-rail engagement. With a relatively short track, the lifting and lowering of the telecabin can be done using a rope.

On long routes, it can be done using a mechanical gearrack-wheel drive. To stabilize the car in space, four-axle fixed bogies should be used as running gear, and the telecabin itself should not be monolithic, but articulated with the bogie installed under each section. When developing a traction drive, it is necessary to take into account that the drive motor must develop the required tractive effort, and its power circuits must provide a regenerative braking mode in order to return part of the consumed energy. Therefore, the telecabin should use self-generated power supply, where a storage battery is effectively suitable for use [2, 3].
3. Methods
The analysis of circuit solutions and designs of the funicular car drives (Figure 1) showed that the gear rack–wheel drive is more reliable and meets the requirements [4].

![Figure 1. Schematic solutions of the cable car drives: a – rope drive; b – gear rack-wheel drive.](image)

When analyzing possible options for the funicular body (figure 2), the body arrangement shown in option b is more preferable, since in this case less exacting requirements are imposed on the profile elevation of the track structure: it can vary in a certain range of values, which will not lead to a loss of traction and braking forces because each section is equipped with a drive [5].

![Figure 2. Funicular body options: a –wagon type; b –articulated type.](image)

The developed schematic diagram of the power circuits of the drive is shown in Figure 3.

![Figure 3. Schematic diagram of the power circuits of the drive.](image)
Studies have shown that a three-phase synchronous machine with permanent magnets should be used as a drive motor [6, 7].

Since the funicular car is a system that includes mechanical and electrical parts, models in the Math Lab Simulink environment, shown in Figures 4 and 5, were created for its study.

![Figure 4. The mechanical part of the cable car drive.](image1)

![Figure 5. The mechanical part of the cable car drive.](image2)

4. Results and Discussion
To determine the required engine power, the following initial data were taken: the length of the stretch between stops – \( l = 300 \) m, speed on the stretch – \( v = 5.5 \) m/s, slope angle – \( \alpha = 30^\circ \).

When starting up to speed on a grade, the tractive effort is determined [8]:

\[
F = (1 + \gamma) \cdot \frac{G_{Rs} \cdot 10^3}{g} \cdot a + W + F_{rol} = (1 + 0.15) \cdot \frac{143.5 \cdot 10^3}{9.8} \cdot 0.2 + 731.8 + 71.7 \cdot 10^3 = 76 \text{kN},
\]

where \( \gamma = 0.15 \) is the coefficient of the rotating mass of the car; \( G_{Rs} = 143.5 \cdot 10^3 \text{N} \) is wagon weight; \( g = 9.81 \text{ m/s}^2 \) is acceleration of gravity; \( a = 0.2 \text{ m/s}^2 \) starting period; \( F_{rol} = G_{RS} \cdot \sin \alpha = 143.5 \cdot 10^3 \cdot 0.5 = 71.7 \text{kN} \);
The required power is \[ P = F \cdot V = 75799.6 \cdot 5.5 = 417 \, kW \].

For reasons of the reliability of the car, including the value reduction of the longitudinal loads on the frame, it was decided to use two electric machines - in the head and tail parts. This also contributes to the reduction of the engine's weight-size, which simplifies their placement on the car. Thus, the power of one engine is \( P_1 = P_2 = 208 \, kW \). Since in the mode of intermittent operation, the motor allows 3-fold overload, its rated power will be \( P_1/3 = 70 \, kW \). In accordance with the power requirements, the ORION synchronous traction motor -18-3M-01 has been chosen [9, 10].

When the car is moving down, regenerative braking is used to limit the travel speed. The energy consumer is the battery installed on the car (Figure 3). The regeneration energy during braking in accordance with the initial data will be:

\[ A = G_{RS} \cdot h = 14637 \cdot 9.8 \cdot 150 = 21 \, MJ, \]

where \( h = l \cdot \sin \alpha = 300 \cdot 0.5 = 150 \, m \) is the height difference between the upper and lower points of the stretch (Figure 6).

\[ W = wG_{RS} = \left( 5 + 0.005 \cdot V^2 \right) G_{RS} = \left( 5 + 0.005 \cdot 5.5^2 \right) \cdot 142.5 = 731.8 \, N. \]

In order to determine the dependence of the value of the car engine power as a function of the ascent angle, a program was compiled in the environment «MathCAD». The calculation example for an angle \( \alpha = 30 \) is in Figure 7.
Figure 7. Calculation of the magnitude of engine power at an angle of rise of 30 degrees.

Based on the calculations, the dependence of the engine power on the ascent angle was built (Figure 8).

Thus, it could be concluded that on the route with an ascent angle of 30 degrees, a funicular is required to be equipped with an engine power of 150 kW [11,12].

5. Conclusion
Studies have shown that the power value of the drive motor of the funicular car is linearly dependent on the ascent angle. The achieved dependence enables to determine its value for a particular angle.
It is effectually to use a three-phase permanent magnet motor as a traction motor. The coupling of the wheel with the track structure is used by means of a “gearrack-wheel connection”.

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