

Method of Electric Bus Protection from Rolling Back on Slopes

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ABSTRACT

Urban environments may have slopes, and therefore vehicles that operate therein have to ascend and descend these slopes. Ascending slopes may feature signal-controlled intersections, passenger stops, and other points that require vehicles to stop. All these situations are associated with the risk of the vehicle rolling back and causing a traffic accident. This requires a functionality to keep the vehicle on a slope. This problem is especially relevant for electric vehicles. This paper presents the results of developing an electric bus protection method to prevent rolling back on slopes as an algorithm to keep the vehicle in place using the traction motor. This method and algorithms are developed with the MATLAB and Simulink software package. The primary virtual and field trials are carried out on the proving ground of the KAMAZ PJSC Research and Development Center. The authors justify the development of the protection method to prevent electric vehicles from rolling back on slopes. They suggest a method to keep the vehicle in place that does not require measuring the slope angle. Virtual trials were carried out to confirm the control strategy, and field tests were performed to confirm the applicability of the method in real-life conditions. The practical significance of the research and developments lies in the possibility of applying the design methods and principles of the algorithm responsible for keeping an electric car or electric bus in place on slopes and their subsequent implementation.

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1. Introduction

Modern vehicles are often propelled by traction electric motors. This can be attributed to the advantages of these devices compared to internal combustion engines. Increased layout options, continuously and reliable torque transfer from electric motors to wheels (Biryukov & Porsev, 2020) allow for the elimination of the gearbox, including clutch or hydraulic transmission mechanisms that synchronize the rotation speeds between the motor and transmission. This, however, fails to prevent an electric vehicle from rolling down slopes. An automatic transmission may keep a car in place using the hydraulic torque converter (Fischer et al., 2015; Jarso et al., 2024; Naunheimer et al., 2011), semi-automatic or robotized gearboxes can keep a car in place on a slope using the crawling mode (Fischer et al., 2015; Naunheimer et al., 2011). A traction electric motor cannot keep an electric vehicle in place on a slope without dedicated software solutions. Electric vehicles can be kept in place on a slope using software programs because their movement is controlled with microcontroller-based control modules. The design features of asynchronous and synchronous electric motors (Kondratyuk & Egorov, 2006; Liu et al., 2018) allow them to keep a vehicle in place for 5-10 seconds maximum because prolonged stoppage may cause the overheating of electric motor windings. This is not a serious problem as it is only necessary to keep the electric vehicle in place while the driver moves their foot from the brake

pedal to the accelerator pedal, which normally takes up to 1-2 seconds. As a rule, vehicles are kept in place on a slope by an electronic brake system. However, this may not always be provided by brake system vendors, and even if it is in place, this function may be activated by the driver. This means that the driver is involved in ensuring safety during potential vehicle rollback, making it vulnerable to human error. To minimize the risks of rollbacks and accidents that may be caused by human errors, it is necessary to prevent vehicle rollback using the slope stoppage function based on the traction motor. An analysis of open sources shows that a significant part of the work on preventing the rollback of an electric vehicle when starting on an incline relies on the use of an electronic parking brake (EPB) or mechanical locks. In the publication (Wu et al., 2020), hill-start logic is implemented using an EPB with pressure control, but the traction electric motor loop is not used.

A similar approach can be found in the engineering works (Bomble et al., 2022; Nimisha & Chaudhari, 2022), where mechanical or combined schemes are proposed, but the synthesis of the motor torque controller is not performed, and there is no analysis of the transient processes when the hold is released. In parallel, the direction of traction electric motor torque control in zero-speed mode is developing, mainly through PID-/Fuzzy-PID controllers for creep control (Shamseldin, 2023), or through predictive Direct Torque Control (DTC) (Kasri et al., 2024). However, these studies are aimed at smooth starting and reducing torque pulsations, without highlighting the hill-hold (anti-rollback / hill-hold) mode as a separate task. In this regard, the task is to develop an algorithm for holding on the rise and derive the equations necessary for the analytical design of the controller. Unlike the mentioned approaches, in the proposed work, the PID controller is used not to smooth out the start-up or suppress oscillations during start (creep control mode), but as a means of forming a holding moment in the micro-displacement zone during rollback. A fundamental feature is that the controller is activated not by a known slope or an external sensor, but by the fact of the minimum rollback, which is used to calculate the initial integral charge. This allows for the instant generation of a holding torque without the time delay typical of classical PID schemes, where the integral component is accumulated only after an error occurs. In addition, the paper validates the algorithm not only in a simulation environment, but also on real electric vehicles, with the registration of torque and rotational speed via the CAN bus.

2. Developing the Electric Vehicle Slope Stoppage Algorithm

Some modern vehicles are fitted with pitch angle sensors. These assist in keeping the vehicle in place on a slope by informing the control system that calculates the required stoppage torque. There are also methods to assess pitch angles, e.g., in (Guo et al., 2022; Liu, 2025). However, these require a number of calculations to assess and pitch angle, particularly during movement. Electric vehicles can be kept in place without it by using a controller. The control system detects the electric car's rollback as its speed and distance traveled increase using a controller with the required response rate, then generates the required torque to keep the car in place on the slope. Since this action involves actual speed, its derivative, and distance traveled, a proportional-integral-derivative controller or PID-controller is the preferred option (Denisenko, 2013; Kachala, 2017). Controller's error is the rollback speed, its integral is the distance traveled, and its derivative is the acceleration. The required stoppage torque is pre-calculated using the traction-dynamic calculation (Larin, 2010; Rajamani, 2012; Tarasik, 2006) with total weight and pre-evaluated slope angle.

When developing an algorithm to keep an electric vehicle in place on the slope, we make the following assumptions and requirements:

- To facilitate rollback detection, a vehicle may roll back slightly at a speed of $v_{x\text{ perm}} = 0.5$ km/h maximum;
- the wheels that the torque is applied to during stoppage roll without slipping;
- the vehicle may slightly move forward at a speed of 0.1 km/h maximum when the stoppage torque is applied;
- the maximum distance that can be traveled during rollback must not exceed 100 mm.

2.1 Developing a Rollback Detection and Reaction Method

Rollback detection is a key stage in the operation of the entire system. On one side, it is necessary to keep the vehicle in place, and on the other side, this requires a specific condition. As a tradeoff, we may assume that the electric vehicle shall roll back to some "guaranteed distance" L_0 to prevent erratic decisions on torque generation without the driver's knowledge. The formula for the calculation of the "guaranteed distance" looks as follows:

$$L_0(t) = r_{eff} \int_0^t \omega_w(t) dt, \quad (1)$$

where:

r_{eff} is the effective radius of rotating tire, m.;

ω_w is the angular speed of wheel, rad/s:

$$\omega_w = \frac{2\pi \cdot n_{TEM}}{i_{ratio} \cdot 60}, \quad (2)$$

where:

i_{ratio} is the gear ratio;

$n_{TЭД}$ is the rotor speed of traction electric motor, rpm.

When the vehicle rolled back to a distance of L_0 , we can record the time t_{rlb} in which this distance was traveled and the rotation rate at the moment of detection $n_{t_{rlb}}$. After that, initial conditions for the operation of the PID-controller can be formed. These may include the slope angle during rollback and the value of the integral component in the initial moment of the controller's operation. The assessed slope angle can be calculated using the following formula:

$$\hat{\alpha} = \arcsin\left(\frac{2L_0}{g \cdot t_{rlb}^2}\right), \quad (3)$$

g is the acceleration of gravity, m/sec².

2.2 Developing and Justifying the Control Action

To form the controller, consider first the direct linear motion equation on the slope calculation (Larin, 2010; Rajamani, 2012; Tarasik, 2006):

$$m_{veh} \frac{dv_{x\,veh}}{dt} = F_t - F_f - F_{aero} - F_h, \quad (4)$$

where:

$v_{x\,veh}$ is the travel speed of the vehicle, m/sec;

m_{veh} is the vehicle's weight, kg;

F_t is the tractive effort of the driving wheels, N;

F_f is the roll drag force of all wheels, N;

F_{aero} is the aerodynamic drag force, N;

F_h is the climbing resistance, N.

In this case, the climbing resistance F_h equals:

$$F_h = m_{veh}g \sin(\alpha), \quad (5)$$

where:

α is the angle inclination of the road in degrees.

Since the rotor speed is used as the error during the controller development, the travel speed of the vehicle $v_{x\,veh}$ and rotor speed n_{TEM} of the electric motor should be linked with the following dependency:

$$n_{TEM} = v_{x\,veh} \frac{i_{ratio} \cdot 30}{r_{eff} \cdot \pi}. \quad (6)$$

Hereinafter, we shall use the constant Ω that links the kinematics of the electric motor rotor shaft rotation and that of the vehicle movement:

$$\Omega = \frac{i_{ratio} \cdot 30}{r_{eff} \cdot \pi}. \quad (7)$$

Assume that when $n_{TEM} > 0$, the electric vehicle moves forward, and when $n_{TEM} < 0$, it moves backwards. In the general case, controller error may be written down as follows:

$$\Delta n_{TEM}(t) = n_{TEM}(t) - n_{TEM0}; \quad n_{TEM0} = 0, \quad (8)$$

where:

n_{TEM0} is the rotor speed equal to zero (setting), rpm;

$\Delta n_{TEM}(t)$ is the controller error, rpm.

In equation (8), the subtractor (setting) n_{TEM0} equals zero, as the control goal is to prevent the motor rotation rate from increasing. When designing a controller, assume that the normal operating mode of the system during stoppage on a slope is the state of immobility or at least a tendency to keep the vehicle in place. In other words, the following

condition must be fulfilled:

$$\Delta n_{TEM}(t) = n_{TEM}(t) = 0.$$

Figure 1 shows a structural diagram of generating the required torque in the developed algorithm:

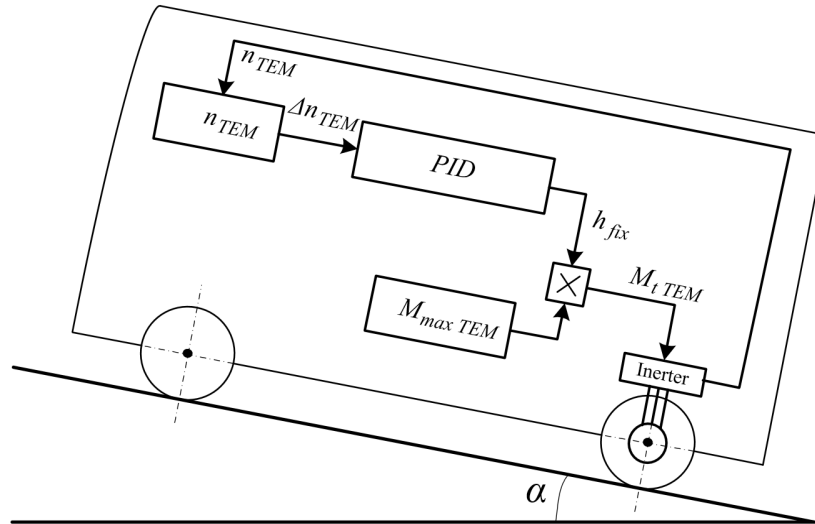


Figure 1: The Structural Diagram for the Generation of the Required Torque

To justify the controller selection and study its operation, introduce controller operation phases (see Figure 2): I – immobility with rollback detection, II – rollback deceleration, III – vehicle stoppage. During Phase I, the rollback is detected when the “guaranteed distance” L_0 is exceeded, while the electric vehicle is accelerating as it is moving backwards. During Phase II, the controller generates the peak torque value required to slow the vehicle down. In Phase III, the electric vehicle is stationary, but the stoppage torque does not equal zero and is sufficient to keep the vehicle in place. Like any device of this type, the PID-controller starts actively generating commands when deviations (control errors) are detected (Denisenko, 2013; Kachala, 2017; Kim, 2019). In this case, we may assume that, during rollback detection, $\Delta n_{TEM}(t) = n_{TEM}(t) < 0$ and, in a short time, $\Delta n_{TEM}(t) = n_{TEM}(t) = 0$. In other words, the controller generates a command with which the rollback must be impossible. Although $\Delta n_{TEM}(t) = n_{TEM}(t) = 0$ in the state of immobility, it is necessary to maintain the equality to zero on the slope for a long time. This problem can be solved by the integral component that sets direct proportionality between the rotor rotation angle during rollback and the prolonged stoppage torque on the slope. The physical sense and link between the rotor rotation angle and the torque are illustrated in Figure 2.

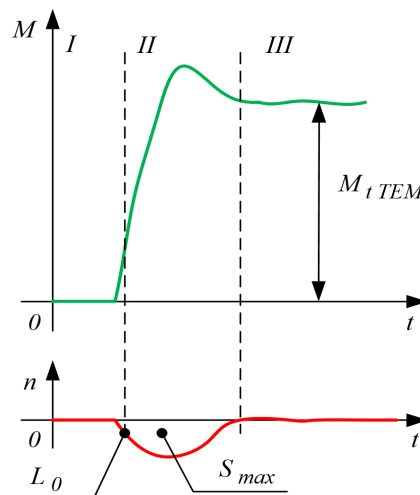


Figure 2: The Physical Sense and the Link Between the Rotor Rotation Angle and the Stoppage Torque, As Well as the Operation Phases of the Controller Responsible for Stoppage on a Slope

In other words, the controller must aim to prevent any changes in the rotor rotation angle, i.e. $\Delta\varphi_{rot}(t) = \varphi_{rot}(t) \rightarrow const$:

$$\Delta\varphi_{rot}(t) = \varphi_{rot}(t) - \varphi_{rot 0}; \varphi_{rot 0} = 0. \quad (9)$$

As mentioned previously, the controller starts operating after the rollback is detected. Thus, it is also feasible to prevent the electric motor rotor shaft acceleration $\dot{n}_{TEM}(t) \rightarrow 0$. Since we consider control in the state of immobility, assume that the rolling drag force of all wheels F_f and the aerodynamic drag force F_{aero} equal zero in equation (4). In addition, the inertial force $F_{inert} = m_{veh} \frac{dv_{x,veh}}{dt}$ also equals zero. This leads us to the conclusion that the controller must apply a torque with which the tractive effort F_t will balance out the climbing resistance F_h :

$$F_t = F_h = U, \quad (10)$$

where:

U is the main control action vector, N·m.

In the general case, a PID-controller looks as follows:

$$u(t) = K_p e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt}, \quad (11)$$

where:

K_p is the proportional coefficient;

T_i is the integration time constant, sec;

T_d is the derivative time constant, sec;

$e(t)$ is the error value (misalignment).

As part of the problem in question, replace $u(t) \rightarrow h_{fix}$ and $e(t) \rightarrow n_{TEM}(t)$ in formula (11). Then the controller equation will look as follows:

$$h_{fix} = K_p n_{TEM}(t) + \frac{1}{T_i} \int_0^{t_{stop}} n_{TEM}(t) dt + T_d \frac{dn_{TEM}(t)}{dt}, \quad (12)$$

where:

h_{fix} is the torque co-factor generated by the controller for fixing the vehicle;

t_{stop} is the moment in time when the vehicle stops after the torque is applied, sec.

Since the integral component in the initial moment cannot be calculated with integration but must be different from zero, the initial integral component value at the moment of controller activation should be calculated as follows:

$$I_0 = h_{fix stat} - K_p n_{t rlb}, \quad (13)$$

where:

$h_{fix stat}$ is the cofactor generated as a relative stoppage torque:

$$h_{fix stat} = \frac{M_{t TEM}}{M_{max TEM}} \in [0, 1], \quad (14)$$

where:

$M_{t TEM}$ is the traction electric motor torque required for vehicle stoppage, N·m;

$M_{max TEM}$ is the maximum available traction electric motor torque, N·m.

Similarly, we can write equation (15) for the case with two electric motors:

$$h_{fix stat} = 2 \frac{M_{t TEM}}{M_{max TEM}} = \frac{M_{t \Sigma TEM}}{M_{max \Sigma TEM}} \in [0, 1], \quad (15)$$

where:

$M_{t \Sigma TEM}$ is the total torque on traction electric motors required for vehicle stoppage, N·m;

$M_{max \Sigma TEM}$ is the maximum total available torque on traction electric motors, N·m.

At the initial moment, the co-factor will be calculated using the following formula:

$$h_{fix} = K_p n_{TEM}(t) + I_0 + T_d \frac{dn_{TEM}(t)}{dt}. \quad (16)$$

3. Determining PID-Controller Factors

Determining controller coefficients is a crucial stage of operation. Controller coefficients can be determined in experiments. However, the problem with this approach is associated with selecting the initial coefficient values. Thus, it is preferable to first set the order of numerical values for each of the coefficients K_{p0} , K_{i0} , K_{d0} , after which calibration will be possible.

3.1 Calculating the Integral Coefficient

Considering that the proportional and differential components are negligible while the electric bus is kept stationary, the co-factor can be generated mainly based on the integral component. It is pre-determined that the electric bus must not roll back to a distance of S_{max} . Therefore, the co-factor h_{fix} in Phase III of the controller operation based on equation (12) can be calculated as follows:

$$h_{fix} = h_{fix\ stat} = \frac{1}{T_i} \int_0^{t_{stop}} n_{TEM}(t) dt + I_0 = \frac{\Omega \cdot S_{max}}{T_i}. \quad (17)$$

Thus, we can use equation (13) to produce the initial value of the integral coefficient K_{i0} :

$$K_{i0} = \frac{1}{T_i} = \frac{M_t \Sigma_{TEM} / M_{max} \Sigma_{TEM}}{\Omega \cdot S_{max}}. \quad (18)$$

3.2 Calculating the Proportional Coefficient

Previously, we calculated the climbing resistance using formula (5) and the required stoppage torque on the electric motor. Besides, we previously assumed that the permitted rollback speed must not exceed 0.5 km/h. In this case, we may calculate the co-factor $h_{y\pi}$ for the proportional component using the following formula:

$$h_{fix} = K_p n_{TEM}(t) = K_p \cdot \Omega \cdot v_{x\ veh}. \quad (19)$$

Thus, the proportional coefficient can be calculated using the following formula:

$$K_{p0} = \frac{M_t \Sigma_{TEM} / M_{max} \Sigma_{TEM}}{\Omega \cdot v_{x\ veh}}. \quad (20)$$

3.3 Calculating the Differential Coefficient

Since the generation of torque to keep the vehicle stationary on the slope is associated with surges during rollback deceleration, we referred to paper (Barabino et al., 2019), which mentioned that the comfortable acceleration $a_{x\ perm}$ is between 1.5 and 2 m/sec², to calculate the differential coefficient. On one side, the increase of the torque and its peak value must be significant, and, on the other side, they must not provoke high acceleration values. Due to this and using the same approach as in equations (17) and (19), the equation for the calculation of the differential coefficient will look as follows:

$$K_{d0} = \frac{M_t \Sigma_{TEM} / M_{max} \Sigma_{TEM}}{\Omega \cdot a_{x\ perm}} \quad (21)$$

4. Field Experiment with an Electric Bus

Field trials were carried out with an electric bus, presented in Figure 3, weighing 18 tons on the proving ground. The electric bus climbed a slope and stopped. While on the slope, the drive released the brake pedal to reduce the pressure in brake cylinders, and, when the vehicle rolled back, the slope stoppage algorithm generated torque to prevent rollback. Trials were carried out on 6% and 12% slopes.



Figure 3: The Electric Bus During Tests

To analyze the records, we used a special device connecting to the onboard CAN bus. To illustrate our points, we provide the graphs of electric motor rotor rotation speed, brake cylinder pressure, and torque (Figures 4, 5) while keeping stationary on the 6% and 12% slopes. Since the electric bus is fitted with a portal electric driving axle, the graphs show the rotation speeds and torques of the right and left electric motors. The graphs of climbing the 6% slope are shown in Figure 4:

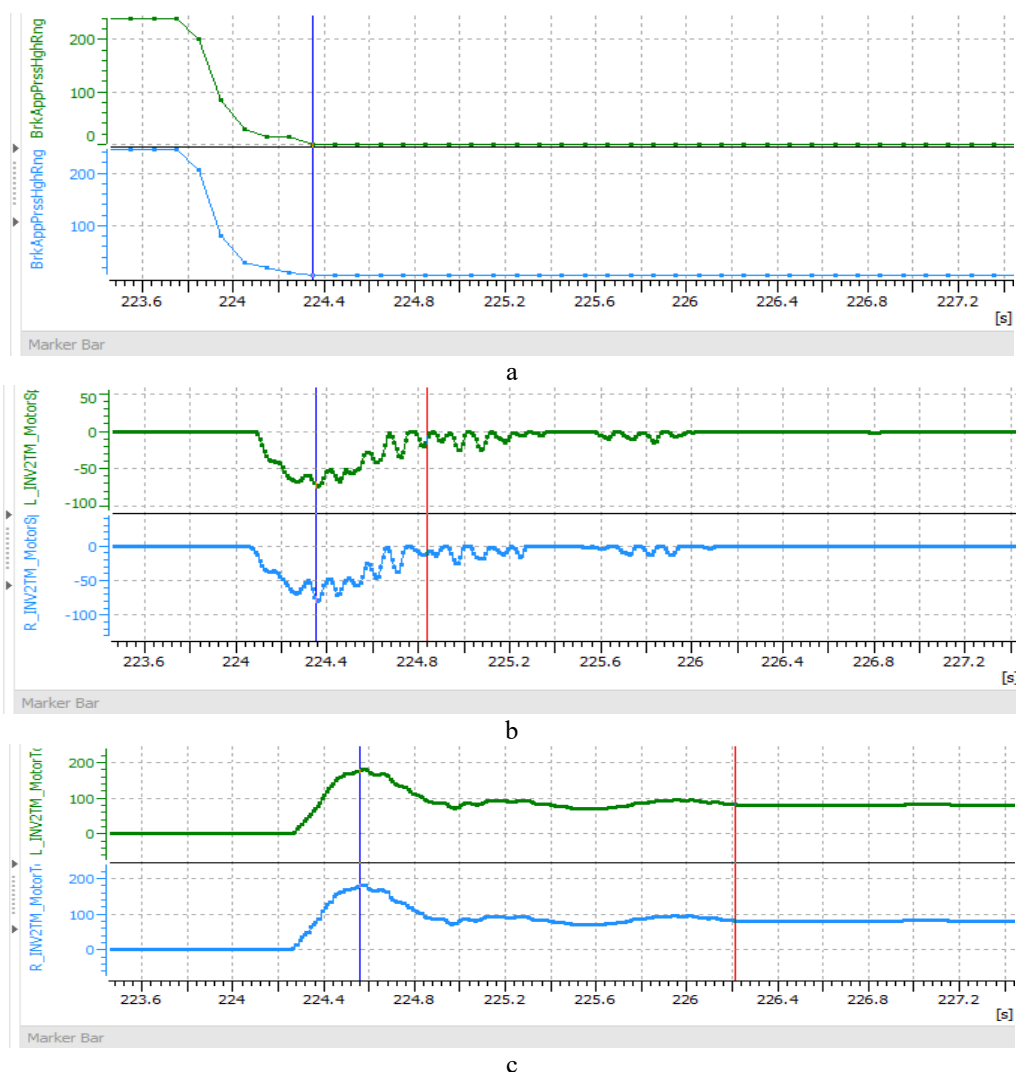


Figure 4: The Climbing and Stoppage Graphs for the 6% slope: *a)* Brake Cylinder Pressure, *b)* Rotor Rotation Speed, *c)* Torque. The Green Graphs Represent the Left Side, and the Blue Graphs Represent the Right Side.

The graphs show that the electric bus rolled back slightly when the pressure in the brake cylinders was released at second 224 (Figure 4a). During the rollback, the rotation speed did not exceed 70 rpm (Figure 4b). When the rollback was detected, the slope stoppage algorithm generated the required torque (Figure 4c). As required by the assumptions made above, the rollback speed did not exceed 0.5 km/h. Table 1 shows the key parameters characterizing the rollback of the electric bus and the operation of the stoppage algorithm.

Table 1: The Key Parameters Characterizing the Stoppage Algorithm Operation

Electric Bus Rollback, mm	Peak rotor Speed During Rollback, rpm	Peak Torque During Stoppage, N·m	Prolonged torque During Stoppage, N·m
67	70	186	90

The graphs of climbing the 12% slope are shown in Figure 5:

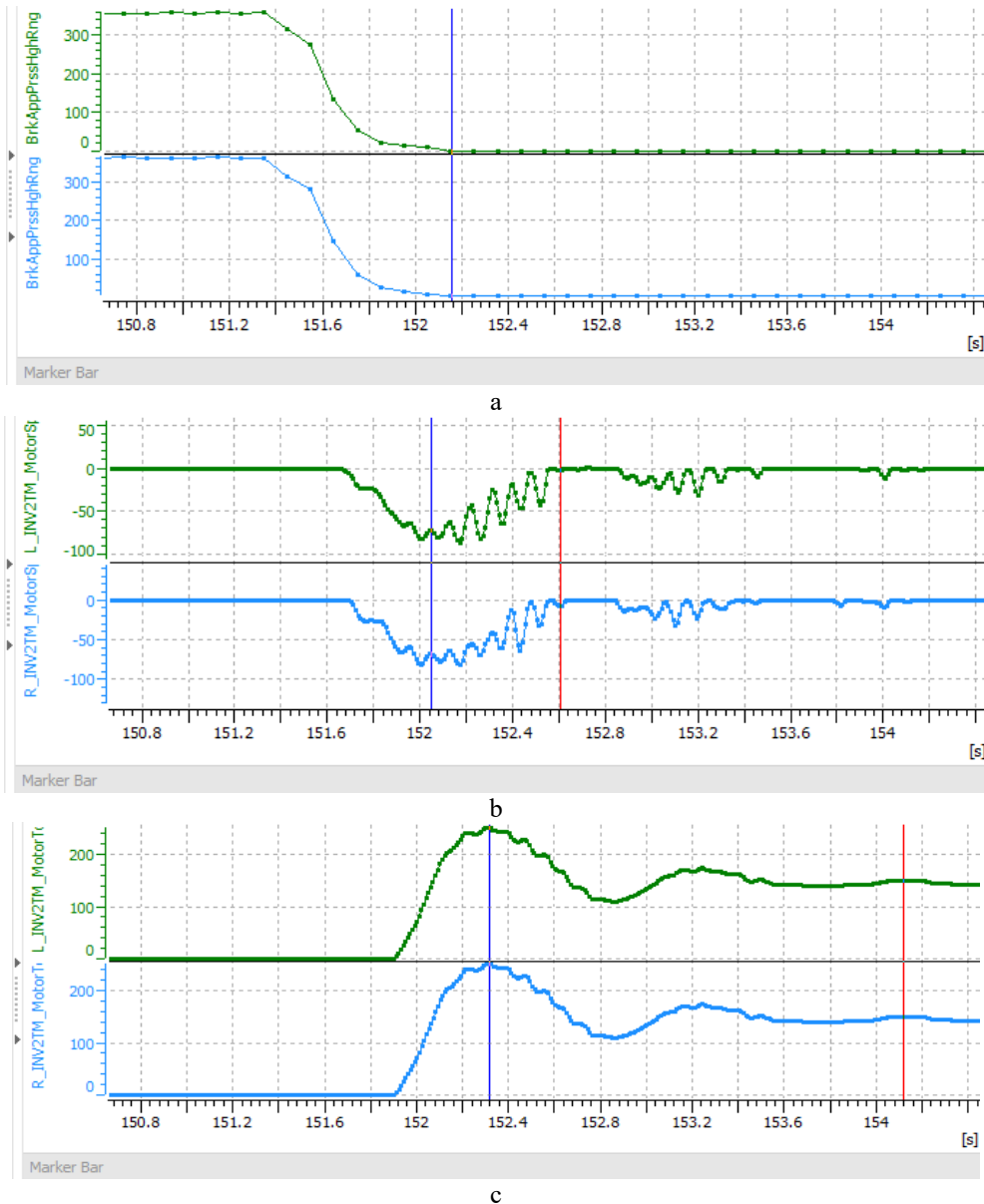


Figure 5: The Climbing and Stoppage Graphs for the 12% slope: a) Brake Cylinder Pressure, b) Rotor Rotation Speed, c) Torque. The Green Graphs Represent the left Side, and the Blue Graphs Represent the Right Side.

Similar to the previous case, the rotor speed graph (Figure 5b) shows that the electric bus starts rolling backwards

after the brakes are released at second 151 (Figure 5a). At this moment, the algorithm detects the rollback and applies torque to keep the electric bus stationary (Figure 5c). Table 2 shows the key parameters characterizing the rollback of the electric bus and the operation of the stoppage algorithm.

Table 2: The Key Parameters Characterizing the Stoppage Algorithm Operation

Electric Bus Rollback, mm	Peak Rotor Speed During Rollback, rpm	Peak Torque During Stoppage, N·m	Prolonged Torque During Stoppage, N·m
90	80	240	150

The trial run with the 12% slope showed the efficiency of the developed algorithm, as it allowed for the electric bus rollback of 90 mm. When using a traction electric motor instead of mechanical brakes to hold the vehicle on an incline, there is indeed an increase in energy consumption and a short-term thermal load on the windings. However, according to the results of field tests, the holding period does not exceed 2-3 seconds, and the rotor speed is extremely low at this time. This means that the energy consumption is low and does not result in significant heat generation. This mode corresponds to the permissible short-term loads, similar to the starting modes of the electric motor, and does not cause overheating. Therefore, the use of a traction motor for temporary retention on an incline can be considered an energy-safe and thermally stable solution, provided that it is activated for a short period of time.

5. Conclusions

This paper presents a comprehensive methodology for the development and implementation of an anti-rollback protection system for electric buses, utilizing the vehicle's traction motor as the primary actuator. The core achievement of this work is the design and validation of a novel control algorithm that ensures vehicle immobilization on a slope without the necessity of a direct road grade measurement, thereby simplifying the system architecture and enhancing its robustness. The proposed PID-based control strategy was rigorously developed through traction-dynamic calculations and theoretically justified. Its efficiency was subsequently confirmed via a two-stage validation process. First, virtual trials were conducted to verify the control logic and optimize the controller parameters within a simulated environment. Second, the field experiments on a prototype electric bus demonstrated the practical applicability and performance of the method under real-world conditions. The algorithm successfully limited rollback to a maximum of 90 mm on a 12% grade, well within the predefined safety threshold of 100 mm, while maintaining the rollback speed below the permitted 0.5 km/h. The results obtained from both virtual and physical testing lead to the following conclusions. The developed method is technically viable and effectively prevents an electric bus from rolling back on slopes by generating sufficient counter-torque from the traction motor. The algorithm demonstrates practical significance as it provides a software-based safety feature deployable on existing electric vehicle platforms, potentially reducing reliance on driver intervention and mechanical brake systems for this specific function. This research establishes a foundational framework for designing and calibrating similar control systems, including the methodology for determining initial PID coefficients based on vehicle parameters and performance requirements. Future research directions may include the adaptation of this algorithm for various electric vehicle configurations (e.g., trucks, passenger cars), its integration with higher-level Advanced Driver-Assistance Systems (ADAS) for automated hill holding, and the optimization of the control strategy for enhanced energy efficiency during prolonged stops.

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