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Adhesion Control of Heavy-Duty Locomotive Based on Axle Traction Control System

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ABSTRACT The traction force of heavy-duty locomotive is reduced significantly and unable to fulfill the actual traction demand when the wheel slip phenomenon occurs. Aiming at this problem, an adhesion control method is proposed in this paper. The proposed method achieves online search of optimal traction torque based on adhesion coefficient-slip ratio relationship which is analyzed using Polach model. The optimal traction torque is the maximum torque which is operating under current wheel-rail condition without slip phenomenon. The proposed method detects wheel slip phenomenon by wheel slip velocity and wheel acceleration. Each axle in locomotive achieves individual traction torque adjustment by utilizing the advantage of axle control system. Considering the complexity of real heavy-duty locomotive, a co-simulation model is proposed by using MATLAB/Simulink to build the electric power circuit and control system as well as SIMPACK to build the locomotive mechanical system. The simulation is realized based on the StarSim real-time simulator platform and the experimental results verify the effectiveness of the proposed method.

INDEX TERMS Adhesion control, axle traction control, heavy-duty locomotive, optimal traction torque.

I. INTRODUCTION

With the rapid development of heavy-duty transportation, the requirements for traction performance and transportation capacity of heavy-duty locomotives are increasing [1]. Thus, the locomotive must be able to steadily provide the traction force to satisfy the actual traction demand with the increasing load [2]. Adhesion utilization of wheel-rail plays an important part to ensure the stabilization of traction force [3]. Therefore, it is crucial to research effective adhesion control methods to improve adhesion utilization and ensure the stable traction force to fulfill the actual demand [4].

In fact, rail generates adhesion force to wheel due to the adhesion utilization of wheel-rail when the wheel moves relative to the rail. The adhesion force is as the traction force of the locomotive. The adhesion utilization of wheel-rail is strongly affected by the wheel-rail conditions such as water, oil, and so on [5], [6]. When the force generated by the traction torque is over the maximum adhesion force that the rail can provide, the wheel slip phenomenon occurs. As a result, the traction force is decreased significantly, and both wheel and rail can suffer significant damage [7]. Therefore, the control method must be able to restrain wheel slip phenomenon as soon as possible when wheel-rail condition became bad and adjust the traction torque at an appropriate value to achieve excellent adhesion performance.

Much research and application have focused on the adhesion control. Generally, the adhesion control methods can be divided into the methods based on re-adhesion. In [8], [9], the traction torque is greatly reduced when the wheel slip phenomenon occurs and gradually restored when the slip phenomenon stops. Yuan adds nonlinear model predictive control in his method [10]. Song develops the fault-tolerant adaptive control strategy with virtual parameters-based approach [11]. Gao uses the self-structuring neural networks in the fault tolerant control for high speed trains [12]. Modern methods try to preserve the adhesion state at the optimal operation range to obtain the maximum adhesion utilization [13]–[15]. In [16], disturbance observer is used to estimate the adhesion characteristic and quickly search the optimal adhesion zone. Huang Z adopts forgetting factor recursive least-square algorithm to estimate the optimal slip ratio [17]. Sadr designs the adhesion coefficient estimation strategy by constructing the locomotive acceleration model [18]. Spiryagin estimates

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the adhesion coefficient based on wheel speed and traction torque [19]. Castillo uses neural network to estimate the adhesion coefficient in ABS system [20]. Liu applies the fuzzy control method in adhesion control [21]. In [22], [23], the methods achieve the estimation by the Extended Kalman filter and the Unscented Kalman filter.

The HXD2 heavy-duty locomotive has the characteristic of heavy load, which needs powerful and stable traction force to satisfy the actual traction demand. The re-adhesion methods have fast response and easy adjustment, which can restrain the slip phenomenon effectively. However, they are hard to preserve the adhesion state at optimal state. The relevant adhesion performance still needs further optimization. Modern methods generally can achieve optimal adhesion utilization. But the relevant algorithms are usually so complex that they are difficult to achieve ideal control result in practical engineering.

The application object of the adhesion control is the electric locomotive, but the actual characteristics of traction control system are hardly considered in the previous research. At present, the common locomotive traction control systems are mainly divided into two modes. One is axle traction control, which one motor is controlled by one converter. The other is bogie traction control or vehicle traction control, which two or four motors are controlled by one converter. There is a huge gap in control among different traction control systems. Therefore, it has a significant engineering value for considering these differences in adhesion control research.

The main contribution of this paper is as follows. An adhesion method considering the axle traction control system is proposed. The method online obtains the optimal traction torque based on re-adhesion method. It achieves the maximum adhesion utilization without complex computation, which improves the traction force as much as possible. And by taking advantage of the axle traction control system, each locomotive axle can individually adjust the traction torque during the adhesion control process. To implement this method, a co-simulation model is simulated by using MATLAB/Simulink to build the electric power circuit and control system as well as SIMPACK to construct the locomotive mechanical system.

This paper is organized as follows. The theory of wheel-rail adhesion is introduced in Section 2. The locomotive multi-body model using SIMPACK is presented in Section 3. The proposed adhesion control method for online search optimal traction torque is discussed in Section 4. The verification of the proposed method in StarSim real-time simulator platform is discussed in Section 5. The conclusion is provided in Section 6.

II. WHEEL-RAIL ADHESION

When the wheel contacts with the rail, the elastic deformation is produced under vertical pressure generated by axle load F_G. Elliptic patch is caused by the elastic deformation in the wheel-rail contact area. The elliptic patch divides into adhesion area and slip area [24]. There is relative slip in the slip area. The wheel velocity is greater than the locomotive velocity v_t due to the relative slip. The difference is called slip velocity v_s [25]. The relation is presented in Equation (1).

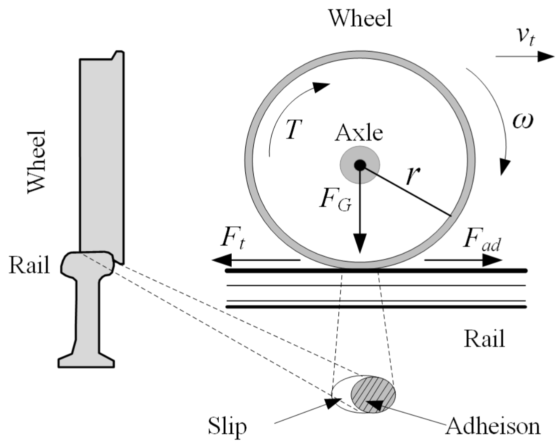

FIGURE 1. Wheel-rail contact and force analysis.

$$v_s = \omega r - v_t \tag{1}$$

In Equation (1), ω represents the wheel angular velocity, r represents wheel radius.

Driven by the traction torque T, the wheel generates a longitudinal force F_t to the rail when the wheel moves relative to the rail. At the same time, the rail also produces an opposite reaction force F_{ad} to the wheel, that is adhesion force. The wheel-rail contact and force analysis is shown in Fig. 1.

III. LOCOMOTIVE MULTI-BODY MODEL

The wheel-rail adhesion behavior is complex, which has strong nonlinearity and time-vary property [26]. Furthermore, the wheel-rail adhesion can be influenced by the mechanical structures of the electric locomotive [27]. The wheel-set single axle model is generally used to analyze the adhesion behavior [28]. However, it ignores the integrity of locomotive as well as the interaction among the different axles. In comparison, the multi-body model can fully simulate the adhesion dynamic response under the influence of the complex mechanical structure of locomotive.

The HXD2 electric heavy-duty locomotive is selected as the research object in this paper. HXD2 is an eight-axle electric locomotive. It consists of two identical four-axle locomotives. Therefore, we only analyze one four-axle locomotive in this paper. The multi-body model of locomotive is established by using the multi-body software SIMPACK. The integral multi-body model in SIMPACK is shown in Fig. 2.

The locomotive model has a B0-B0 wheel arrangement, which each bogie has two axles. The bogie model consists of primary suspension and secondary suspension which are formed of spring elements and damper elements. The spring elements dynamically simulate the interaction of force. The damper elements are used to attenuate the vibration.

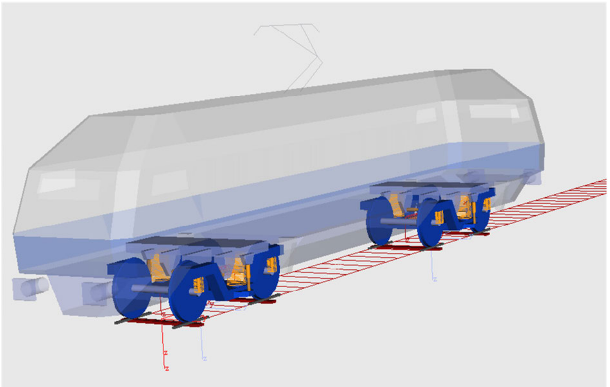

FIGURE 2. Integral multi-body model in SIMPACK.

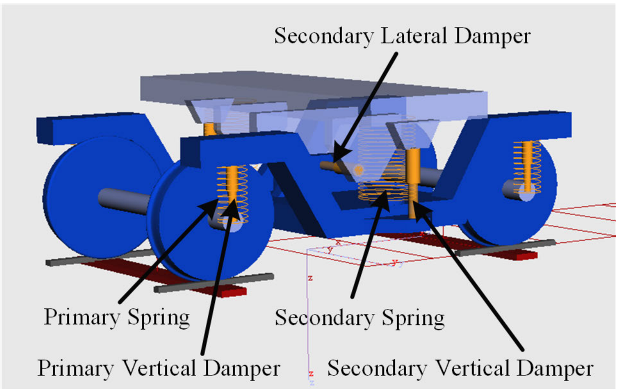

FIGURE 3. Bogie model in SIMPACK.

The track uses the elastically foundation model which prevents unrealistic force values during simulation. The bogie model is shown in Fig. 3.

Through the multi-body software, the interaction among locomotive mechanical structure is accurately simulated in longitudinal, transverse and vertical direction. It makes the wheel-rail dynamic behavior close to the actual working condition.

The resistance of locomotive is complex which is influenced by many factors during operation. Thus, the empirical formula based on practical engineering is usually used to compute resistance in simulation. The resistance of HXD2 heavy-duty locomotive F_d is shown in Equation (2).

$$F_d(v_t) = (0.84 + 0.0012 \cdot v_t + 0.000313 \cdot v_t^2) \cdot M \cdot g \tag{2}$$

In Equation (2), M represents the total locomotive weight, g represents the gravity acceleration.

IV. ONLINE SEARCH OPTIMAL TORQUE METHOD

A. MAXIMUM TRACTION FORCE BASED ON ADHESION CHARACTERISTIC CURVE

Currently, Polach model [29] is usually used to calculate the adhesion force in heavy-duty locomotive traction control.

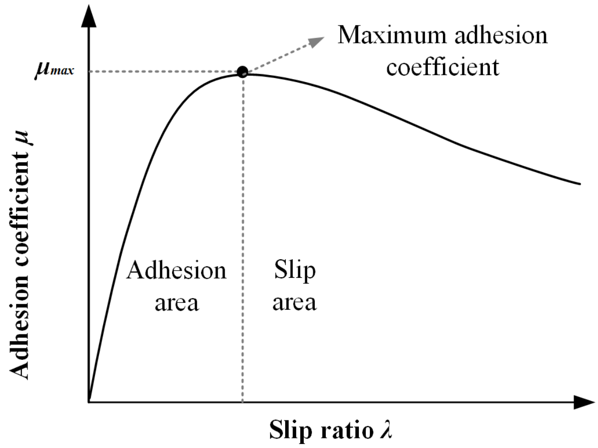

FIGURE 4. Characteristic curve of adhesion.

The relevant formulas are presented in Equation (3), (4), (5).

$$F_{ad} = \frac{2\mu F_G}{\pi}\left[\frac{k_A\varepsilon}{1+(k_A\varepsilon)^2} + \arctan(k_s\varepsilon)\right] \tag{3}$$

$$\mu = \mu_0\left((1-A)\,e^{-Bv_s} + A\right) \tag{4}$$

$$A = \frac{\mu_\infty}{\mu_0} \tag{5}$$

In Equation (3), μ represents the adhesion coefficient, k_A, k_S respectively represent reduction factor in the adhesion area and in the slip area, ε represents gradient of the tangential stress in adhesion area, μ_0 represents maximum friction coefficient at zero slip velocity, μ_∞ represents friction coefficient at infinity slip velocity, A represents ratio of friction coefficients μ_∞/μ_0, B represents coefficient of exponential friction decrease (s/m).

In order to reflect the slip degree, the slip ratio [30] is presented in Equation (6).

$$\lambda = \frac{v_s}{v_t} \tag{6}$$

Adhesion characteristic curve [31], which represents the relationship of adhesion coefficient and slip velocity or ratio, is usually used to reflect wheel-rail adhesion state in practical engineering. In this paper, the adhesion coefficient-slip ratio relationship is adopted as shown in Fig. 4.

As shown in Fig. 4, the peak point of the adhesion characteristic curve is corresponding to the maximum adhesion coefficient. The adhesion characteristic curve can be divided into two parts by this point. The left part represents the adhesion area and the right part represents slip area. In adhesion area, the slope of the curve is positive, the adhesion coefficient increases with the slip ratio. On the contrary, in slip area, the adhesion coefficient decreases with the increase of the slip ratio. With the traction toque increasing, F_t is greater than the maximum F_{ad} which current wheel-rail condition can provide. It causes the slip ratio to increase sharply. And the adhesion coefficient rapidly decreases coming with it. As a result, the normal adhesion of wheel-rail is lost, and the wheel slips. Equation (3) shows that locomotive traction force is proportional to the

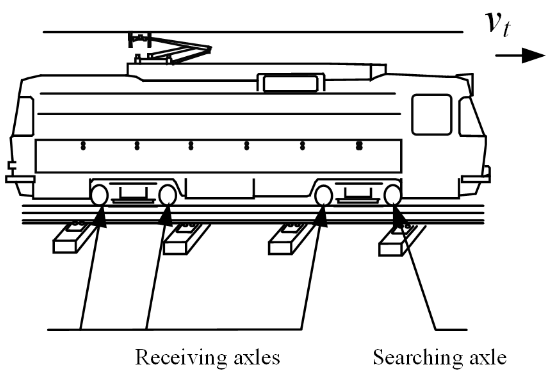

FIGURE 5. Axles classification.

adhesion coefficient. Obviously, the maximum traction force can be safely obtained when the operating point near the left side of peak point. Therefore, maintaining the operation point at the adhesion area, especially near the peak point, is the key factor to avoid the wheel slip phenomenon and obtain the optimal traction performance.

B. ONLINE SEARCH USING THE ADVANTAGE OF AXLE TRACTION CONTROL SYSTEM

The heavy-duty locomotive is generally provided with axle traction control system. In axle control systems, each motor is equipped with one converter, which means that each motor can individually control the output traction torque. It is flexible for each axle to adjust the torque during adhesion control and conducive to the coordination among axles.

Based on the advantages of axle traction control system, this paper proposes an adhesion control method which online searches of the optimal traction torque. The method divides the four axles into two categories. The axle which first encounters wheel slip phenomenon is defined as the searching axle, and the other axles are as the receiving axles. For convenience to explain the method, this paper assumes the front axle towards moving direction as the searching axle and the other axles as the receiving axles, shown in Fig. 5.

The proposed method is focused on the adhesion control during acceleration. The adhesion control system detects the slip phenomenon by comparing the slip velocity and the wheel acceleration of each axle with their predetermined values. The predetermined values are the threshold of slip phenomenon which were obtained from many experiments. If the slip velocity or acceleration exceeds the predetermined value, there is a slip phenomenon.

When the wheel-rail condition becomes severe, the slip phenomenon triggers the adhesion control system. Based on the above classification, the searching axle searches the optimal traction torque, which is the maximum torque operating under current wheel-rail condition without slip phenomenon. The relevant algorithm is shown in next part. The remaining receiving axles takes the optimal torque information transmitted by the searching axle as the reference and quickly adjusts the traction torque. Through the cooperation between the searching axle and the receiving axle, all axle's wheel

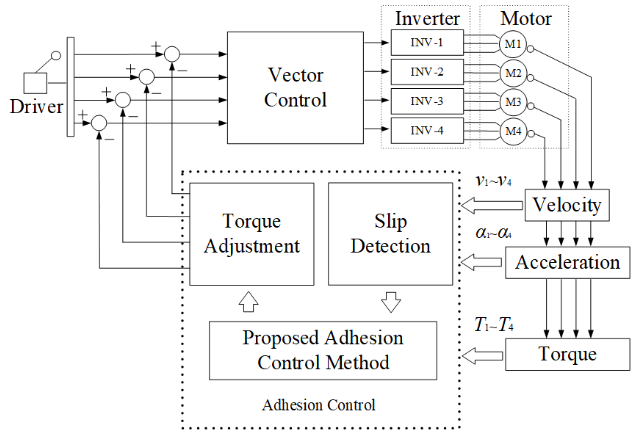

FIGURE 6. Block diagram of adhesion control system.

can quickly restrain slip phenomenon and restore the normal adhesion performance under current wheel-rail condition. The traction motor is three-phase asynchronous motor which is controlled using vector control and voltage Space Vector Pulse Width Modulation (SVPWM). The block diagram of the adhesion control system is shown in Fig. 6.

C. ALGORITHM FLOW

The initial traction torque per axle is T_0. The locomotive starts operating normally on the rail. The flowchart of the optimal torque online search algorithm is shown in Fig. 7. The algorithm process is mainly divided into four phases.

In phase 1, the searching axle first happens to slip when the wheel-rail condition becomes severe. The traction torque of the searching axle is rapidly reduced to suppress slip until the slip velocity and wheel acceleration less than the predetermined values. At this moment, the traction torque is T_1.

$$T_1 = T_0 - C_1 \cdot t_1 \tag{7}$$

In Equation (7), C_1 represents the adjustment coefficient of torque decrease, t_1 represents the period of torque decrease.

In phase 2, After the slip phenomenon stopping, the traction torque is slightly increased step by step. With the traction torque increasing, the wheel slips again when the force driven by traction torque exceeds the maximum adhesion force. From the discussion in part A of IV, the current operating point is between adhesion area and slip area, which near the peak point of adhesion characteristic curve. Record the traction torque value $T_{\max}$ at this moment, which is the maximum threshold value under the current wheel-rail condition. The wheel will slip when the output traction torque greater than or equal to it.

$$T_{\max} = T_1 + C_2 \cdot t_2 \tag{8}$$

In Equation (8), C_2 represents the adjustment coefficient of torque increase, t_2 represents the period of torque increase.

In order to avoid secondary slip phenomenon and make the operating point near the left side of peak point, the traction

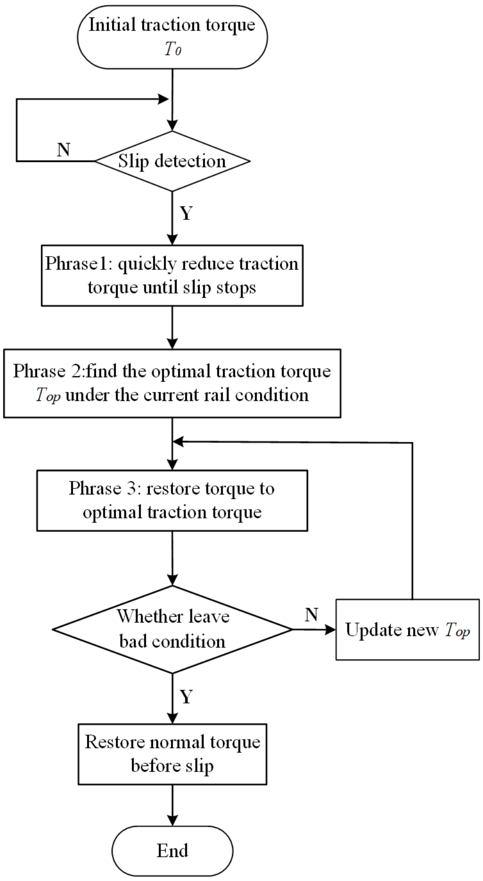

FIGURE 7. Flow chart of optimal torque online search control.

torque should be adjusted slightly smaller than the maximum, that is, the optimal traction torque T_{op}.

$$T_{op} = K \cdot T_{\max} \tag{9}$$

In Equation (9), K represents the adjustment coefficient of optimal traction torque.

In phase 3, due to the wheel slip after phase 2, the process of torque decreasing in phase 1 is executed again after obtaining the optimal traction torque value. When the slip phenomenon ends, the traction torque is quickly restored according to T_{op}.

$$T_3 = T_1 + C_3 \cdot t_3 \tag{10}$$

In Equation (10), T_3 represents traction torque after restoring which equals to T_{op}, C_3 represents the adjustment coefficient of optimal traction torque restoration, t_3 represents the period of torque restoration.

In phase 4, the process mainly confirms whether the locomotive has left the bad wheel-rail condition or not. Repeat the process in phase 2. If the new maximum traction torque T_{new} is less than or equal to the original maximum traction torque $T_{\max}$, it represents that the locomotive is still in the bad wheel-rail condition. Then the $T_{\max}$ value will update to T_{new}. If there is no slip phenomenon while the T_{new} exceeds $T_{\max}$, it represents that the locomotive has driven out of the bad wheel-rail condition. Then the control process is terminated, and the traction torque is restored to the initial value before slip phenomenon.

TABLE 1. Locomotive parameters.

Quantity	Value	Unit
Axle loading	23	t
Bogie weight	18.690	t
Wheel radius	0.54	m
Gear ratio	120/23	
Locomotive weight	92	t
Wheel spacing	2.6	m
Bogie spacing	10.6	m
C1	25000	N·m/s
C2	1250	N·m/s
C3	6250	N·m/s
Initial traction torque per motor	6000	N·m
Wheelset moment of inertia	1850	kg·m^2
Motor moment of inertia	70	kg·m^2

TABLE 2. Traction motor parameters.

Quantity	Value	Unit
Motor model	YJ90A	
Rated power	1275	kW
Rated voltage	1391	V
Rated current	620	A
Rated torque	8124	N·m
Rated frequency	76	Hz
Number of phrases	3	
Number of poles	6	

V. SIMULATION ANALYSIS

In order to verify the correctness of the proposed method, a co-simulation model is proposed. The electrical traction system and control system are built in MATLAB/Simulink, and the locomotive mechanical system is built in SIMPACK. The main locomotive parameters are shown in Table 1. The traction motor parameters are shown in Table 2. The block diagram of the co-simulation model is shown in Fig. 8. Generally, the actual locomotive testing of adhesion control is costly and it needs to coordinate a large number of manpower and material resources. The real-time simulator can efficiently test the accuracy and feasibility of the algorithm with low cost, which is widely used in adhesion control implement. Therefore, the simulation in this paper is done in StarSim real-time simulator platform as shown in Fig. 9.

Dry, wet, and oil wheel-rail conditions which are the most common in real environments are tested in the simulation. The calculation coefficients of different rail conditions are shown in Table 3. Furthermore, the sudden change between two different wheel-rail conditions are designed to verify the correctness and efficiency of the proposed method. In step one, the wheel-rail condition changes from dry to wet. In step two, the condition gets worse, the wheel-rail condition changes from wet to oil. In step three, the condition returns to dry from oil.

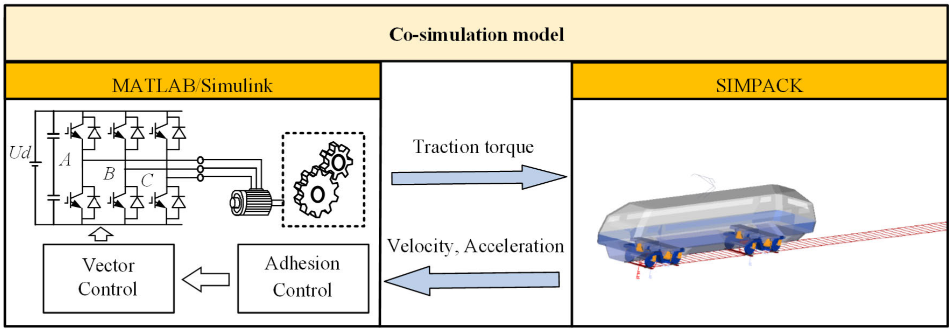

FIGURE 8. Co-simulation model.

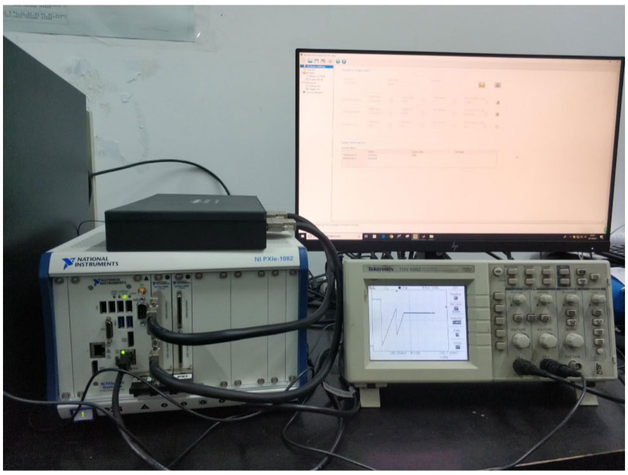

FIGURE 9. Real-time simulator.

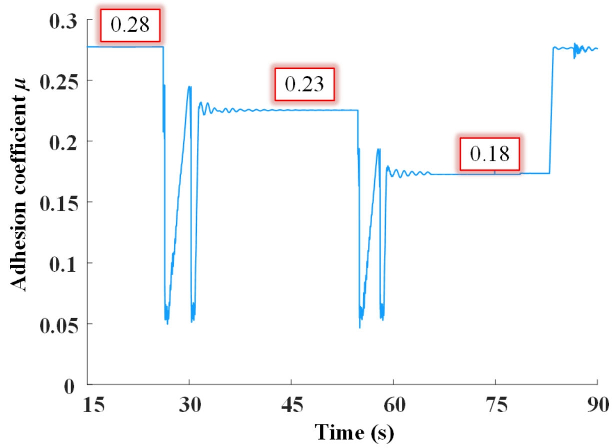

FIGURE 10. Adhesion coefficient of searching axle.

TABLE 3. Calculation coefficients of different rail.

Wheel-rail conditions	Dry	Wet	Oil
K_A	1.00	0.30	0.30
K_B	0.40	0.10	0.10
$\mu 0$	0.44	0.35	0.28
A	0.43	0.39	0.50
B	0.72	0.17	0.30

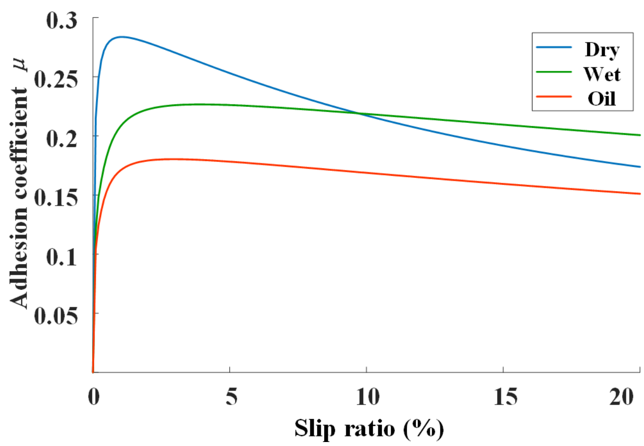

FIGURE 11. Characteristic curves of adhesion in different conditions.

The adhesion coefficient of searching axle is shown in Fig.10. The locomotive initially runs on dry condition. The adhesion of wheel-rail is good and the wheel slip phenomenon does not occur. The adhesion coefficient maintains stably around 0.28.

The adhesion coefficient decreases sharply at 26 s. This represents that wheel slip phenomenon occurs while the wheel-rail condition changes from dry to wet. After a short time, the adhesion coefficient is stabilized around 0.23. This represents that the slip phenomenon triggers the adhesion control, the traction torque is adjusted effectively under proposed control algorithm and the adhesion of wheel-rail is gradually recovered. Similarly, at 60 s, the adhesion coefficient gradually stabilized around 0.18 after the wheel-rail condition changes from wet to oil. At 80 s, the condition changes to the initial dry condition, the adhesion coefficient returns to the normal value in dry condition.

Comparing the above adhesion coefficient value with the adhesion characteristics curves in Fig. 11, which are based on Table 3, the operating points under different wheel-rail conditions all in the range near the peak value in adhesion coefficient curves. It can be verified that the algorithm can effectively find the optimal traction torque under different

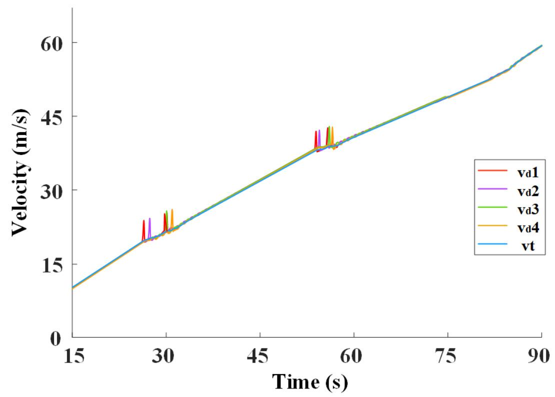

FIGURE 12. Locomotive velocity and wheel velocity of each axle.

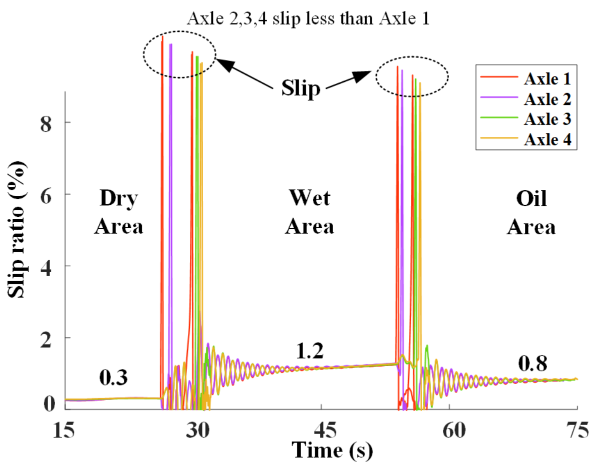

FIGURE 13. Slip ratio of each axle.

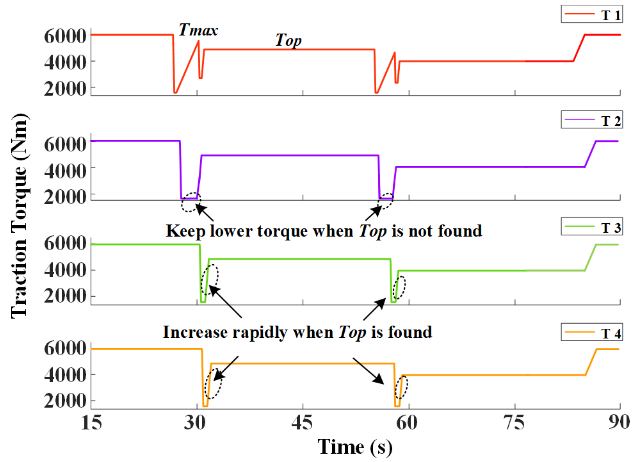

FIGURE 14. Traction torque of each axle.

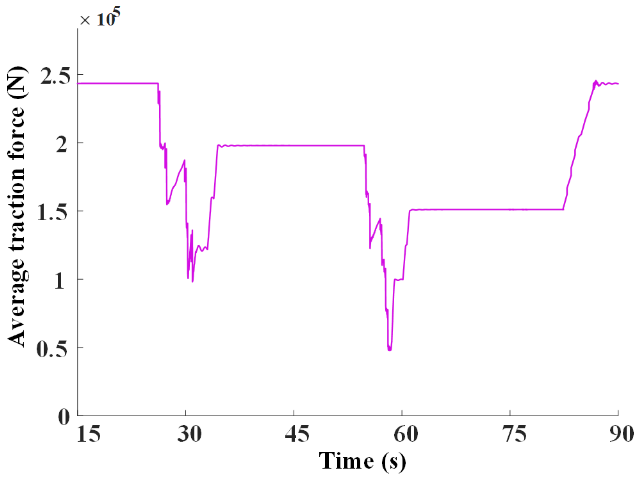

FIGURE 15. Average traction force of whole locomotive.

wheel-rail conditions and restrain the slip phenomenon and improves the adhesion utilization as much as possible.

The locomotive velocity v_t and wheel velocity v_d of each axle are shown in Fig. 12 and the relevant slip ratio is shown in Fig. 13. Axle 1 which serves as the searching axle first slip when the wheel-rail condition changes. And axle 2, 3 and 4 which serve as the receiving axles happen to slip in succession. The traction torque of each axle is shown in Fig. 14. The receiving axles keep the lower torque to avoid secondary slip when the T_{op} is not found. After the T_{op} is received, the receiving axles rapidly restore the torque to this value. The four axles slip ratio is finally stabled at 0.3%, 1.2%, 0.8% respectively in dry, wet, oil wheel-rail condition under the proposed method. And the slip ratio is meet the adhesion characteristics curves in Fig. 11. Comparing the four axles, the number of times which receiving axle occurs slip are less than searching axle. It can be verified that slip phenomenon is effectively reduced when the optimal traction torque is found.

The average traction force of the locomotive is shown in Fig. 15. Under the adjustment of the algorithm, the average traction force is kept stably under all dry, wet, oil conditions. It can efficiently guarantee the actual traction force of locomotive regardless of wheel-rail conditions.

VI. CONCLUSION

In this paper, an adhesion control method of heavy-duty locomotive is proposed. The method considers the advantage of the axle traction control system. The optimal traction torque which is suitable for operating on current wheel-rail condition is searched online. The co-simulation model is established which uses MATLAB/Simulink to build electrical traction system and control system as well as SIMPACK to build the locomotive mechanical system. The proposed method is verified under a changed wheel-rail condition including dry, wet, and oil, which are the most common conditions in practical engineering. The simulation is implemented on the StarSim real-time simulator platform. The results illustrate that the proposed method effectively restrains the slip phenomenon, improves the adhesion utilization, and guarantees the actual traction force of locomotive.

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