Anti-slip Re-adhesion Control Method to Increase Starting Tractive Effort of Inverter-fed Electric Locomotive

Michihiro YAMASHITA
Traction Control Laboratory, Vehicle Control Technology Division

Tadashi SOEDA
Japan Freight Railway Company

The Japan Freight Railway Company has developed an inverter-controlled diesel hybrid shunting locomotive, type HD300, to replace aging DE10 diesel shunting locomotives. In the early stage of development, it was difficult to secure sufficient tractive effort just after starting. Therefore, a re-adhesion control method was developed to minimize torque reduction by improving the delay in wheel rotational acceleration signals, used to determine when torque reduction is stopped during anti-slip re-adhesion control, thereby increasing the average tractive effort. The results of running tests verified an increase of 5% or more in the average tractive effort. The developed control method has been applied to the mass-production of the HD300 model.

Keywords: wheel slip, electric locomotive, tractive effort, re-adhesion control, inverter control, acceleration

1. Introduction

A locomotive traction system must produce traction for a train with a limited number of driving axles. When the rolling contact between a rail and a wheel becomes wet due to rain or other reasons, the frictional force between the rail and the wheel falls, resulting in a decrease in tractive effort. In addition, when a locomotive is running on a gradient in wet conditions and a wheel slip occurs, the train speed decreases and in the worst case, the train stops on the gradient. Furthermore, if a wheel slip occurs when starting, such as on departure, this may cause a reduction in acceleration or the train may move backwards if on a gradient. If a wheel slip is repeated in that state, this may cause damage to the wheels and/or rails. Therefore, when a driving axle has slipped, anti-slip re-adhesion control (torque control) must be provided immediately. The Railway Technical Research Institute has conducted extensive studies on re-adhesion control for electric rolling stock to address these issues [1-4].

The Japan Freight Railway Company (JRF) has developed an inverter-controlled diesel hybrid shunting locomotive, type HD300, to replace the aging type DE10 diesel shunting locomotives used in station yards [5]. The constant acceleration region (constant torque region) of a shunting locomotive ranges up to a velocity of approximately 10 km/h. Considering the need to pull a train out of a gradient in a station yard and the diagram of occupancy of tracks for trains up to a velocity of approximately 40 km/h, it is crucial to secure sufficient tractive effort just after starting. In the early stage of development, JRF used an anti-slip re-adhesion control algorithm for electric rolling stock to address these issues [1-4].

As a countermeasure, the possibility of preventing excessive drops in torque during wheel slips was investigated, and a re-adhesion control method was developed to decrease the amount of torque reduction by using a rotational acceleration signals with faster detection of wheel slip convergence (signal to stop torque reduction) compared to the conventional signal for detecting wheel slips (signal to start torque reduction) and thus increase the average torque value, thereby increasing the average tractive effort [6]. Work has also been conducted to increase the traction motor’s current value (torque) on a Shinkansen train by reducing the drop in torque, followed by verification of its effect [2].

The effectiveness of the developed control was validated through on-track testing as well as simulation, the results of which demonstrated that compared to the situation before improvement, the average tractive effort increased by 5% or more.

2. Re-adhesion Control Method

2.1 Re-adhesion control method before improvement

The acceleration performance of a train on a gradient of at least 0.1 km/h/s was evaluated assuming a maximum traction load of 1300 tons for an inverter-controlled main line locomotive developed by JRF. However, in wet conditions, wheel slips occurred, and acceleration became difficult using the conventional re-adhesion control method because of the loss in tractive effort.

Figure 1 shows the characteristics of tractive effort of a shunting locomotive against speed in consideration of gradients and tractive tonnage assumed during commercial operation in a freight siding. To accelerate a freight train, the required tractive effort should exceed the train gradi-
ent resistance assumed just after starting. Therefore, it is necessary to secure tractive effort much larger than 100 kN at a velocity in the region of 0–10 km/h.

Inverter-controlled electric locomotives possess a re-adhesion control function (Fig. 2), which controls torque by detecting slipping, using the rotational velocity and acceleration signals from the rotor of the traction motor, as follows:

1. A slip is deemed to have occurred (slip detection) when the rotational velocity and acceleration values exceed certain threshold values, upon which the torque of the traction motor is lowered.

2. When slipping appears to have started to converge (without exceeding the slip detection threshold) from the velocity difference and acceleration signals, torque reduction is stopped and torque may then be lowered based on the difference (hysteresis) between the threshold values of slip detection and slip convergence detection, or by a certain value according to the difference in velocity during slip detection.

3. After the torque is no longer being reduced, the torque is held at that level for a given period of time before being restored to a value equivalent to the adhesion estimated during slipping.

Figure 3 shows the relationship between the tangential force and tractive force at the wheel rim (force proportional to torque; hereafter referred to as “tractive force”). In this chart, when a slip occurs at ①, the slip velocity/rate increases due to the negative gradient characteristics of the tangential force if the torque remains equal to the value which existed just before the slip, which requires the detection of a slip and subsequent reduction of the torque. Then, when the tractive force is less than the tangential force after the torque reduction, the slip acceleration decreases, which causes slip convergence to begin towards re-adhesion in the direction of ②.

Figure 4 shows an example of the results obtained from water spray tests performed at the initial stage of development, and which verified that wheel slips occurred on all axles about 11 seconds immediately after starting, which caused a large reduction in the torque of each axle and consequently the occurrence of coupler force vibrations (as shown in the bottom part of the chart in Fig. 4) the p-p values of which were around 70 kN.

If after the slip detection, tractive effort is reduced excessively, more than the tangential force, the difference between the tractive effort and tangential force increases at the time of re-adhesion, which causes car-body longitudinal vibrations and coupler force vibrations and is considered to make all axles prone to slipping. Thus, it is critical to prevent any excessive drop in torque.
2.2 Calculation of rotational velocity and acceleration of traction motor

This section discusses how to calculate the rotational acceleration of a traction motor, along with its characteristic features.

For an inverter-controlled locomotive, the rotational velocity and acceleration of the rotor are calculated by using the pulse signals from the PG sensor mounted at the end of the traction motor, the results of which are used for re-adhesion control. These signals include vibration components other than wheel rotational components (hereafter referred to as “noise components”) produced by bogie vibrations, gear engagement vibrations etc.

If the noise components of the rotational acceleration are significant, a wheel slip may easily be incorrectly detected. Therefore, false detection is prevented by damping the noise components through a smoothing process. A moving-average method for smoothing was used for the present research.

2.2.1 Velocity calculation

As shown in Fig. 5, velocity is calculated using the wheel diameter and gear ratio by measuring $T_p$, the period between the rise times of adjacent PG pulses (pulse time width), using a frequency counter with a range of approximately 1 MHz, where the speed counting error depends on the $T_p$ counting time unit, which is 1 μs.

Here, if the wheel diameter is represented by $D$ (in meters) and the number of pulses per wheel rotation by $P$, Eq. (1) is established to calculate the velocity ($V$) from the count of PG pulses. Currently, on the assumption of $D = 0.91$ m and $P = 80$ G (G: Gear ratio, 4.267), the velocity error is less than 0.1% at a velocity of 10 km/h, which means that the velocity error dependent on the counting time unit is negligible, except for cases of extremely low speeds.

$$V = \frac{3.6\pi D}{T_p} \frac{1}{P} \quad [\text{km/h}] \quad (1)$$

The velocity information used for re-adhesion control is found as the mean value for the moving average time period ($T_a$). The lag time according to the velocity calculation is half the value, $T_a/2$.

2.2.2 Acceleration calculation

The rotational acceleration is calculated by the following Eq. (2), where $V(T)$ is the moving average velocity at the present time, and $V(T-T_a)$ is the velocity calculated ahead of the present time by the time period ($T_a$) for smoothing (Fig. 6).

$$\alpha = \frac{V(T) - V(T-T_a)}{T_a} \quad (2)$$

The acceleration is calculated using the same time period as that for the moving average of the velocity. When the time period of the moving average of the velocity is $T$, the lag time is $T/2$. Thus, the acceleration detection delay $\Delta T$ is expressed as the following Eq. (3).

$$\Delta T = (T + T_a)/2 \quad (3)$$

The delay in the acceleration signal is $T_a$, the same as the moving average time period.

Hereafter “X ms acceleration” means the acceleration calculated for the time period X ms from the X ms moving average velocity.

2.2.3 Frequency analysis of acceleration signals

Figure 7 shows example waveforms of the rotational velocity and acceleration gained when a single locomotive was running. Figure 8 shows the results of the frequency analysis for accelerations of 10 and 40 ms at a velocity of around 10 km/h. The figure indicates that the main noise component is contained in the frequency of approximately 62 Hz. This frequency is almost in agreement with the gear engagement frequency (63 Hz) at the velocity of 10 km/h and therefore can be considered as a noise component generated by the gear engagement vibration. Similar noise components were identified at other velocities as well.

Using a similar frequency analysis and the 40 ms ac-
2.2.4 Frequency components of acceleration signals

As the slip detection threshold reduces the frequency of incorrect detection, the detection threshold values should generally exceed the train acceleration by 1.5 to 2.0 km/h/s. Accordingly, it is desirable to keep the acceleration for slip detection to less than the noise components (under 0.5 km/h/s) contained in the 40 ms acceleration, which is equal to the current acceleration.

2.3 Developed re-adhesion control method [6]

The 10 ms acceleration signal was proposed to detect wheel slip convergence, which has less of a delay than the 40 ms acceleration signal, used for wheel slip detection, in order to decrease the excessive amount of torque reduction at the time of re-adhesion control in consideration of the delay of the rotational acceleration signal described in the preceding section (Fig. 9), where, since the starting acceleration of an approximately 1,000-ton traction train is about 0.5 km/h/s, the threshold values were set so that a slip could be detected when the 40 ms acceleration rises above the slip detection threshold value of 3 km/h/s, while a slip convergence could be detected when the 10 ms acceleration falls below the detection threshold value of 0 km/h/s.

The following study was conducted to find the target amount of excessive torque to be reduced due to the delay in acceleration signals: With 40 ms acceleration signals, there is a delay of 40 ms from the actual wheel rotational acceleration. Hence, if the inclination between the start and end points of the drop in traction motor torque is set at 3 to 5 times the maximum torque per second at starting (approximately 5,000 Nm), this will cause an excessive reduction of the starting torque by 12–20% (600–1,000 Nm). On the other hand, it is considered that using the 10 ms acceleration for detecting wheel slip convergence could be expected to decrease the reduction to about 3–5% (150–250 Nm). Such a reduction of the drop in torque could make it easier for the wheel to slip again. However, it was confirmed that re-occurrence of a slip was unlikely, if the function was simultaneously used to change the temporary holding time (a function to continue temporary holding until re-adhesion is judged to be provided when the velocity difference becomes less than 0.3 km/h during the temporary holding operation). After the torque holding operation ends, the torque will be restored to a value equivalent to the adhesion estimated at the time of slip detection [3]. If no new slipping occurs, the value will be restored to the torque pattern value established in accordance with the velocity notching properties.

3. Simulation

A test to simulate running in rainy weather was carried out to verify the usefulness of the developed re-adhesion control method.

3.1 Vehicle simulation model

Figure 10 shows a diagram of the vehicle model used in the simulation, consisting of sprung masses, masses between the springs on the front and rear bogies, and unsprung masses. A nose suspension driving device was employed. The traction motor torque on each axle could be controlled individually, and it was assumed that it would follow the traction coefficient ($\mu$), obtained by dividing the tractive effort by the axle weight, in the microslip region.
The top axle in the direction of travel was assumed to be the first axle, and a target value was established for the traction motor torque on each axle so that the traction coefficient for each axle would be 0.31. The parameters for the traction coefficient, $\mu$, were established as follows by referring to the wheel slip data of the on-track testing: $\Delta \mu = 0.01$ and $\rho = 0.03$.

The static axle weight was set to 147 kN on each axle, and the mass of the load vehicle was set to 1,000 tons.

### 3.2 Simulation results

Simulations were performed for two scenarios: The 40 ms acceleration signal for slip detection was used for slip convergence detection in one of the cases, and the 10 ms acceleration signal for slip convergence detection, proposed in this paper, was used for the same purpose in the other case. The results are shown in Figs. 12 and 13.

<table>
<thead>
<tr>
<th>$\mu_s$</th>
<th>Adhesion coefficient before slip ($V_s=0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \mu$</td>
<td>Drop in adhesion coefficient just after slipping</td>
</tr>
<tr>
<td>$\mu = \mu_s - \Delta \mu - \rho V_s$</td>
<td>Traction coefficient</td>
</tr>
<tr>
<td>Gradient : $\rho$</td>
<td></td>
</tr>
</tbody>
</table>

(Fig. 11) as a model of tractive effort applied between the slipping wheels and the rails.

The adhesion coefficient, $\mu_s$, was kept higher than the traction coefficient on each axle until 2 seconds after simulation was begun (no wheel slip occurred during that period). Only the adhesion coefficient of the first axle was set to 0.28 after 2 seconds, which caused the traction coefficient of the first axle to start exceeding the 0.28 adhesion coefficient at around 4 seconds, when a wheel slip occurred, and re-adhesion control was provided (no waveform is shown for the other axles because they were not slipping).

In the simulation, the restored value was set to the starting torque value. The slip detection threshold value was set to detect a slip above the acceleration of 3 km/h/s, while the slip convergence detection threshold value was set to detect a slip convergence below the acceleration of 0 km/h/s.

Here, an acceleration signal that causes an increase in frequency as well as in velocity at the amplitude of 2 km/h/s was added to the acceleration for slip convergence detection in order to simulate the noise signal generated by the gear engagement vibration.

The simulation results indicated that the torque drop was approximately 1,000 Nm when the 40 ms acceleration signal for slip detection was used for slip convergence detection, while the torque drop was approximately 400–600 Nm when the 10 ms acceleration signal was used, as proposed. Results from the proposed method showed a 5.9% increase in the average torque value for the first axle at velocities of between 0 and 10 km/h. This confirmed that preventing an excessive drop in torque when a slip was detected led to an increase in the average torque value. Similarly, it was found that improvement of the tractive effort could also be expected.

### 4. Running Tests (On-Track Testing)

#### 4.1 Running test conditions

Table 1 shows the running test conditions. A running test was performed using a type HD300 diesel hybrid shunting locomotive, to which two type EF65 locomotives were coupled for loading. With braking forces given to the loading locomotives to simulate a load equivalent to 1,000 tons of loaded freight cars, the traction performance was verified on wet rails by spraying water on the wheels of the HD300 hybrid locomotive (Figs. 14 and 15).

In the running test, the detection threshold values were set so that slipping would be detected when the 40 ms acceleration rose above 3 km/h/s, while slip convergence would be detected when the 10 ms acceleration fell below 0 km/h/s, as in the simulation.
Table 1 Test conditions

<table>
<thead>
<tr>
<th>Test site</th>
<th>Container platforms of Tokyo Freight Terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axles sprayed with water</td>
<td>All wheels; in front of wheels in advancing direction</td>
</tr>
<tr>
<td>Water quantity</td>
<td>0.5 liters/min per wheel</td>
</tr>
<tr>
<td>Maximum tractive effort</td>
<td>200 kN</td>
</tr>
<tr>
<td>Load</td>
<td>Equivalent to 1,000 tons</td>
</tr>
<tr>
<td>Running velocity</td>
<td>0–10 km/h</td>
</tr>
</tbody>
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4.2 Running test results

Figure 16 shows the results of the running test applying the developed re-adhesion control. Accelerations of 40 ms and 10 ms were used separately and respectively for slip detection and slip convergence detection. The results shown in Fig. 17 confirm that the delay in slip convergence detection improved, reducing the drop in torque. In addition, the maximum fluctuation width (p-p value) of the coupler forces (bottom chart of Fig. 16) was reduced by half (relative to the situation before improvement) to about 25 kN (Fig. 4).

The developed re-adhesion control method was also found to allow a significant increase in coupler forces up to a velocity of around 6 km/h by comparison with the situation before improvement (Fig. 18). Confirmation was also obtained that the average tractive effort of the locomotive immediately after starting and up to a velocity of 10 km/h increased by 5% or more as a result of the improvement, as evidenced by the simulation results (Fig. 19).
5. Conclusion

When the operation of a type HD300 diesel hybrid shunting locomotive in a JRF station yard was assumed at the initial stage of development, it was found that not enough tractive effort could be secured just after restarting from a stop on a gradient, where an increase in the tractive effort was needed. A re-adhesion control method was therefore proposed, to lessen torque reduction when a slip was detected by using a less delayed rotational acceleration signal for the detection of wheel slip convergence compared to the delay in acceleration signals used for wheel slip detection thereby increasing the tractive effort when starting the locomotive. The results of running tests where water was sprinkled on the track confirmed a significant increase in tractive effort (coupler forces), compared with data from the early stage of development.

Consequently, JRF has introduced this new re-adhesion control method on mass-produced HD300 diesel hybrid shunting locomotives. This study focused on increasing the tractive effort of shunting locomotives in at low-speeds. Future research plans to explore the possibility of expanding the method to new locomotives and trainsets running at medium and high speed.

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References


Authors

Michihiro YAMASHITA, Dr. Eng.
Senior Researcher, Traction Control Laboratory, Vehicle Control Technology Division
Research Areas: Traction Control, Motor Control

Tadashi SOEDA
Manager, Ohmiya Workshop, Japan Freight Railway Company