Re-adhesion Control without Speed Sensor in Multiple Induction Motor Drive

I. INTRODUCTION

Since the advent of railway vehicle with three-phase drive in 1970s, power semiconductors used in electric railway vehicles have been changed from thyristors to GTO thyristors and IGBTs. As for traction motor control, vector control has come into wide in use in place of slip frequency control and speed sensorless vector control is in trial stage for commercial trains[1]. Anti-slip and re-adhesion control of railway vehicles has also taken a great progress by utilizing wheel axle speed information[2],[3],[4],[5],[6],[7](Fig.1). So future locomotives and electric multiple units with speed sensorless vector control should have at least the same adhesion performance as alternatives with speed sensors.

In this paper a novel anti-slip re-adhesion control without speed sensor is proposed. With this method small wheel slip can be detected and the performance of this control is expected as high as the control with speed sensors.

II. TREND OF DRIVE TECHNOLOGY OF ELECTRIC RAILWAY VEHICLES

Electric drive technology was progressively changed from d.c. motor drive with rheostat control to induction motor drive with inverter control especially in early 1990s. By introducing the new technology railway company could save maintenance cost of rolling stock by half. In large cities where transport density is relatively high, energy consumption of commuter trains also reduced drastically by regenerative brake in place of mechanical brake and by train weight reduction. As far as commuter multiple units are concerned, the three phase drives which one inverter feed several traction motors in parallel, say multiple motor drive, is much less expensive than ones of individual motor drive. This solution will be applied to more railway vehicles in future.

If railway vehicle has possibility to make railway operation more efficient, one candidate will be pure electrical normal brake that can minimize vehicle maintenance staffs and simplifies train operation. Introducing this technology, all brake force from the top speed to zero is generated electrically and there is no mechanical wear of brake materials.
III. SPEED INFORMATION OF ELECTRIC RAILWAY VEHICLES

Normally wheel axle speeds are used in various applications of railway vehicles. On the one hand most applications use the train speed derived from one or two wheel axle speeds, on the other hand all wheel axle speeds in a vehicle are used for motor control, anti-slip control and anti-skid control (Table 1). If we can eliminate speed sensors from powering and braking equipment, there would be following advantages,

a) We can cut the cost of cabling between speed sensors and the inverter that requires know how to avoid electromagnetic noise troubles and so on.

b) There occurs no failure of the speed sensors. According to some statistics around 5% of traction inverter malfunction is due to speed sensor failures. So if we introduce motor control without speed sensor, we will have less troubles of traction equipment.

c) Powering and braking equipment becomes simpler with small number of assemblies that will be beneficial for cost reduction and reliability.

Table. 1 Speed information used in a train

<table>
<thead>
<tr>
<th>Application</th>
<th>Type of speed information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety installation</td>
<td>train speed</td>
</tr>
<tr>
<td>Speed meter</td>
<td>train speed</td>
</tr>
<tr>
<td>Door close safety</td>
<td>train speed</td>
</tr>
<tr>
<td>Inverter control</td>
<td>rotor speed of each traction motor or a virtual motor</td>
</tr>
<tr>
<td>Anti-slip control</td>
<td>axle speeds</td>
</tr>
<tr>
<td>Anti-skid control</td>
<td>axle speeds</td>
</tr>
</tbody>
</table>

To do without axle speed information for powering and braking in a vehicle, we will have following choices,

a) Traction motor control without speed sensor is under development for railway vehicles so that sooner or later this technology can be applied to commuter trains by itself.

b) Regarding anti-slip and anti-skid control of the inverter, we can use estimated motor speeds for each axle instead of detected axle speeds if they are available from the inverter controller. In case of multiple motor drive, the estimated speed is only available for the virtual motor. So only large slip can be detected by acceleration derived from the estimated motor speed. We propose to add motor current sensors to improve this situation.

c) If normal brake becomes completely electrical and there is no opportunity to use anti-skid control devices of mechanical brake, we have choice to do without them.

So it does not seem unrealistic to conceive three-phase drive railway vehicles without speed sensor for
traction control and our objective is to realize high performance of anti-slip re-adhesion control in case of multiple motor drive by installing motor current sensors in place of speed sensors.

IV. RUNNING TEST RESULTS FOR A BASIC ADHESION STUDY

Fig.3, fig.4 and fig.5 show running test results with an inverter-controlled electric multiple units composed of a motor coach and a trailer. An inverter with slip frequency control feeds four traction motors. We spayed water on the rail in front of the front bogie of the motor coach in the case of fig.3 and in front of the rear bogie in case of fig.4 and fig.5. In these cases slip is detected mainly by wheel axle acceleration. At point A in fig.3, the axle 4 slipped and the traction motor current 4 reduced due to steep torque slip characteristics of induction motors. The slip was detected at point B and the inverter current reference was reduced. At point C the axle 4 slipped again. At point D all-axle slip occurred and it continued in spite of slip detection and reduction of the inverter current reference value. During point C and D only the traction motor current 4 reduced. From these phenomena the current differences among traction motors can be used to detect wheel slip at its early stage.

In case of Fig.4 the axle 1 and axle 2 slipped due to spayed water. The slip speed was lower than two km/h and the inverter of the e.m.u. did not detect wheel slip. The traction motor current 1 and 2 reduced substantially and became much lower than the value when the wheel adhered.

In case of Fig.5 slip is detected by slip speed no less than 0.8 km/h. Traction motor currents 1 and 2 held higher values than the case of fig.4.

From these results we concluded as follows.
1) It is difficult to avoid all-axle slip only by slip detection of axle acceleration.
2) Adding to axle acceleration, slip velocity is an effective value to detect small slips. Slip speed is the remainder of the subtraction “(axle speed) – (reference speed)”. Normally the minimum value of axle velocities in a vehicle is used for the reference speed.
3) In case of multiple motor drive, motor current difference value can be used in place of slip velocity for slip detection.

Up to this time anti-slip re-adhesion control has been developed to cope with various wheel-rail conditions adding adhesion force prediction for high speed Shinkansen trains and commuter e.m.u.s[5],[6].

---

**Fig. 3. Running test of e.m.u. with multiple motor drive. All-axle slip occurs**
Fig. 4. Running test of e.m.u. with multiple motor drive
AXLE 3 AND AXLE 4 ADHERE AND SLIP DETECTION BY ACCELERATION IS INACTIVE

Fig. 5. Running test of e.m.u. with multiple motor drive
Slip is detected by slip speed (threshold value is 0.8km/h).
V. OUTLINE OF ANTI-SLIP RE-ADHESION CONTROL WITHOUT SPEED SENSOR

Considering our experience of anti-slip re-adhesion control with speed sensors, we think the control must detect small slip by slip speed, torque reduction must be done following adhesion phenomenon and adhesion force must be presumed for the torque recovery in time of re-adhesion [5], [6], [7]. So we propose a following anti-slip re-adhesion control without speed sensor (Table.2).

1) We focus on multiple motor drive that is widely used for e.m.u.s.
2) We detect currents of each traction motors. Normally inverter output current (i.e. summation of motor currents) is used for inverter control for multiple motor drive.
3) As for wheel axle acceleration alternative by which slip is detected, we use time differential of traction motor rotational speed (estimated rotor speed) that is derived from inverter frequency and slip frequency. If motor flux is constant, slip frequency is proportional to q-axle component of the motor current. So in vector control we can obtain slip frequency of each traction motor from relevant motor current. If we cannot use the estimated rotor speed of the inverter controller, we will be able to use directly the time differential of motor current.
4) As for slip velocity alternative, by which slip is detected, we propose to use the current difference of traction motors. The difference due to imbalance of wheel diameters or motor characteristics can be compensated in time of motor field excitation or adhesion run for example.
5) Adhesion force at the point of slip detection can be deduced from motor torque and motor rotational acceleration. They can be obtained from vector controller.

<table>
<thead>
<tr>
<th>Table.2 Comparison of anti-slip re-adhesion controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed method</td>
</tr>
<tr>
<td>Acceleration detection</td>
</tr>
<tr>
<td>Slip speed detection</td>
</tr>
<tr>
<td>Adhesion force presumption</td>
</tr>
</tbody>
</table>

VI. SIMULATION MODEL AND CONTROL

A. Motor Drive

Fig. 6 shows a block diagram of the multiple induction motor drive system.
The state equations of induction motor and drive system on the d-q co-ordinates used for simulation are as follows.

$$\frac{d\phi_1}{dt} = \frac{1}{j}v - \frac{1}{j}v$$  \hspace{1cm} (1)

$$\frac{d\phi_2}{dt} = -\frac{r_2}{L_2}\phi_2 - j\omega_2\phi_2 + \frac{r_2M}{L_2}i_1$$  \hspace{1cm} (2)

$$\frac{di_1}{dt} = -\frac{R}{\sigma L_1}i_1 + \frac{r_2M}{\sigma L_1L_2}\phi_2 - j\frac{M}{\sigma L_1L_2}\omega_2\phi_2 - j\omega_1i_1 + \frac{1}{\sigma L_2}v_1$$  \hspace{1cm} (3)

Where

- \(i_1\): Stator current vector;
- \(v_1\): Stator voltage vector;
- \(\omega_1\): Primary angular velocity;
- \(\omega_2\): Rotational angular velocity;
- \(\alpha_1\): Slip angular velocity;
- \(\tau\): Induction motor torque;
- \(P\): Number of pole pairs (2);
- \(r_1\): Stator resistance;
- \(r_2\): Rotor resistance;
- \(L_1\): Primary self inductance;
- \(L_2\): Secondary self inductance;
- \(M\): Mutual inductance;
- \(\omega\): the load torque corresponds to the adhesion; 
- \(n\): n means a number of induction motor;

The torque \(\tau\) is expressed as follows.

$$\tau = \frac{M}{L_2}\left(\phi_2d_i - \phi_2d_i\right)$$  \hspace{1cm} (4)

B. Motor Current

Fig. 7 shows the diagram of the relation between the voltage and current vectors in adhesion. The phases and amplitudes of primary-current vector \(i_{1_1}\) and \(i_{1_2}\) supplied to each induction motor are identical.

Fig. 8 shows the behaviour of stator current vector with constant current control when the second wheel slips. The amplitude of the stator current \(i_{1_1}\) of IM_1 holds same value. On the other hand, the stator current \(i_{1_2}\) of IM_2 in fig.6 becomes \(i_{1_2}'\) in fig.6, and the slip angular velocity \(\alpha_2\) of IM_2 and torque current \(i_{q_2}\) decrease due to slip, so the torque of IM_2 \(\tau_2\) decreases too. From the figure it is shown that the current difference expressed as vector \(\Delta i_1\) can be used for slip detection.

![FIG.7 VECTOR DIAGRAM UNDER ADHESION](image-url)
Fig. 8 Vector diagrams when a slip occurs. (With constant current control)

C. Slip Detection without Speed Sensor

Since the torque current of each induction motor behaves as mentioned above, a threshold is set in the torque current differences between two motors to detect slips. Fig. 9 shows the diagram of slip detection. Regarding the use of wheel acceleration, we use the motor speeds derived from the vector controller and the same detection method as is commonly used in the conventional anti-slip re-adhesion control with speed sensor.

![Diagram of slip detection](image)

Fig. 9 Method to detect slips without speed sensor.

D. Adhesion Presumption

The load torque $\tau_{l,2}$ equivalent to adhesion torque is expressed by the following equation from the state equation (1) of the drive system.

$$\tau_{l,2} = \tau_{l,2} - J \frac{d \omega_{m,2}}{dt}$$

where $J$: Moment of inertia of a drive system.

If we can use information of vector controller of the inverter, we can calculate the load torque. If we do without information of the vector controller, motor torque can be estimated by amplitude of motor current under assumption of constant flux and acceleration by time differential of motor current. It is possible to recover the torque current on the basis of the presumed value after re-adhesion.
VII. SIMULATION

We perform simulation to verify the effectiveness of the proposed anti-slip re-adhesion control method with a two-motor (IM_1 and IM_2) drive system fed by one inverter. For the proposed control without speed sensor, slips are detected by the torque current difference of 30 [A] between the two motors. In the simulation adhesion i.e. load torque $\tau_2$ was suddenly decreased when the time was 0.1 [sec]. The amount of adhesion drop is 15%.

Fig. 10 shows the simulation results when a slip is detected without speed sensor and with adhesion presumption. By the proposed method of slip detection based on the current difference, slip was detected very quickly. The presumed adhesion force is almost the same as the decreased adhesion, good presumption of adhesion force is performed. The Fig.10 prove the effectiveness of the anti-slip re-adhesion control without speed sensor.

Fig.10 Readhesion control with assumed adhesion force.
(15% decrease in adhesion force, without speed sensor)
VIII. CONCLUSION

This paper proposed a novel anti-slip re-adhesion control method without speed sensor for electric railway vehicle with multiple induction motor drive, as summarized below.

1) It is possible to detect slips by finding the torque current difference of each induction motor.
2) The proposed method makes it easier to detect small slips than conventional method with speed sensors.
3) It is possible to presume adhesion force based on the behavior of motor current when a slip occurs.
4) For all axle slip we can use the differential of motor speeds derived from vector controller.
5) Simulation results show the effectiveness of the proposed anti-slip re-adhesion control without speed sensor.

ACKNOWLEDGMENT

This study is supported by the Program for Promoting Fundamental Transport Technology Research. The authors wish to thank the Corporation for Advanced Transport & Technology (CATT).

REFERENCE