Full Regenerative Braking in a Train at High Speed and Enhancement of Voltage, Powered by DC-electrification with Regenerative Substations

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Abstract

Mechanical brakes are often used by an electric train. It has a few problems like response speed, coefficient of friction, maintenance cost and so on. Therefore, methods using regenerative brakes actively are required. In this paper, the authors propose pure electric brakes which mean ordinary brakes by only the regenerative brakes without any mechanical brakes at high speed. DC-electrification system with regenerative substations can regenerate energy to commercial power system. And a train can use the full regenerative braking force. The authors furthermore evaluate the effects running time and energy with regenerative substations in proposal method.

Keywords: Regenerative brakes, High Speed, Regenerative Substation, Energy

1 INTRODUCTION

A recent electric train uses electric brakes which converts mechanical to electric energies and sends the regenerated energies to other trains on the same route. It is called regenerative brakes. Conventional mechanical brakes using frictional force have to be used with the regenerated brake at high speed. Since regenerative braking force is less than simultaneous service braking force at high speed.
The response of mechanical brakes is much slower than electric brakes. The source of mechanical braking force is the friction which strongly depends on environment. It worsens ride quality for a change of frictional force. Furthermore, mechanical brakes cost a lot of time and money for maintenance. In this paper, the authors propose pure electric brakes [1][2][3] which mean ordinary brakes by only the regenerative brakes without any mechanical brakes at high speed. The advantage of the proposed braking concept is evaluated under the assumption of regenerative substations in a modern DC-electrification system. In addition, the authors evaluate the effect of increasing sending voltage at substation.

2 CHARACTERISTICS OF REGENERATIVE BRAKE

Speed characteristics of a train driven by an induction motor are shown in Figure 1. These characteristics are grouped into three modes. One is constant torque mode at low speed. Another is constant power mode that torque is in inverse proportion to train speed. The other is characteristic mode

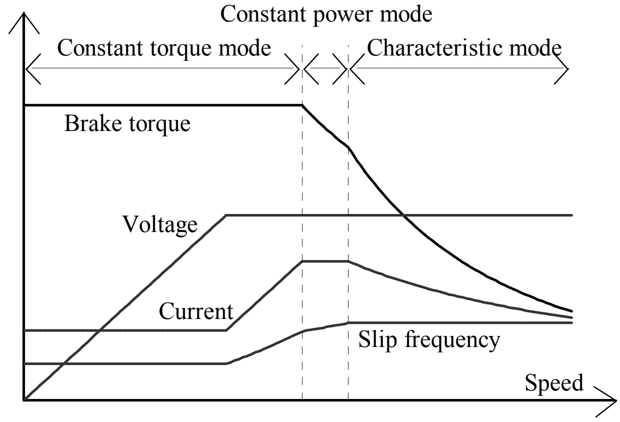

Figure 1. Speed characteristics of an electric train driven by induction motor

that torque is inversely proportional to the square of train speed. Regenerative braking force decreases at high speed as shown in the figure. In general, braking force is set to values of the force which reaches a constant acceleration at different speeds. Therefore, mechanical brakes compensate for shortfall of braking force at high speed range. Feeding voltage increases unless there are loads like powering trains expending regenerative energy. So railway operators have to break circuits to protect electric equipments and squeeze regenerative current to control voltage. Regeneration canceled does not occur so much at railway routes where train density is very high such as inner-city area. But regenerative braking force does not reach designed value of performance, as regenerative current is squeezed at railway routes where train density is not high. If regenerative substations are set up, regeneration canceled and squeezing regenerative current is expected to be prevented. Then regenerative brakes would show better performance. The advantages are being able to reduce wear of brake shoe and time and money for maintenance. The authors propose operation method which occurs full regenerative braking force in the range of torque characteristic of electric motor and generator assuming such advanced electrification equipment with regenerative functionality. The authors estimate the effects on run curve and energy balance.

3 NUMERICAL METHOD AND ASSUMPTION IN CASE STUDIES

3.1 Condition of Case Studies

Condition setting for quantitative validation of using the full regenerative brakes at high speed is shown in Table 1.

Table 1. Conditions of the investigated line

The length of railway route	37.4 km
The number of stations	15 stations
Sending voltage in substations	1500V or 1600V
Number of a train	1 train set
Feeding	DC-electrification

In addition, regenerative substations can regenerate energy to commercial power system. Three cases in calculation are examined. One is conventional method which use both regenerative brakes and mechanical brakes to set to values of the force which reaches a constant acceleration. Another is proposal method which use only regenerative brakes as braking force. The other is also proposal method and a train is driven by off brake operation without coasting operation to shorten running time.

3.2 Numerical Method for Train Motion and Simplified Circuit Calculation

Input values of this calculation are running speed and notch. Acceleration, speed and running distance as outputs are derived from total weight of a train, running resistance and so on. Discretization with bilinear transform based on linear approximation (Tustin transform) is used for derivation of recurrence equation. Time step of calculation is 0.1 sec. The values of resistances including running resistance and gradient resistance are functions of train speed and position. A function of voltage fluctuation at pantograph is shown in Equation 1.

$$V = E/2 \pm 1/2\sqrt{E^2 - (4PRd_1d_2)/(d_1 + d_2)} \qquad (1)$$

The parameters of Equation 1 are shown in Figure 2. V is voltage at pantograph. E is sending voltage in substations. I_1

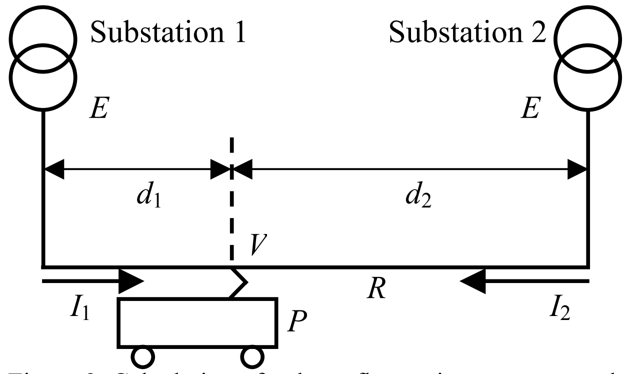

Figure 2. Calculation of voltage fluctuation at pantograph

and I_2 are powering and regenerative current. P is powering and regenerative energy. R is feeding resistance. d_1 and d_2 are distance between a train and substations. Powering and regenerative energy is derived from mechanical energy of a train to consider conversion efficiency.

4 EFFECTS OF USING THE FULL REGENERATIVE BRAKES AT HIGH SPEED

4.1 Effects on Run Curve

Run curve is changed significantly when mechanical brakes is not used like proposal method. An example of run curve at a station interval is shown in Figure 3. When conventional method is changed to proposal method, braking force is not enough at high speed range. Accordingly, braking distance increases by 150 m. The maximum increment of braking distance is about 400 m. This leads to problem of increasing running time.

Total running time is shown in Figure 4. When proposal method is compared to conventional method, total running time increase by 21.6 sec. Even if a train is driven by off brake operation to shorten running time, the time increases by 13.5 sec. However increase from regular running time is mere 4.1 sec. Increment of time per a station interval is 0.3 sec. 0.3 sec is not a value not being able to ignore. But train scheduling has a margin time. Therefore, increment of time is able to be included in a margin time.

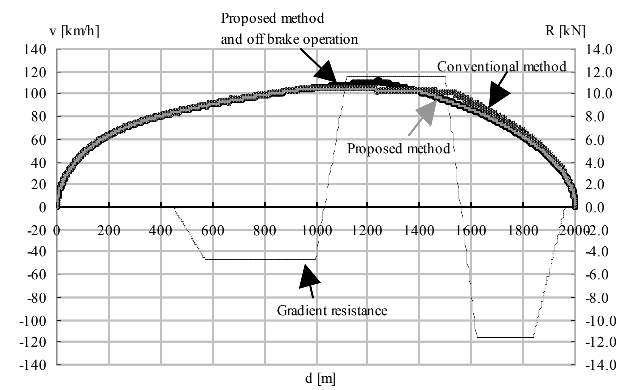

Figure 3. Comparison of run curve at a station interval

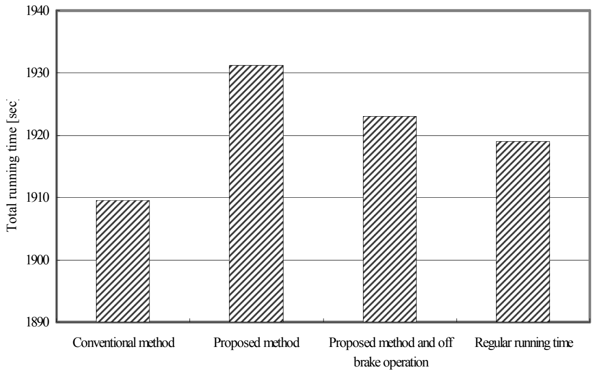

Figure 4. Comparison of total running time

4.2 Effects on Energy Balance

Regenerated energy is shown in Figure 5. Total energy consumption is shown in Figure 6. When conventional method is changed to proposal method, regenerated energy increases by 44.46 kWh. It is increase of 17 percent by ratio. In case of proposal method with off brake operation, the energy increases by 93.02 kWh. It is increase of 35 percent by ratio. This reduces total energy consumption by 25.20 kWh and 37.62 kWh. It is reduction of 8 percent and 11 percent compared to conventional method. This is because all energy expended by mechanical brakes is recovered as regenerative energy. Therefore, regenerative factor increases as shown in Figure 7. Regenerative factor is shown in Equation 2. Increase of regenerative factor is 5.9 point by proposal method and 10.5 point by proposal method with off brake operation. It is found that regenerative brake is used more effectively. Proposal method has a good performance of energy conservation.

$$\text{Regenerative Factor} = \frac{\text{Regenerated energy}}{\text{Total powering energy}} \qquad (2)$$

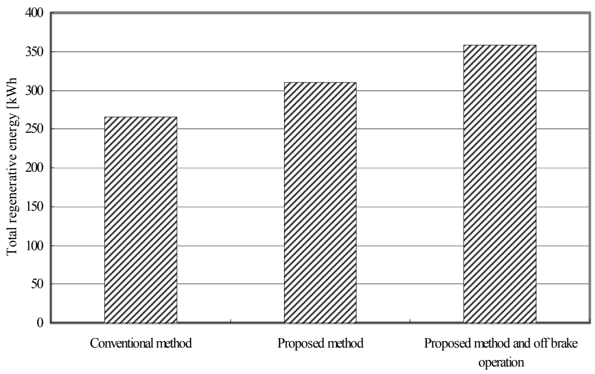

Figure 5. Comparison of regenerated energy

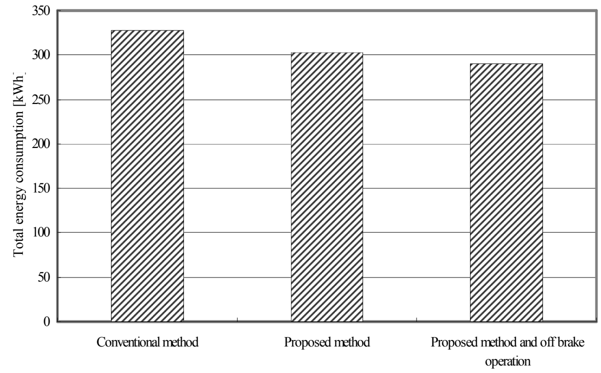

Figure 6. Comparison of total energy consumption

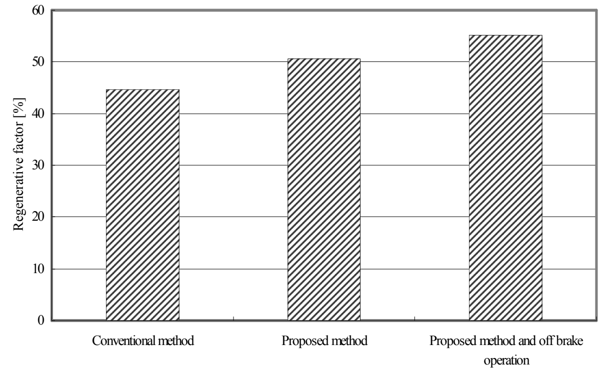

Figure 7. Comparison of regenerative factor

5 EFFECTS OF ENHANCEMENT OF SUBSTATIONS OUTPUT VOLTAGE

5.1 Effects on Run Curve

Regenerative braking force increases at medium and high speed ranges when sending voltage increases at substations. This can make up for deficiency in braking force at middle and high speed ranges by proposal method. An example of run curve at a station interval is shown in Figure 8. Compared to proposal method in 1500 V, acceleration and deceleration increase by proposal method in 1600 V. This induces reduction of braking distance. It decreases by 30 m

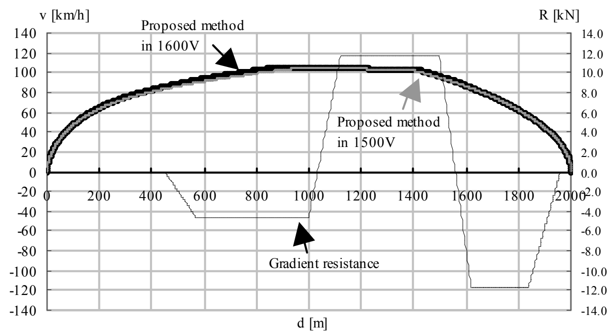

Figure 8. Comparison of run curve at a station interval in different output voltages at substations

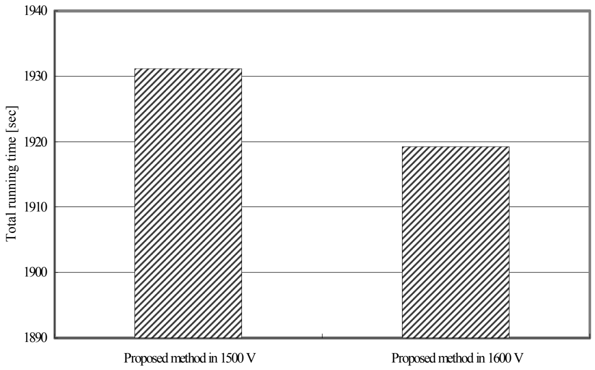

Figure 9. Comparison of total running time in different output voltages at substations

when sending voltage increases. Accordingly, this leads to reduction of total running time.

Total running time is shown in Figure 9. When sending voltage increases by 1600 V, total running time is reduced by 12.0 sec. Even if it is compared to regular running time, increment of total running time is only 0.2 sec. Therefore, a train can run in nearly regular running time by proposal method in 1600 V. Increasing sending voltage have a profound effect on running time.

5.2 Effects on Energy Balance

Regenerated energy is shown in Figure 10. Total energy consumption is shown in Figure 11. When sending voltage increases by 1600 V, regenerated energy is reduced by 1.24 kWh. It is increase of 0.4 percent by ratio. This reduces total energy consumption by 2.27 kWh. It is reduction of 0.7 percent compared to a case in 1500 V. This is because powering time and braking time is shortened by increments of tractive force and braking force at middle and high speed ranges. That cannot be very effective in energy conservation.

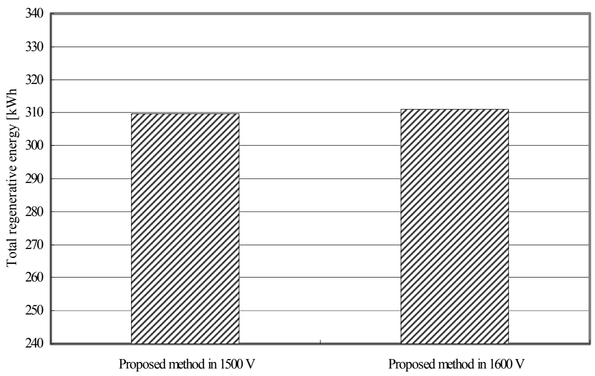

Figure 10. Comparison of regenerated energy in different output voltages at substations

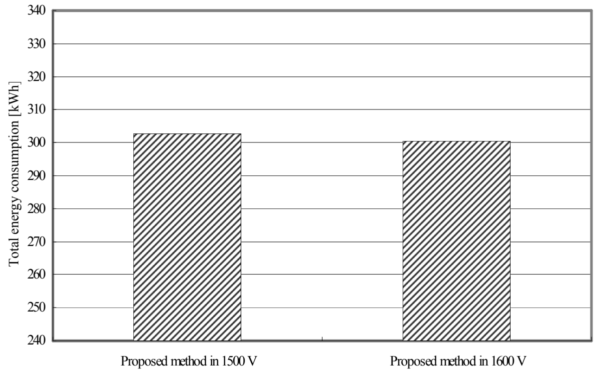

Figure 11. Comparison of total energy consumption in different output voltages at substations

6 PRACTICAL APPLICATION OF PURE ELECTRIC BRAKES – COMBINATION WITH ADVANCED TRAIN OPERATION SYSTEMS

Pure electric brakes have a characteristic that deceleration decreases at middle and high speed ranges. For this reason, implementation of pure electric brakes is difficult on several counts like operability by manual operation. If a driver is called on to manipulate notch in line with regenerative braking torque, he needs to be given some supporting information to [4]. However, if a train equips ATO and TASC which are proceeding adoption recently, pure electric brakes is realizable.

7 CONCLUSIONS

This paper describes an idea of pure electric brakes for an electric train at high speed. The authors have proposed a method of using the full regenerative braking force powered by DC-electrification with regenerative substations. And the authors verify the performance of proposed method. Total energy consumption has been reduced drastically by proposal method. As future works, we are going to advance the calculation model based on train scheduling.

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