Train Group Control for Energy-Saving DC-Electric Railway Operation

Shoichiro WATANABE and Takafumi KOSEKI
Electrical Engineering and Information Systems
The University of Tokyo
Bunkyo-ku, Tokyo, Japan
shoichiro@koseki.t.u-tokyo.ac.jp

Abstract— Effective use of regenerative brake is important to manage energy-saving. This paper presents a running method for energy-saving on DC-electric railways considering restriction of keeping running time. First, two methods are compared for an energy-saving operation. One is applying a low notch-off speed with a strong brake. The other one is applying a fully regenerative brake with an ordinary notch-off speed. Second, we propose a manual train operation assistance method based on a power-limiting brake for an energy-saving train operation. Drivers are assisted to realize the power-limiting brake notch by an on-board system consisting of computers and interface devices. In order to consider the power limitation and resolve assistance operation problems focusing on braking delay time, this method has been checked by experiments on a revenue service line. Third, we propose electric circuit models of railway systems to analyze power flow. Keywords— Regenerative brake, On-track test and Energy-Saving

I. INTRODUCTION

Recently we are facing many environment problems and researchers are expected to solve these problems. Railway engineers have studied methods to reduce CO2 emission as follows. The project of ERRAC (European Rail Research Advisory Council) proposed general frame work for reducing CO2 emission [1]. Regenerative braking is a key technology to reduce energy consumption. Furthermore, storage devices are installed [2] and super capacitors are installed in substations to use regenerated energy effectively [3]. However, these methods have drawbacks, such as cost, place and expensive additional electric devices.

We focus on a train operation and propose an energy-saving manual operation method by using an on-board drive assistance system. The system is developed for drivers to assist energy-saving notch operation considering effective use of regenerative brake. Results of on-track tests on revenue service line will be reported to show whether and how this assistance method can increase regenerated energy.

The consideration of energy-saving, peak-off power and rescheduling in train operation still remains an open research issue. This paper shows a trial to visualize power for a train-group control and electric circuit models of railway systems to analyze their electric power flow.

II. ANALYSIS OF ENERGY-SAVING OPERATION FOR A TRAIN

The following two methods, which keep identical traveling time, are compared.

1) Method I (marked as I in Fig. 1): This mode uses hybrid brake control consisting of electric and mechanical brakes, as marked as I in Fig. 1. It can reduce a notch-off speed and keep running time because strong brake is made by the hybrid brake. In this braking control, air supplement control is used and regenerative brake is used priority.

2) Method II (marked as II in Fig. 1): This mode uses only regenerative brake, below the blue curve in Fig. 2. This operation increase regenerated energy but it requests higher notch-off speed because the brake of the method II is weaker than the brake of method I in high speed operation.

Fig. 1. Train run curves in the analysis for different energy-saving operation.
III. **NUMERICAL RESULTS AND ANALYSIS OF ENERGY-SAVING OPERATION**

The main idea of this simulation is to clear the priority of using regenerated brake. Fig. 3 shows numerical results of relationship between running time and energy consumption of a train. The method I corresponds to cooperation brake and mechanical brake and the method II corresponds to regenerative brake.

The energy consumption increases when a train runs faster because coasting distance and time have to be reduced.

The method II is better than the method I in so many cases.

IV. **POWER-LIMITING BRAKE FOR EFFECTIVE USAGE OF REGENERATIVE POWER**

The operation method II is useful for effective usage of regenerated energy. In addition, the power-limiting reduces the possibility of regeneration squeezing. Fig. 4 shows the relationship between regenerated power and initial braking speed. Here the regenerative braking power is limited to 70% of the maximal capability. This paper proposes a “best effort method” for energy-saving train operation, which does not use information on other train conditions since train drivers cannot obtain information on actual status of other trains in present railway systems. This idea cannot completely avoid regeneration cancellation, however, it works effectively for energy-saving operation in many practical cases.

The “regeneration ratio” defined in Eq. (1) is calculated and it will be used for comparing different cases in the following part of this paper.

![Fig. 3. Relation between running time and energy consumption at full number of passengers.](image)

![Fig. 4. Relationships between regeneration power and initial braking speed.](image)

\[
\text{Regeneration ratio} = \frac{\text{Regenerative energy of motor cars}}{\text{Brake energy of a train set}} \times 100 \%
\]  

(1)

V. **DRIVE ASSIST SYSTEMS FOR EFFECTIVE USING OF POWER-LIMITING BRAKE**

A. **Proposal of This Assistance Systems**

On-track tests have been executed to verify the effectiveness of energy-saving operation on the revenue service line. It is difficult for human drivers to take the braking action according to the regenerative performance curve in Fig. 2. Our project team member [4] have therefore developed on-board operation assistance system and the assistance system has been applied to the on-track tests to realize the best use of regenerative brakes.

B. **Configuration of the On-Board System**

The assistance system consists of on-board computers, GPS and interface devices shown in Fig. 5. For appropriate and timely assistance, the following data are measured; train speed, position, running time and pantograph voltage.

C. **Driver Assistance Methodology**

The first purpose of the system is to determine the power-limiting brake running curve which fulfills safety, scheduled running time and planned stopping position by using the measured information. The “braking dictionaries”, one of which is shown in Fig. 6, were prepared before the on-track tests, for real-time
assistances. It has two-dimensional indices of speed and time, depending on various prospective braking patterns.

The second purpose is to assist drivers. Human braking actions are assisted by interface devices consisting of monitor and speaker. The interface timely informs necessary notch numbers to a driver. In these experiments, the following significant knowledge has been obtained. Female voices and fan shape visualization are effective since driver room is noisy. And notch assistance shall be limited to three steps since drivers usually operate in three notch steps.

D. The Idea for Reducing Operation Delay Time

Proceeding research [4] showed that operational delay, which consists of human driver’s delay in response to the assist command and mechanical delay between driver’s action and consequent activation of braking force, caused unintentional shortage of braking distance. Consequently, the drivers could not use the assistance effectively. To resolve this problem, assistance based on prognosis of train motion has been introduced as shown in Fig. 7. Firstly, the on-board system measures actual speed and position. Secondly, the on-board computers explore the predictive index tags in a couple of seconds. Finally, the system compares actual speed and scheduled speed and indicates assistance commands.

VI. RESULTS OF ON-TRACK TESTS IN A SIMPLE RUNNING PROFILE

A simple running profile means that train performance pattern is designed with simple brake pattern since there is not speed limitation in braking section.

A. Verification of Advantages of the Proposed Operation

Fig. 8 shows unassisted running curve, assisted running curve, and assist-command curve. Fig. 8 shows that the assistance method considering the delay time has the advantage of low speed deceleration in comparison with conventional operations.

B. Advantages of the Proposed Operation in Regenerated Energy

Figs. 9 show unassisted and assisted running results of pantograph voltage and braking powers in the simple running profile. The pantograph voltages in Figs. 9 indicate that power-limiting brake has a good influence since the voltage of assisted running is lower than unassisted one. It is useful for reducing the possibility of regeneration squeezing.

Figs. 9 also reveal that this method makes a good use of regenerative brake in comparison with the rate of motor car power in train-set power. The motor power at 1200m in Fig. 9 (a) shows that regenerated power is limited to much loss amount of than the braking command. According to Figs. 9 and Table I, the proposed assistance method can increase ratio of regeneration by keeping the regular running time.

Fig. 5. The situation of operation assistance

Fig. 6. 2D-table for searching the power limiting tag.

Fig. 7. The method of reduction for delay time.

Fig. 8. Assistance pattern running curves under the simple running profile.
Unassisted running results

VII. RESULTS OF ON-TRACK TESTS IN DIFFICULT BRAKING RUNNING PROFILES

The difficult profile means that train performance pattern is designed without simple brake pattern since there is speed limitation based on shape curve or some rail environments. For this reason, drivers operate brake notch two times.

A. ADDITIONAL ASSISTANCE PATTERN FOR A DIFFICULT RUNNING PROFILE

Fig. 10 shows assisted running curve and notch operation under the difficult running profile. This assisted braking section contains a speed limitation. For this reason, on-board systems assists coasting and brake notch two times. In addition, 2 STEP notch is considered by means of questionnaire data obtained from drivers.

Fig. 11 shows manual notch operation by a driver. Fig.11 also indicates that the driver did not use 5 notches since this train has plenty of time for running. According to Table II, this assistance method can keep regular running time.

In this sense, this assistant method was successful.

B. DRAWBACKS OF THE PROPOSED OPERATION IN REGENERATED ENERGY OPERATION ON PANTOGRAPH VOLTAGE AND BRAKE POWER

Figs. 13 show unassisted and assisted running results of pantograph voltages and brake powers in the difficult running profile. The pantograph voltages in Figs. 13 indicate that power-limiting brake did not have a good influence.

Figs. 13 also reveal that this method made a worse use of regenerative brake in comparison with the rate of motor car power in train-set power. According to Figs. 13 and Table II, the assistance method can keep regular running time but it cannot increase percentage of regeneration.

C. REASONS FOR A REGENERATION CANCELLATION

The experimental results are understood in the following ways.

1) COASTING SECTION (iii) IN FIG. 13

There is an apparent difference of the pantograph voltages between Fig. 13 (a) and (b). Whereas the voltage in Fig. 13 (a) is standard voltage of 1500V. The voltage of Fig. 13 (b) is higher than the standard voltage. It may mean that other trains were regenerating in the same electric section in the case of Fig. 13 (b).

2) BRAKING SECTION (iv) IN FIG. 13

There is a significant difference of pantograph voltages in Fig. 13 (a) and (b). A comparison of Figs. 13 (a) and (b) shows that power-limiting brake is effective since the maximal power of the train set has been reduced of 10.3%. The power of the motor car in Fig. 13 (a) is about -3000kW and keeps this power in (iv) section. However, the power of the motor car in Fig. 13 (b) is reduced from -2000kW to -1000kW and the train-set power decreases at the same time in section (iv) since pantograph voltage of Fig. 13 (b) is higher than that of Fig. 13 (a).
VIII. SUMMARY OF THE ON-TRACK TESTS

Based on our experiences, we would like to emphasize that the “best effort method” for energy-saving train operation is successful, but we must consider a train-group control for more effective energy-saving. For this reason, power flow among multiple trains is discussed in the following parts.

Fig. 10. The assistance running curve and notch operation.

Fig. 11. Notch operation by driver.

Fig. 12. Unassisted, assisted running curves and assist command curve under the difficult running profile.

Fig. 13. Regenerative and train-set power and voltage on pantograph at different operation modes.
TABLE II
RUNNING DATA ON THE DIFFICULT RUNNING PROFILE

<table>
<thead>
<tr>
<th>Assistance pattern</th>
<th>Without assistance</th>
<th>With assist (1 step)</th>
<th>With assist (2 step)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running time</td>
<td>114 sec</td>
<td>118 sec</td>
<td>115.6 sec</td>
</tr>
<tr>
<td>Acceleration energy</td>
<td>18.02 kWh</td>
<td>17.01 kWh</td>
<td>18.45 kWh</td>
</tr>
<tr>
<td>Braking energy</td>
<td>-14.64 kWh</td>
<td>-13.84 kWh</td>
<td>15.03 kWh</td>
</tr>
<tr>
<td>Regenerative energy</td>
<td>-10.50 kWh</td>
<td>-9.31 kWh</td>
<td>-9.10 kWh</td>
</tr>
<tr>
<td>Percentage of regeneration</td>
<td>71.70 %</td>
<td>67.28 %</td>
<td>60.57 %</td>
</tr>
</tbody>
</table>

Regular running time is 124 sec.

IX. TRAIN-GROUP CONTROL AND POWER VISUALIZATION

A. Motivations of Considering Train Group Control

The previous section has described that the “best effort method” for energy-saving train operation is basically successful. However, other train conditions have an influence on the regeneration. It is, therefore, necessary to consider train-group control to reduce total energy consumption in railway systems.

In addition, power flow in electric railway circuit should be considered since each train consumes regenerative power and sends regenerated power to other trains.

B. Approaches and Conditions

Acquisition of the information on system peak power is significant in both cases of scheduled and rescheduled train operation. We propose to visualize power on a running curve as shown in Fig. 14 in order to analyze the power on train diagrams. Red curve means power consumption, and blue curve means power regeneration. This power is calculated using Eq. (1). Where $W_p$ is power of train set, $F_m$ is tractive force, $v$ is speed and $\eta$ is efficiency. This running curve was calculated under the constant voltage condition of DC 1500V.

$$W_p = F_m v \eta$$

Fig. 14. The running curve with power visualization

Fig. 15. Train diagrams consisting 5 stations

Fig. 16. The diagram with power visualization
Fig. 17. The peak power on rescheduled train diagram

Figs. 15 show scheduled and rescheduled diagrams [5]. This rescheduled diagram was optimized based on all passengers’ travel time by using mixed integer programming. The power is computed for the condition of 1km distance between stations as shown in Figs. 16 to visualize the power on the train-diagrams. Figs. 17 shows time-dependent summation of the train powers in each diagrams of Figs. 16.

C. Analysis of Peak Power

A comparison of Figs. 17 (a) and (b) shows that peak power is larger by 50% in rescheduled diagram since multiple trains are powered simultaneously in Fig. 16 (b). Regenerating of multiple trains are also over rapped in Fig. 16 (b).

Area A in Fig. 17 (b) shows that the power fluctuates more in rescheduled diagram since number of trains per time is higher in rescheduled diagram than in scheduled diagram in the area A in Fig. 16 (b).

The area B in Figs. 17 (a) and (b) shows possibility of improving energy-saving furthermore. The power in this area B has to be absorbed by mechanical brakes as heat loss if there are no active regenerating substations. For this reason, it is possible to use this regenerative power if train group control is considered.

X. ELECTRIC CIRCUIT MODELS FOR POWER AND ENERGY-SAVING IN TRAIN GROUP CONTROL

A. Problems of the Discussion in the Previous Section

The discussions above have suggested the importance of the power flow analysis. However, this was no explicit calculation of power-feeding electric circuits.

B. Modeling of Trains and Electrification Systems

To resolve the problem, the electric circuit models in Fig. 18 and Fig. 19 shall be studied. Fig. 18 shows the model of electric circuit in DC-electric railway systems. A wayside substation consists of constant voltage source, internal resistance and diode. The diode limits the direction of power flow just from the substation to a train.

Trains are modeled as a nonlinear current source, on which the pantograph voltage affects, where the relationships among tractive force, motor voltage, and current is given in Fig. 19.

XI. CONCLUSIONS AND FUTURE WORK

In this paper, a method for energy-saving on DC-electric railways considering restriction of keeping running time has been proposed. The following problems have been solved in this research.

The method of using regenerative brake fully is better. On-track tests give support to the good influence to use power-limiting brake with the assisted operation considering braking delay time. However, we conclude that train group control should be furthermore studied if we want more effective use of regeneration.

Peak power and fluctuation of power are bigger in rescheduled diagram in irregular cases of train group. In addition, mechanical braking heat loss is analyzed in scheduled and rescheduled diagram. It is possible to use this heat loss power if train group control is considered.

It remains a challenge for future research to complete a calculation model for analyzing the power flow, which explicitly includes electric circuit model. The running curves of train group should be designed by using the model and also need to be discussed in more detail. Such theoretical studies shall be a base of energy-saving ATO (Automatic Train Operation) in future.
Fig. 19  Relationships between tractive force, motor voltage and current.

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REFERENCES

List only one reference per reference number according to the following samples: