Energy Management for Regenerative Brakes on a DC Feeding System

Yuruki Okada*[1], Takafumi Koseki*[2], Satoru Sone*[3]

*[1] *The University of Tokyo, okada@koseki.t.u-tokyo.ac.jp*
*[2] *The University of Tokyo, koseki@koseki.t.u-tokyo.ac.jp*
*[3] *Kogakuin University, sone@cc.kogakuin.ac.jp*

ABSTRACT

Recently, regenerative brakes are implemented in trains at DC fed electric railways in Japan. Regenerative braking system converts kinetic energy to electrical energy. And other powering trains at the identical feeding circuit must consume the electrical energy.

Therefore, when the electrical loads are not sufficient at feeding circuit, braking trains must squeeze regenerative power. The problem is that such braking trains often squeeze regenerative power excessively, that results in low energy efficiency of the regenerative system in average[1][2].

Authors have tried to calculate the maximal regenerative action in an ideal case, in which the full usage of the regenerative brake in guaranteed by an ideal data communication system named PDIS (Power Distribution Instruction System). And, authors furthermore realistic squeezing controls of regenerative brakes in future based on the results in the ideal case.

1. INTRODUCTION

On braking, regenerative trains convert kinetic energy to electrical energy. And regenerative loads at feeding circuit consume the electrical energy.

Therefore, when electrical loads are not sufficient at the ideal feeding circuit, braking trains must reduce regenerative power following the characteristic shown in Fig.1 to avoid excessive feeder line voltage. This control is called squeezing control.

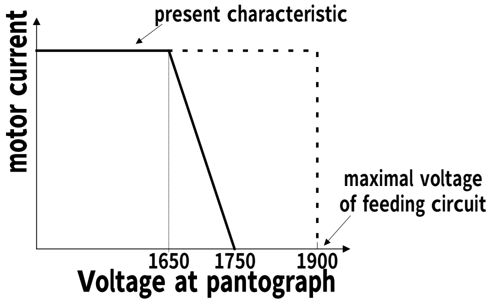


Fig1 Characteristic of Squeezing Control

However, present regenerative trains often squeeze regenerative power excessively. The reasons for the excessive squeezing are as follows;

1. VVVF-controlled inverters squeeze regenerative power excessively in low-speed range because it squeezes AC motor current directly instead of its DC current.
2. Traction controller squeezes motor current at lower voltage than maximal voltage limit of feeding circuit as shown by the solid line in Fig.1.
3. Actual traction controller often squeezes motor current at lower voltage the conservative voltage limit shown by the solid line in Fig.1.

2. IMPROVEMENT OF SQUEEZING CONTROL

We can propose the following two solutions to the problem.

1. Traction controller should squeeze its DC current instead of motor current.
2. We will replace the static upper voltage limit indicated by solid line in Fig.1 with ideal characteristic indicated by dash line in the identical figure.

The solution 2 will need a substantially new control technology whereas the solution 1 may be relatively easy in present technology. The reason for the excessive reduction of the motor current is that the braking controller cannot recognize states of electrical loads in the feeding circuit from the measurement of the voltage at the pantograph and its motor current. The real-time data communication of the states of the feeding circuit will inherently improve the squeezing control. We have tried the simulation of five cases in table 1 according to this idea.

Table 1 Examination of squeezing control

	Characteristic of squeezing control	With PDIS	Without PDIS
Squeezing control with motor current	Solid line in Fig.1	CASE 0	CASE 2
Squeezing control with DC current of traction controller	Solid line in Fig.1	CASE 1	CASE 3
	Dashed line in Fig.1	×	CASE 4

3.COMMUNICATION IN FEEDING CIRCUIT

Traction controller needs data on actual states of the feeding circuit for a precise and efficient squeezing control. We propose a methodology of data communication in the feeding circuit.

First, an ideal power management system called PDIS (Power Distribution Instruction System) is installed in a feeding circuit. The PDIS measures the position and the power consumption/generation of all trains in the feeding circuit. And it instructs regenerative power to each regenerative train in the feeding circuit, so that the output of substations may be minimum, and the voltage at the pantograph may not excess specified maximal voltage limit.

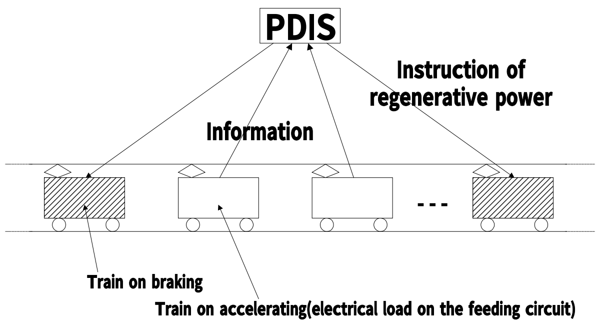


Fig.2 The Concept of PDIS

4.SIMULATED CASES

In this paper, we evaluate methods of squeezing control indicated by from CASE 0 to CASE 4 in Fig.1, and we compare them. We concretely evaluate the contents indicated in Table 2.

Table 2 Contents of examination

Comparison	Effect
CASE 0 and CASE 1 CASE 2 and CASE 3	Effect when squeezing control with motor current turns to that with DC current of traction controller
CASE 0 and CASE 2 CASE 1 and CASE 3	Effect of communication
CASE 3 and CASE 4	Effect of communication and modification of squeezing control from solid line to dashed one in Fig.1

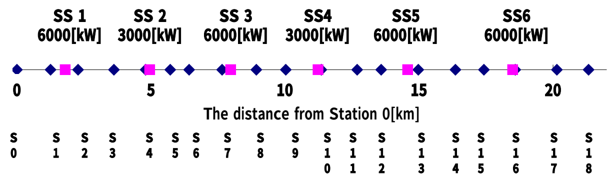
5.EVALUATION AT AN ACTUAL RAILWAY

We have evaluated methods of the squeezing controls illustrated in Fig.1, and have compared them. The purposes of the comparison is explained in table 2

5.1 The model for calculation

The following model is assumed for the calculation.

1. We apply the squeezing controls from CASE 0 through CASE 4 in table 1 to an urban subway, whose stations and substations are illustrated in Fig.3.
2. Trains run at ten-minute intervals.
3. The substations don't have regenerative inverter.
4. All trains have an identical running profile. Train stopping duration at a station is assumed fixed. Therefore, one can determine power consumption of the trains in advance, and the PDIS controls only the electrical/mechanical power of the braking trains. The information in the running profile consists of position, speed, and acceleration of the trains. When the regenerative braking force of a train is insufficient, the ideal air brake immediately compensates the lack of the braking force.
5. The PDIS calculates the state of the feeding circuit and decides regenerative power of all regenerative trains in the feeding circuit to minimize the actual input power from the substations.



SS : Substaion
S : Station

Fig.3 Positions of Stations and Substations

5.2 Numerical experiments

We analyze the following items in the calculation for ten minutes;

1. the relation of the voltage at a pantograph and the DC current of a traction controller,
2. the amount of regenerated energy of trains
3. the input energy from substations, and
4. the ohmic loss of feeding resistance

6.THE RELATION OF THE VOLTAGE OF A PANTOGRAPHS AND THE DC CURRENT OF A TRACTION CONTROLLER

Figure 4 shows the relation of the voltage at the pantograph and the DC currents of traction controllers of all regenerative trains with the squeezing controls CASEs 0 and 4. The data are plotted every 0.25 seconds.

The relation in case of CASE 4 shows that trains can regenerate power when electrical loads exist in the feeding circuit even if the voltages at the pantographs are high. The comparison between CASEs 0 and 4 obviously shows the significant contribution of the data communication to the improvement of regenerative action.

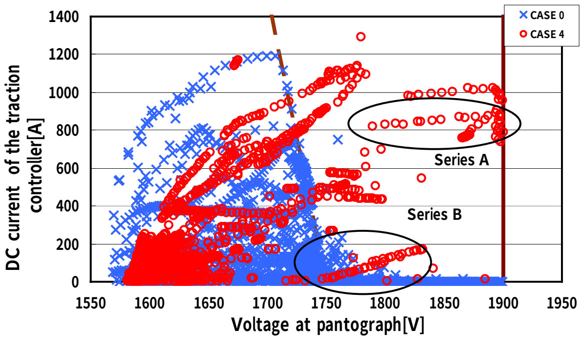


Fig.4 The Relation of the Voltage at Pantographs and the DC Current of Traction Controller

Figure 4 shows that trains can regenerate power even if the voltages of pantographs are high in CASE 4. We have analyzed the data in details in Series A and B to investigate the reason why trains can regenerate power even if the voltages at the pantographs are high.

Firstly, Fig.5 (a) shows the power transiiton of all trains in Series A in Fig.4. Series A is the power transition of Train 1 in Fig.5 (a). Trains 2 and 4 are the electrical loads for Train 1. The power consumption of the electrical loads is large enough, but the distance between Trains 1 and 4 is long, which results in the high pantograph voltage of train 1 because of the feeding resistance. Fig.5 (a) shows that the regenerative powers in CASEs 0 and 1 are less than that in CASE 4.

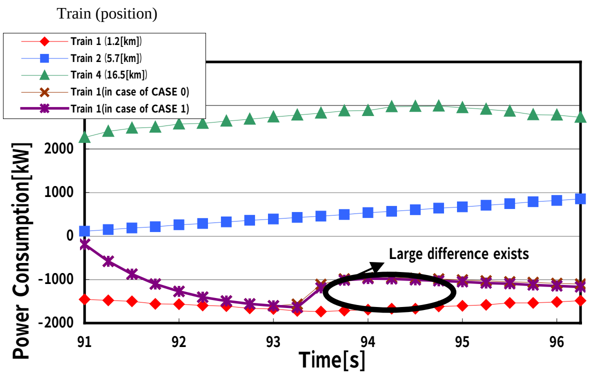


Fig.5 (a) Tradition of Power in Series A

Secondary, Fig.5 (b) shows the power transition of all trains in Series B in Fig.4. Series B is the power transition of Train 4 in Fig.5 (b). Train 2 and 4 regenerate power and Train 1 is their electrical load. Although the power consumption of the Train 1 is large enough, but the distance between Trains 1 and 4 is long, which results in the high pantograph voltage of train 4 because of the feeding resistance. Fig.5 (d) shows that the regenerative powers in CASEs 0 and 1 are less than that in CASE 4. In addition, the regenerative power in CASE 0 is less than that in CASE 1 in low-speed range.

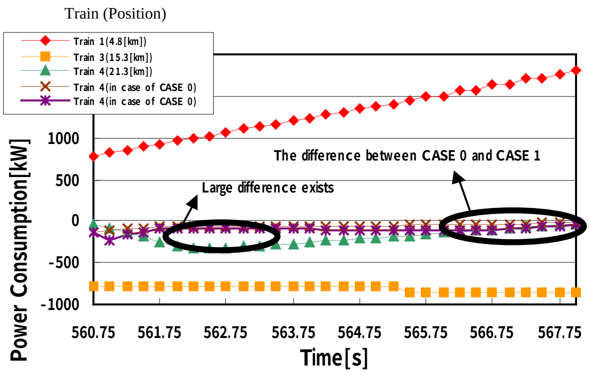


Fig.5 (b) Tradition of Power in Series B

Trains can regenerative their power even if a pantograph voltage is high when other powering trains consume power large enough and the distance between regenerating and powering trains is long. The regenerated powers in CASEs 0 and 1 are substantially less than that in CASE 4.

7. EVALUATION OF ENERGY

7.1 The amount of the regenerated energy

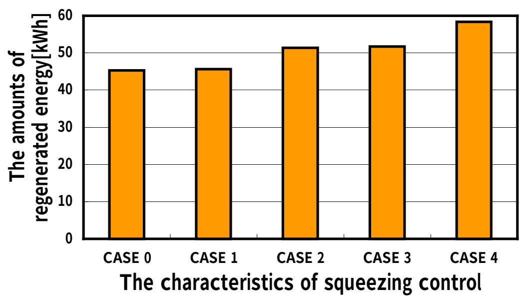


Fig.6 The Amount of Regenerated Energy

Figure 6 shows the comparison of the amount of the regenerated energy of all trains in the feeding circuit. We can conclude as follows;

1. the comparisons of CASEs 0 and 1 and that of CASEs 2 and 3 show that the change of object of squeezing control from motor current to the DC current of traction controller has little effect on the amount of the regenerated energy,
2. the comparison of CASEs 0 and 4 shows that the amount of the regenerated energy increases by approximately 14 [kWh] / 29 [%] by the data communication and the change of the static limitation of squeezing control from solid line to dashed line in fig.1, and

3. the comparisons of CASEs 0 and 2 and that of CASEs 1 and 3 show that the amount of the regenerated energy increases by approximately 6 [kWh] / 14 [%] thanks to the data communication.

A half of the increase of regenerated energy from CASE 0 to CASE 4 is due to the data communication, and another half is due to the change of the static limitation of squeezing control from the solid line to the dashed line in fig.1.

Therefore, the improvement of regenerative braking control needs not only the change of the static limitation of squeezing control but also the regeneration of power based on the status of the feeding circuit given by the data communication. In other words, a traction controller will need actual information of the electrical loads in the feeding circuit through the data communication for a smart regeneration, whereas the present controller squeezes regenerative power often excessively in order to avoid excessive rise of the pantograph voltage, since it works by simply sensing the voltage and the DC current at the pantopraph.

7.2 Evaluation of input energy from substations

Figure 7 shows the comparison of the input energy from the substations into the feeding circuit. We can conclude as follows;

1. the comparisons of CASEs 0 and 1 and that of CASEs 2 and 3 show that the change of object of squeezing control from motor current to the DC current of traction controller has little effect on the input energy from the substations.
2. The comparison of CASEs 0 and 4 shows that the input energy from the substations decreases by approximately 12 [kWh] / 8 [%] by the data communication and the change of the static limitation of squeezing control from the solid line to the dash line in fig.1.
3. The comparisons of CASEs 0 and 2 and that of CASEs 1 and 3 show that the input energy from the substations decreases by approximately 8 [kWh] / 5 [%] thanks to the data communication.

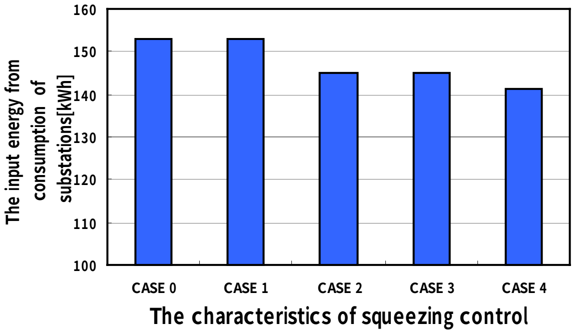


Fig.7 The Input Energy from the Substations

7.3 Loss by feeding resistance

Figure 8 shows the comparison of the loss by feeding resistance in the feeding circuit. It shows that the loss by the feeding resistance increases according to the increase of regenerated energy.

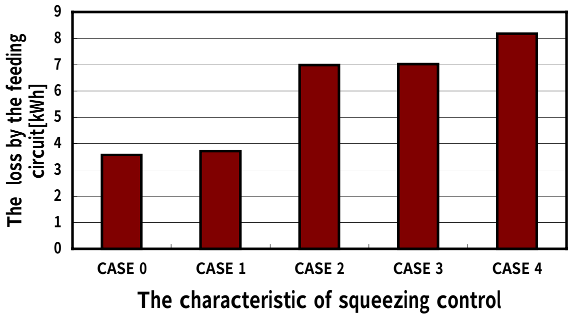


Fig.8 The Loss by Feeding Resistance

The loss by the feeding resistance in CASE 4 is the largest among all, in spite that the total input energy from the substations has been reduced most effectively as shown in Fig.7, since the power regenerated from a braking train is often sent to motoring trains which are far from the braking train under operation with such a smart energy management system like the PDIS.

8. CONCLUSION

This paper is summarized as follows;

1. the change of the object of squeezing control from the motor current to the DC current of the traction controller has little effect on the amount of the regenerative energy,
2. the amount of the regenerated energy of trains increases by approximately 14 [kWh] / 29 [%] in comparison with present squeezing. In addition, a half of the increase of regenerated energy is due to the data communication, and another half is due to the change of the static limitation of squeezing control,
3. the input energy from the substations decreases by approximately 12 [kWh] / 8 [%] in comparison with present squeezing control. In addition, approximately 60[%] of the effect is due to the data communication, and the rest is due to the change of the static limitation of squeezing control, and
4. the data communication of the PDIS and improvement of static voltage limitation will guarantee the regenerative function even if voltages at pantographs are high when other electrical loads consume power large enough even in spite the distance between regenerative and powering trains is long.

9.FUTURE WORKS

One needs the further investigation on regenerative function when the interval of train service changes. One also needs to recalculate the power flow in the feeding circuit considering the power consumption of auxiliary subsystems in trains changes, since such auxiliary subsystems can be considerable electrical loads in a realistic feeding circuit. One should calculate cases with regenerative substations, which would significantly improve the regenerative braking action. The variation of duration of train stopping at a station can be a significant disturbance for such a simulation and a control of electrification. This effect should be furthermore analysed.

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