Power Management Control in DC-electrified Railways for Regenerative Braking Systems of Electric Trains

Yuruki OKADA[1], Takafumi KOSEKI[2], Kohei HISATOMI[3]
[12]*The University of Tokyo, Japan*
[3]*Shin-Keisei Electric Railway, Japan*

Abstract

The most electric trains in DC-electrified railways are presently equipped with regenerative braking system. On braking, traction controller of a train converts kinetic energy to electrical energy during deceleration of the train when other powering trains consume the electrical energy as electrical loads for the regenerating train in the electrical circuit. Therefore, the traction controller of the braking train must reduce the electrical power following *squeezing control of regenerative power* when the electrical loads are too little in the electrical circuit because there is typically no devices which absorb the regenerated energy in the electrical circuit. However, actual traction controllers have often reduced regenerative power excessively because they do not recognize the states of the electrical circuit, which include positions of other trains and substations and power consumption/regeneration of other trains in the electrical circuit.

In this paper, we discuss the improvement of the *squeezing control of regenerative power* based on information of the electric circuit. The information means voltage at pantograph, estimated positions and power consumption/regeneration of other trains etc.

1 Regenerative Braking in DC-Electrified Railway

Fig.1 shows typical power flow on braking in a DC-electrified circuit. And the black solid arrows show typical power flow in present system, in which only the powering train consumes the power regenerated from braking train. Therefore, the braking train must reduce the electrical power following *squeezing control of regenerative power* when power consumption of powering train is too little

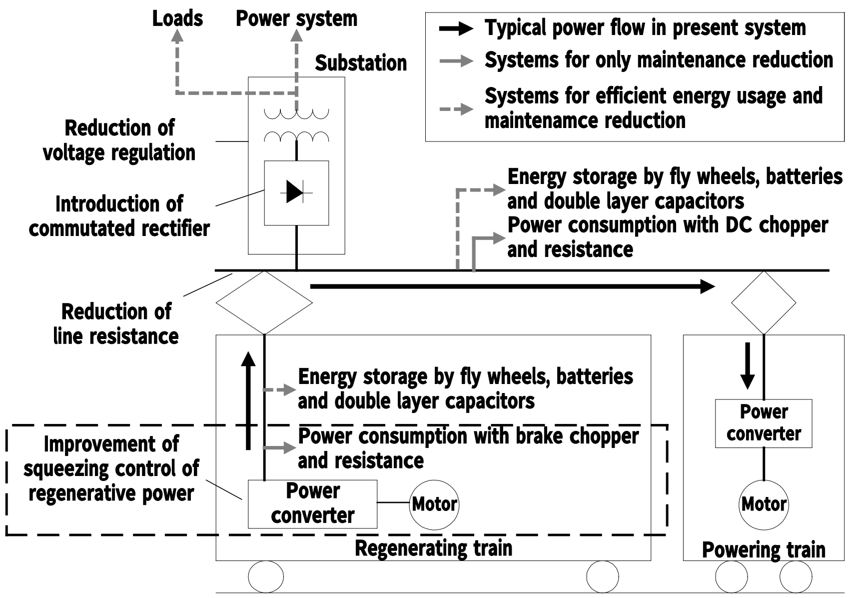


Figure 1: Typical power flow on braking

because there is typically no devices which absorb the regenerated energy in the electrical circuit. However, some devices have recently introduced in DC-electrified railways for effective usage of regenerative braking.

First, brake choppers with resistances on board or in the electrical circuit contribute to maintenance reduction of trains. Second, energy storage devices which include flywheels, batteries and double layer capacitors on board or in the electrical circuit and commutated rectifiers at substations contribute to not only maintenance deduction of trains but also efficient energy usage. In addition, reduction of voltage regulation at substations and reduction of feeding resistance can contribute to effective regenerative braking. Finally, improvement of squeezing control of regenerative power can enhance performance of regenerative braking.

In this paper, we discuss improvement of the squeezing control of regenerative power with information of the electrical circuit and brake choppers with resistances.

2 Problems of *Squeezing Control of Regenerative Power*

On braking, braking train converts kinetic energy to electrical energy. And other powering trains consume the electrical energy as electrical loads in the electrical circuit. Therefore, when electrical loads are too little in the circuit, the braking trains must reduce regenerative power following the characteristic shown by the solid line in Fig.2 to avoid excessive voltage at pantograph. This control is called *squeezing control of regenerative power*.

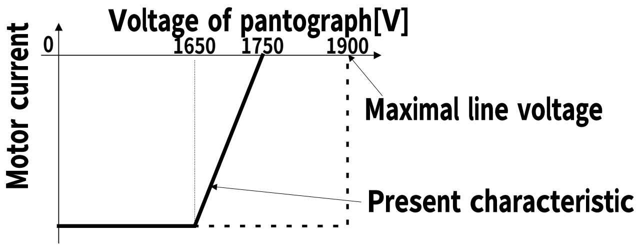


Figure 2: Typical characteristic of squeezing control

However, actual traction controllers often squeeze regenerative power excessively[1]. The reasons for the excessive squeezing are as follows;

1. traction controllers squeeze regenerative power excessively in low-speed range because they squeeze AC motor current directly instead of their DC current,
2. traction controllers squeeze motor current at lower voltage than maximal voltage limit of feeding circuit as shown by the solid line in Fig.2 and
3. actual traction controllers often squeeze motor current at lower voltage than the conservative voltage limit shown by the solid line in Fig.2.

In those problems, squeezing DC current of traction controller instead of AC motor current can solve the problem 1. However, traction controller needs to recognize state of electrical circuit in which braking trains exist to solve the problems 2 and 3. When the traction controller cannot recognize the states of the electrical circuit, it must squeeze regenerative power with statically conservative characteristic shown by the solid line in Fig.2 to avoid excessive voltage at pantograph because the voltage at pantograph rises when a powering train which exist in the electrical circuit cuts off its power consumption. And, the cutoff-speed of power consumption becomes faster, the higher the voltage pantograph rises. Therefore, the traction controller must squeeze regenerative power regarding cutoff-speed of power consumption of register-controlled trains in the electrical circuit which cut off their power consumption faster than any other train. However, cutoff-speed of power consumption of trains controlled by VVVF-inverters, Armature choppers or field chopper is lower than that of resistor-controlled trains so that traction controller squeezes regenerative power excessively when trains controlled by these methods cut off their power consumption.

3 Improvement of Squeezing Control

Improvement of electrical circuit, power management with data communication in electrical circuit etc. are proposed to improve squeezing control of regenerative power[1][2][3]. In this paper, we propose squeezing control of regenerative power which characteristics vary according to states of the electrical circuit. When we improve squeezing control of regenerative power to abolish excessive squeezing of regenerative power, we must regard voltage rise at pantograph when powering trains in same electrical circuit cuts off their power consumption. For that purpose, traction controller must have the information as follows;

1. position, velocity, voltage at pantograph, DC current of traction controller and power regeneration of the regenerating train,
2. running profile of the line which the regenerating train exists,
3. control method of every train on the line,
4. the time when powering trains in the electrical circuit cut off their power consumption and
5. distance between the braking train and the powering trains.

In the information, the information 1 can easily be measured, and the information 2 and 3 can be stored on board as data of traction controller. However, the information 4 and 5 need to be estimated from the information 1, 2 and 3. And the characteristics of squeezing control of regenerative power must be determined based on the information.

We must propose how to estimate the information 4 and 5 and how to determine the characteristics of squeezing control of regenerative power. In this paper, for determination characteristics of squeezing control of regenerative power, we examine voltage regulation at pantograph in case powering trains with various control methods cut off their power consumption.

4 Voltage Regulation at Pantograph

4.1 Electrical circuit for examination of voltage regulation

Fig.3 shows electrical circuit to examine voltage regulation at pantograph. The electrical circuit consists of a substation, a powering train and a braking train controlled by VVVF-inverter. And the powering train is controlled by VVVF-inverter, field chopper or resistor controller. In addition, Fig 4 shows equivalent circuits of powering train and Fig.5 shows characteristics at cutoff of power consumption at a powering train. The line voltage at the electrical circuit is limited up to 1900V. The authors will monitor the voltage at a filter capacitor of a braking train instead of that at pantograph.

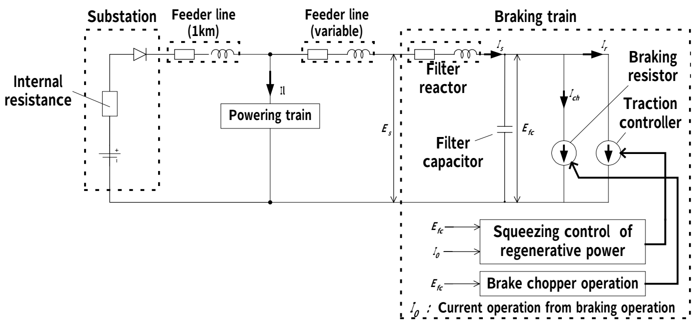


Figure 3: Electrical circuit for examination

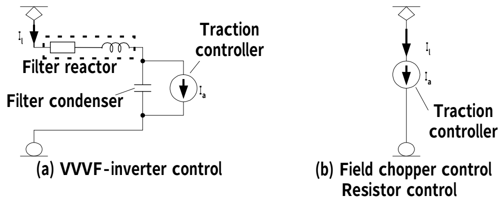


Figure 4: Equivalent circuits of powering train

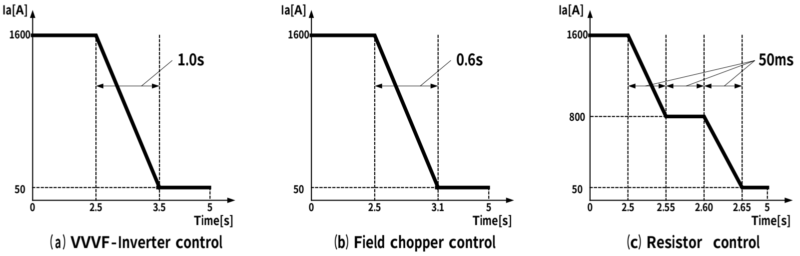


Figure 5: Characteristics at cutoff of power consumption

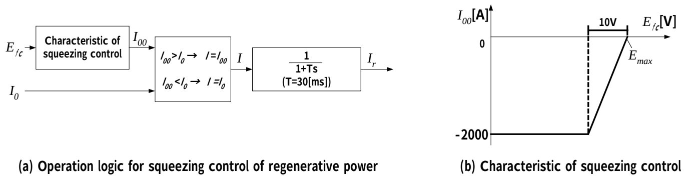


Figure 6: Operation logic for squeezing control (1)

4.2 Voltage regulation at pantograph of the braking train

4.2.1 In case that the powering train is VVVF-inverter controlled

Fig.6(a) shows the operation logic how to reduce the regenerative power when the powering train controlled by VVVF-inverter stops its power consumption. In this logic, the V-I characteristic in Fig.6(b) is assumed as the “characteristic of squeezing control” in (a). The first order delay, the time constant of which is assumed T=30[ms], represents the response of the traction motor current. In addition, the distance between the powering and the braking train is 2km.

Fig.7 shows voltage at the filter capacitor of the braking train. Fig.7 also shows that the braking train can keep electric braking action by reducing its regenerative power continuously for avoiding excessive pantograph voltage, even if the other train stops its powering in various cases from E_{max}=1600[V] up to 1850[V]. In addition, Fig.8 demonstrates relation between the voltage at the filter capacitor and the DC current from the braking train while the powering train reduces its power consumption in the case E_{max} is 1850V. And Fig.8

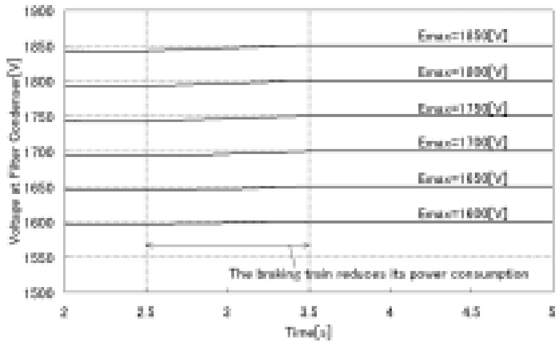


Figure 7: Voltage at the filter capacitor (1)

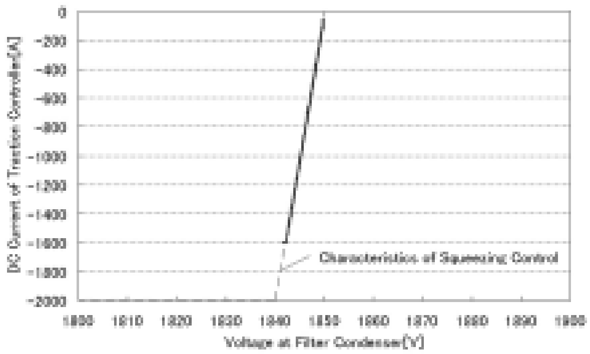


Figure 8: Following characteristic of squeezing control (1)

illustrates that traction controller of the braking train can reduce its regenerative power following the design of its squeezing control.

4.2.2 Case of powering train controlled by field-current chopper

Fig.6(a) shows operation logic for squeezing control of regenerative power when a powering train controlled by a field-current chopper stops its power consumption. In addition, the distance between the powering and the braking trains is 2km.

Fig.9 shows voltage at the filter capacitor of the braking train. Fig.9 also shows that the braking train can keep electric braking action by reducing its regenerative power continuously for avoiding excessive pantograph voltage, even if the other train stops its powering in various cases from E_{max}=1600[V] up to 1850[V]. In addition, Fig.10 illustrates the relation between voltage at the filter capacitor and the DC current of the traction controller of the braking train while the powering train reduces its power consumption in case that E_{max} is 1850V. And Fig.10 illustrates that traction controller of the braking train can reduce its regenerative power following the design of its squeezing control.

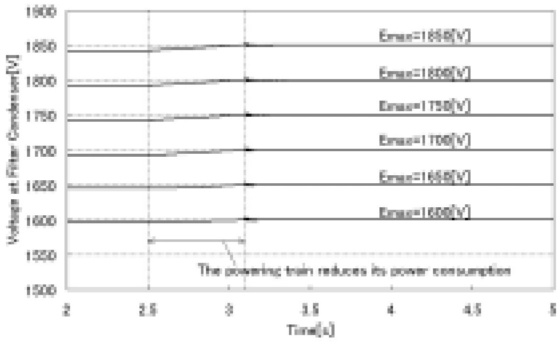


Figure 9: Voltage at the filter capacitor (2)

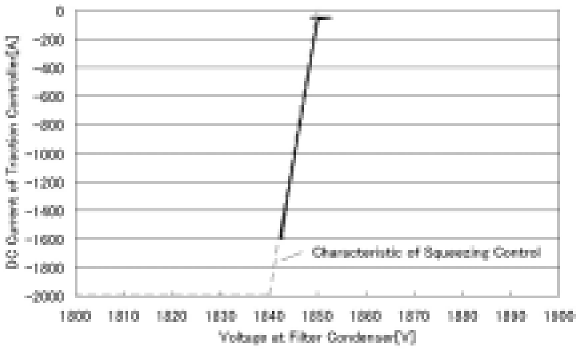


Figure 10: Following characteristic of squeezing control (2)

4.2.3 Resister-controlled powering train

Fig.11 shows operation logic for squeezing control of regenerative power in case the powering train which is resister-controlled reduces its power consumption. In addition, the first order delay, whose time constant is 1.0ms, is used to suppress vibration of I_{00} and the other first order delay, whose time constant is 30ms, indicates characteristic of response of current at traction motor. Moreover, the limiter 1 makes its output zero when its input is negative and the Limiter 2 makes its output zero when its input is positive.

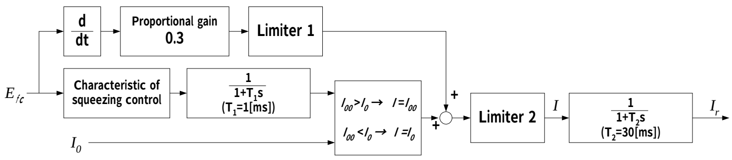


Figure 11: Operation logic for squeezing control (2)

Fig.12 shows voltage at the filter capacitor of braking train when the E_{max} indicated in Fig.6(b) is 1600V and the distance between the powering and the braking trains is 2km. Fig.12 also illustrates that the filter capacitor of braking train rises drastically because the powering train spontaneously reduces its power consumption in several milliseconds. Therefore, E_{max} must be less than 1600V so that traction controller can reduce regenerative power conservatively when resister-controlled train, instead of VVVF-inverter controlled train or field-chopper controlled one, cuts off its power.

In addition, Fig.13 shows maximal voltage at the filter capacitor of the braking train when the distance between the powering and the braking trains varies if E_{max} is 1600V. This figure means that the longer the between the powering and the braking trains is, the lower the maximal voltage at the filter capacitor of the braking train is, since the line resistance proportional to the distance between the two trains restricts the power to be transferred from the braking to the powering train.

Fig.13 also demonstrates that the longer the distance between the powering and the braking trains is, the higher the E_{max} can be. Fig.14 shows maximal E_{max} to avoid excessive voltage at the filter capacitor of the braking train. This figure means the longer distance between the powering and the braking trains allows

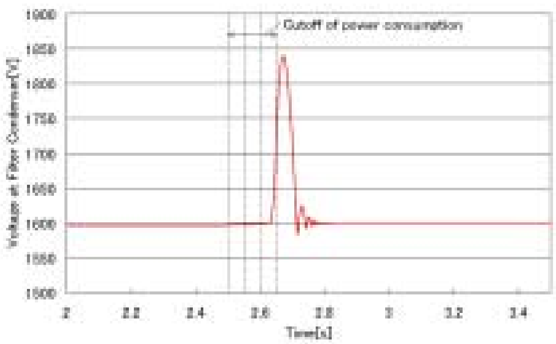


Figure 12: Voltage at the filter capacitor (3)

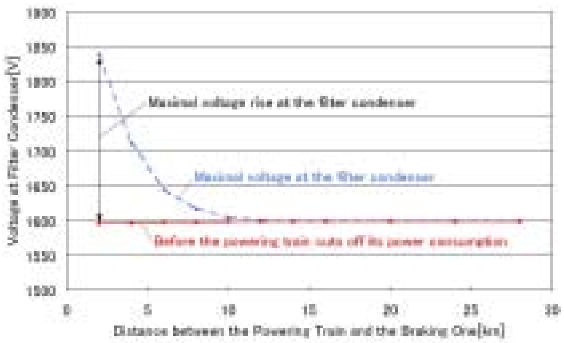
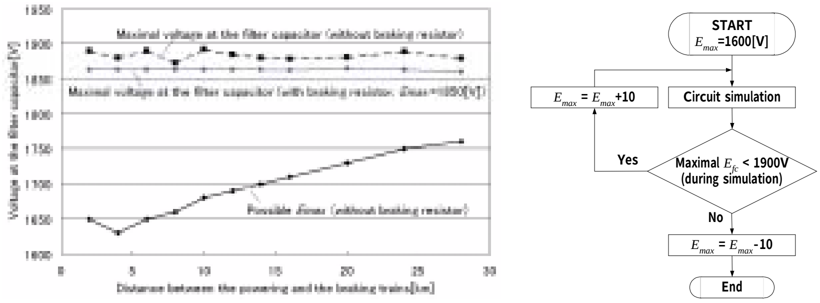


Figure 13: Voltage rise



(a) The possible E_{max} to avoid excessive voltage (b) The logic to determine the possible E_{max}

Figure 14:

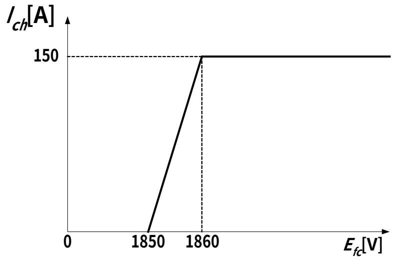


Figure 15:

higher E_{max}, since the influence from the action of the powering train is substantially smaller when the distance between the two trains is longer. The logic indicated by Fig.14(b) determines the possible E_{max} to avoid excessive voltage at the filter capacitor of the braking train.

If the braking train has supplemental braking resistor, whose characteristic for operation is assumed as Fig.15, E_{max}=1850[V] is possible for all the investigated train distance, since the braking resistor can effectively absorb the power deviation from the spontaneous action of the powering train. In addition, maximal power consumption of the braking resistor at all the investigated train distance is 220kW, which is approximately 7% of maximal power consumption of typical electric train on powering.

5 Conclusion

In this paper, the authors have proposed squeezing control of regenerative power whose characteristics vary according to states of electrical circuit. They have examined the voltage at the filter capacitor of the braking train when the different three kinds of powering trains stop their power consumption. They have concluded:

1. when a powering train, which is controlled by VVVF inverter or field chopper, stops its power consumption, braking train can successfully reduce its regenerative power with squeezing control whose E_{max} is close to maximal voltage limitation,

2. the controller of the braking train must reduce its regenerative power conservatively when a resister-controlled powering train close to the braking train stops its power consumption,
3. longer distance between the powering and the braking trains allows higher E_{max}, since the influence from the action of the powering train is substantially smaller when the distance between the two trains is longer,
4. the braking resistor, whose power consumption approximately 7% of maximal power consumption of typical electric train on powering enables $E_{max}$to be 1850[V]for all the investigated train distance.

6 Future Works

The authors have studied only the on board squeezing control of regenerative power. However, they must also investigate how to estimate and use the information as follows to introduce a better squeezing control of regenerative power whose characteristics vary according to states of electrical circuit;

1. the time when powering trains in electrical circuit stop their power consumption and
2. distance between the braking train and the powering train which cuts off its power consumption.

Acknowledgement

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References

[1] S. SONE, Re-examination of Feeding Characteristics and Squeezing Control of Regenerative Trains, Joint Technical Meeting Transportation and Electric Railway and Linear drives, TER-02-49/LD-02-64, 2002

[2] Y. OKADA, T. KOSEKI, Evaluation of maximal reduction of electric energy consumed by DC-fed electric trains, NATIONAL CONVENTION RECORD I.E.E. JAPAN, 5-219, pp307-308, 2003

[3] Y. OKADA, T. KOSEKI, S. SONE, Energy Management for Regenerative Brakes on a DC Feeding System, STECH’03, pp 376-380, 2003