Innovative Power Supply System for Regenerative Trains

Takafumi KOSEKI[1], Yuruki OKADA[2], Yuzuru YONEHATA[3,] SatoruSONE[4]

[12]*The University of Tokyo, Japan*
[3]*Mitsubishi Electric Corp., Japan*
[4]*Kogakuin University, Japan*

Abstract

The authors are proposing pure electric brake which supplies service brake in normal operation solely in electrical mode down to complete stop. This reduces mechanical wear of brake linings and realises much better riding comfort with easier and exacter braking manoeuvre. This full usage of the regenerative braking mode is getting popular in Japan. However, there are still problems to be solved before all related parties can enjoy advantages of this technique; insufficient braking force at high speed due to the power limitation, squeezing of braking force at excessive line voltage at the pantograph of the braking train, and giving up the regeneration when no other trains simultaneously absorb the regenerated power. Combination of regenerative and rheostatic brakes has, therefore, been introduced to some lines, which have long and steep slopes. This paper deals with countermeasures in power feeding system by introducing equipment for absorbing regenerated power effectively. Several case studies show the effectiveness of the wayside power-absorbing components for the full usage of the regenerative electric brakes.

1 Introduction

DC-electrification is often used for urban public transport. Although many trains have power electronic components for regenerative braking as well as powering motors for acceleration recently, it is often difficult to fully use the regenerative electric brake, since the regenerative action requires simultaneous electric loads, which may be mainly other powering trains, in the same electrified line. If there is no considerable electric load in the system, the pantograph voltage immediately increases up to the maximal limitation during its electric braking action, which results in failure of electric motion and supplemental compensation or the braking action by its mechanical braking system. This tendency is being more obvious since the number of train sets, which have regenerative braking function, has been increased. The full usage of the regenerative electric brake for ordinary braking action has the following inherent advantages:

(1) saving energy,
(2) saving maintenance works on account of the reduction of the chance of mechanical braking action, and
(3) better passenger comfort due to good and stable transient response of the braking force.

The main purpose of this paper is to investigate how to reduce the probability of the failure of regenerative braking actions for energy-saving and maintenance-saving railway operation. Several strategies for the full usage of the regenerative brake have been discussed, *e.g.,* :

(1) constant power electric braking pattern, with which the peak regenerative power at high speed drive is suppressed, by giving weak braking command when the train runs fast,
(2) intentional activation of onboard auxiliary equipment, *e.g.*, air- conditioner and compressor when the electric loads are insufficient, and
(3) comprehensive power management controls[1].

The methods listed above have been investigated[1][2] in detail and the validity of the strategies have been proven through numerical simulations. However, such strategies cannot guarantees the regenerative action completely. A substantial solution may be to equip the components which absorb excessive power.

Fig.1 shows a possible type of DC-electrification.

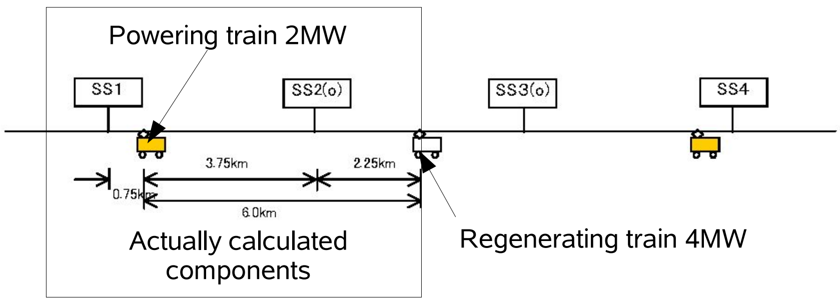

Figure 1: Typical power flow on braking.

2 Substations with Inverter Function and the Definition of Case Studies

Fig. 1 also shows the scenario of numerical studies in this paper. On braking, The decelerating train at the section between substations 2 and 3 converts kinetic energy to electrical one. The location of the regenerating train is assumed just the centre of the two substations for a simple calculation using symmetric assumption without losing generality of the analysis. Thanks to this symmetric assumption, one can manage the simulation in a half size.

Fig. 2 shows the current-voltage characteristics of different types of convertors assumed in this study. The thyristor convertor/inverter can control itself and keep the voltage constant up to its nominal load current, whereas the conventional diode rectifier has voltage drop proportional to its load current. The PWM convertor/inverter can control its voltage constant for all the amount of its load current. The PWM-convertor voltage is set to 1600V, which is of 100V higher than the system nominal voltage, so that one can use out the advantage of constant voltage operation. Inverter voltages for regenerative action is set to 1620V, which is slightly higher than convertors' no load voltage, for avoiding unfavourable direct power flow from converting to inverting substations.

For the case of the PWM convertor/inverter configuration, one can, of course, set the substation voltages to 1500V, which is just identical to their nominal system voltages. A regenerating train could send its generated power from further location to another powering train in this case compared to the case of the 1600V-setting, but one must accept inherently more stationary loss in general, since one needs more current to send the identical power with lower voltage. Therefore, the case of 1600V will be studied in detail here, for energy-saving operation is one of the significant purposes of introducing new regenerative components into the substations.

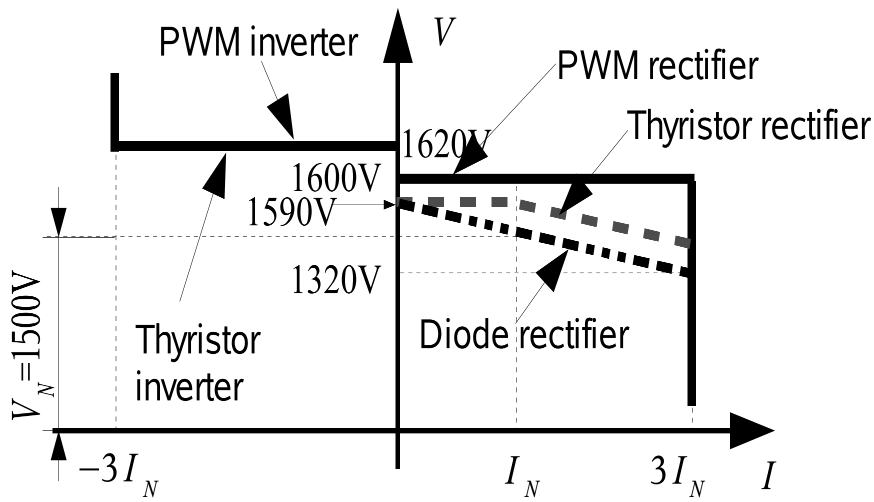

Figure 2:Typical characteristics of different substation convertors.

3 Preconditions for the Calculations of the Case Studies

The distance of two substations is assumed to 4.5km constant as shown in Fig, 2, and the train at the centre between the substations 2 and 3 intends to regenerate and send back the power of 4.0MW to the electric system. The powering train locating at 0.75km-point from the substation 1 is taking power of 2.0MW from the electric line. Hence, the distance between the powering and the braking trains is 6.0km. The trains are modelled as DC-power source in the simulation. The upper power limitation of regenerating components have not been assumed in this study, whereas the real thyristor inverter may keep the inverter voltage of 1620V constant only up to the five times of its nominal regenerative current. The upper limitation of PWM converters may be approximately 300% of its nominal regenerative current. The line resistance is assumed to 0.03 Ω /km . The voltages of the resistor chopper in case II and the chopper for the energy storage in case V are also set to 1620V constant. The difference between these two cases is only the count of regenerated and lost powers after the substantial circuit calculations.

The upper limitation of the regenerated current of the train is 2kA constant up to the pantograph voltage of 1700V and the limit value is linearly reduced to 0A between the pantograph voltages of 1700V and 1800V. The inner loss of the trains contains the joule loss in filter reactors of the onboard inverter.

The power has been doubled and the line resistance has been divided by two, for calculating the power flow of double tracks in a simplified calculation with a single track modelling.

4 Calculated Results and Comparisons

The power flows, current and voltage distributions dependent on different substation equipment, have been obtained from DC-circuit calculations and indicated in figures from 3 through 7.

Fig. 3 represents the basic case of diode rectifiers, which have no regenerative functions. The substation 2 has nothing to do, since the resultant voltage at the entry point of the substation 2 is higher than the no-load voltage of 1590V of the diode rectifier. The pantograph voltage of the regenerating train has been too high, since there is nothing absorbing its excessive power, and the regeneration of the braking power has been partially given up.

The chopper-controlled resistor absorbs the excessive power in Fig. 4. The voltage at the entry point of the substation 2 is suppressed to 1620V of the nominal DC-voltage of the resistor-chopper, which results in the lower pantograph voltage of the regenerating train, and full regenerative braking action has been guaranteed. But the absorbed power has been immediately converted to joule loss in the wayside resistor, and there is no contribution for energy saving in this configuration.

The thyristor inverter in Fig. 5 is also controlling the entry voltage of the substation 2 to 1620V, which is identical to case II. Main difference from Fig. 4

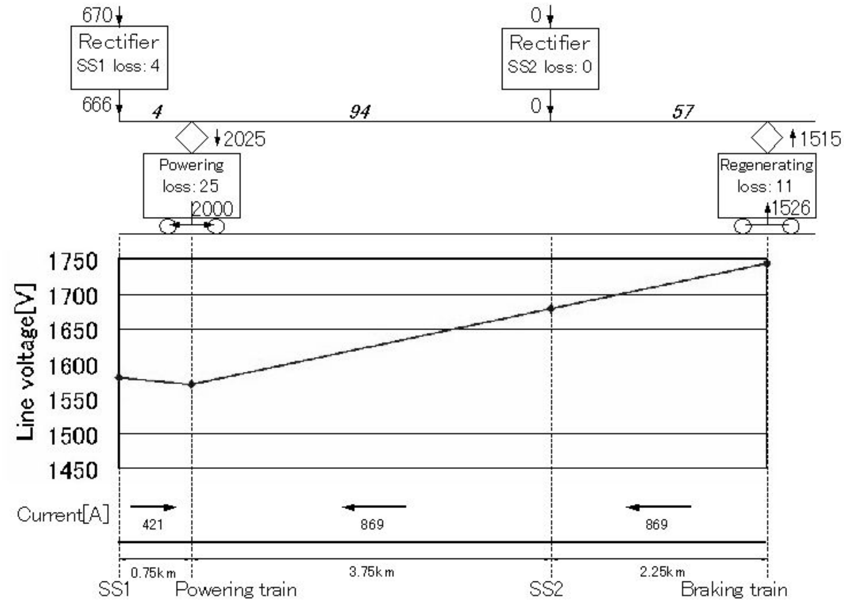

Figure 3: The Case I: Conventional diode rectifiers at the substations 1 and 2.

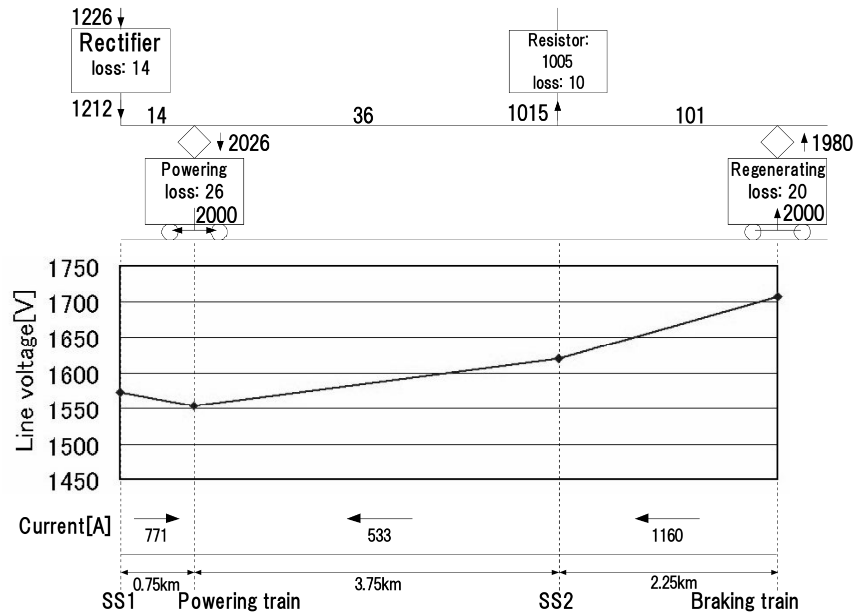

Figure 4: Case II: Conventional diode rectifier with a wayside braking resistor controlled by a chopper.

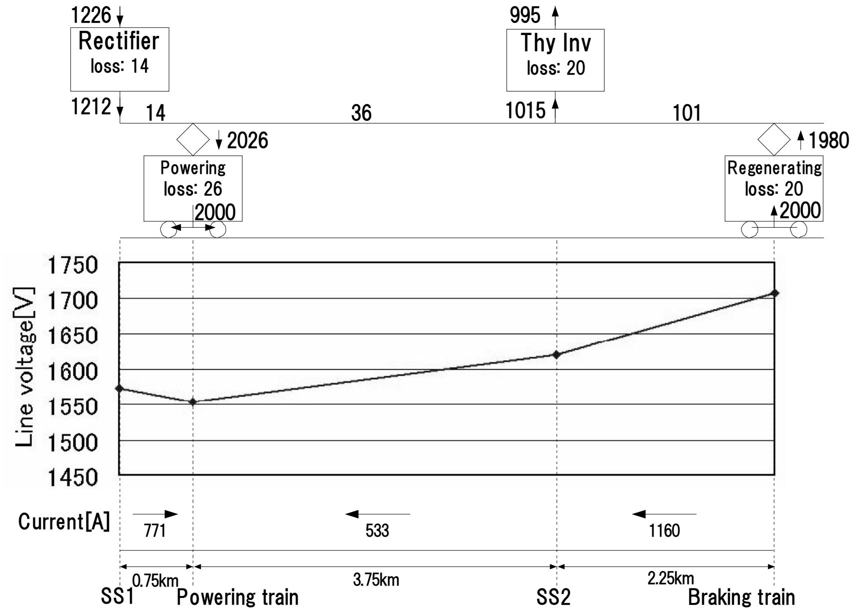

Figure 5: Case III: Conventional diode rectifier and thrystor inverter.

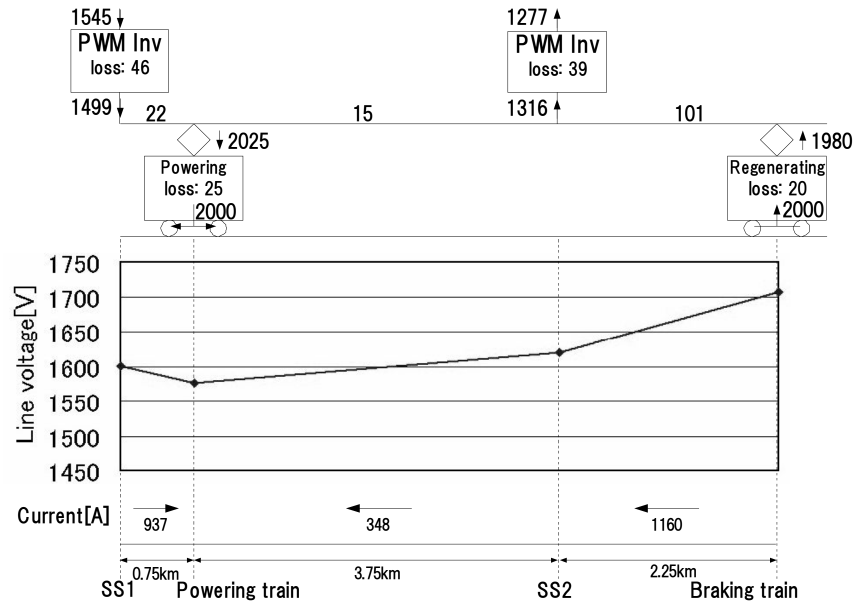

Figure 6: Case IV: PWM inverters in the substations1 and 2.

is that a part of the regenerated energy is sent back to the AC-power system. Since the voltage in the AC-side is high, which may result in the small current sent back into AC-side, the loss in the AC-side has not been considered in this calculation. The rated voltage of the thyristor inverter is designed slightly lower than the case of PWM inverter, since it has relatively large ripples in voltage as well as current waveforms. 12-bridge inverter configuration shall be applied in practice for reducing these ripples and harmful effects from switching harmonics.

Both substations 1 and 2 have PWM-inverters in Fig. 6. This case seems to have slightly worse efficiency than the case in Fig. 5, but this comparison may not be so simple, since the thyristor inverters will need supplemental filter circuits, whose loss is not negligible, for suppressing the effects of the switching harmonics in practice.

Fig. 7 shows a case of the usage of *generic energy storage device* whose total efficiency of charging/discharging actions is assumed 75% in the substation 2. It can be super-capacitors, fly-wheels, battery systems or these combinations. Only the charging efficiency of $\sqrt{0.75}$ has been considered in this calculation. One must pay attention to the fact that the finally reusable energy will be the amount of the stored energy furthermore multiplied by factor $\sqrt{0.75}$. The circuit behaviour has been identical to the case of Fig. 4, but this system has a substantial advantage that you can reuse the stored energy, and the total energy efficiency will be inherently better than Fig. 4.

From these calculations, the criteria values have been summarised in table 1 for comparing the goodness of the possible DC-substation configurations in the

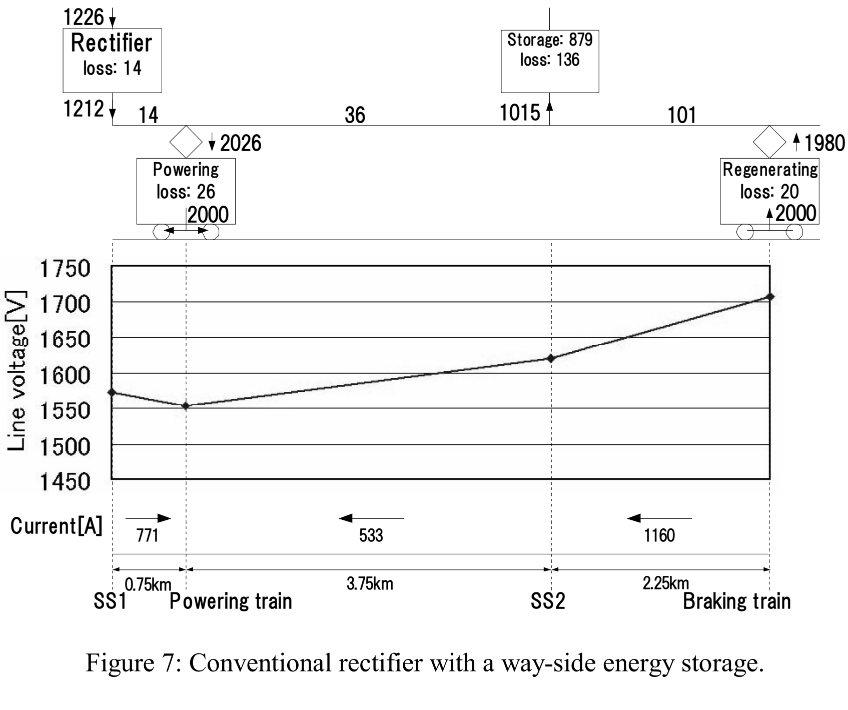

Figure 7: Conventional rectifier with a way-side energy storage.

era of regenerative trains. The restriction for the regenerative action for the braking train has occurred only in the case I. This shows that energy absorbing equipment is inherently effective and useful in order to guarantee the regenerating braking action.

Table 1: Summary of the calculated power flow.

	Electric braking ratio in %	(Reusable power)/ (Regenerated power) in %	Total system energy efficiency in %	Total goodness
Case I	76	*89**	**68**	Not preferable
Case II	100	41	**41**	Not preferable
Case III	100	91	**91**	Preferable
Case IV	100	91	**91**	Preferable
Case V	100	85**	**85****	Preferable

- **seems good, but it is not true, since the "regenerated power " in the denominator of the definition of this criteria is small, because of the squeezing control of its electric brake.*
- *** this figure does not include the efficiency of recharging process. The really usable energy will be smaller, i.e., to be multiplied by* $\sqrt{0.75}$.

5 Conclusions

The authors have calculated and compared power flows in several power regenerating equipment in DC-electrified railway system to make full use of the regenerative braking action of modern trains. It is beneficial for the effective usage of regenerative brakes to send back the power to AC-commercial electrical network through inverters at substations, or to implement energy storage devices at substations.

When one partially introduces inverters to substations, the rated voltage of the inverters should be set slightly higher than rectifiers, otherwise unfavourable power flows would occur from powering to inverter substations. The simultaneous implementation of the inverters to each substation is preferable. Power storage system is often discussed for balancing power demand between daytime and night. The balancing function for the peaky power deviation in very short time scale like this example of railway traction power balance, the charging and discharging energy efficiency may tend to be worse. Therefore, the relatively conservative total efficiency of 75% has been assumed in this conceptual investigation.

From these fundamental calculations, it has been obviously shown that the cases from III to V are preferable for the DC-electrifying equipment for the generation of power electronic traction system with regenerative braking. This study has, however, included neither economical assessment, in which the balance between initial and running costs as well as the life cycle of the total system, nor environmental impacts. Such a comprehensive viewpoint shall be taken into account for a realistic system design in near future. Especially, the power storage device may be implemented concentrated to specific substations from the economical and maintenance reasons, although this aspect has not been quantitatively discussed either in this paper.

References

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

[2] 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