A study of capacity calculation of regenerative inverter for 1500V DC traction system

C. H. Bae, M. S. Han, Y. K. Kim, S. Y. Kwon & H. J. Park
Korea Railroad Research Institute, Korea

Abstract

The paper presents methods of determining the capacity and installation positions of regenerative inverters installed in 1500V DC electric railway system. We suggested a method that calculates using regenerative power obtained from Train Performance Simulation (TPS) and Power Flow Simulation (PFS). We carried out TPS and PFS for Seoul Subway line 5 and 6, calculating regenerative power and determining substations where regenerative inverters would be installed and the optimal capacity and number of inverters to be installed.
Keywords: regenerative inverter, electric railway system, train performance simulation, power flow simulation.

1 Introduction

In DC electric railway system, 22.9kV system voltage is converted to DC 1500V voltage through a 3-phase silicon diode rectifier and supplied to motor cars. Because, in case of diode rectifiers, regenerative power generated at the regenerative braking of motor cars cannot be absorbed into the supply grid, the power is used at nearby powering trains or consumed as heat at resistances mounted on the cars. However, if a regenerative inverter is installed in inverse-parallel with the diode rectifier, it absorbs dump regenerative power consumed at the resistance and transmits it to a high-voltage switchboard for reuse. In this way, energy can be saved by reusing dump regenerative power wasted away as heat and the braking and ATO performance of motor cars can be improved through enhancing the regenerative power absorption rate of catenary lines. Despite these advantages, regenerative inverters cannot be installed in all substations for electric railways because the cost of manufacturing and installing regenerative inverters is higher than the benefit from the use of regenerative

WIT Transactions on The Built Environment, Vol 88, © 2006 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/CR060741

powers. Thus, they are installed at sections with a long continuous slope or where regenerative power loss in resistor bank becomes a problem, and for this it is necessary to calculate accurate regenerative power generated and determine the appropriate installation positions, number and capacity of regenerative inverters.

The present study suggests methods of determining the capacity and installation positions of regenerative inverters installed in 1500V DC electric railway system. We suggested a method that approximates using parameters related to substations where regenerative inverters are installed, railway lines and operating motor cars, and another that calculates using regenerative power obtained from Train Performance Simulation (TPS) and Power Flow Simulation (PFS). For TPS and PFS, we used a program developed by Korea Railroad Research Institute for the development of light rail transit system 1]. We carried out TPS and PFS for Seoul Subway Line 5 and 6, calculating regenerative power and determining substations where regenerative inverters would be installed and the optimal capacity and number of inverters to be installed.

2 Calculating the capacity of regenerative inverters

A regenerative inverter detects the rise of catenary line voltage caused by dump regenerative power, absorbs the regenerative power, and transmits it to a high-voltage distribution system for reuse. Fig. 1 shows a diode rectifier and a regenerative inverter at an electric railway substation. Here, the 12-pulse diode rectifier generates 1500V DC voltage and the IGBT regenerative inverter absorbs dump regenerative power and transmits it to the supply grid for reuse. As for the capacity of regenerative inverters, because if the operating interval of motor cars is very long the instantaneous load rate is even higher than that of a rectifier supplying DC 1500V power, we need a very high peak power rating. However, high peak power rating brings restrictions on the economic efficiency and size of regenerative inverters. Accordingly, maximum power higher than a certain level effectuates regenerative power by allowing current limiting and DC voltage rise to regenerative inverters, and acknowledges it as peak power rating.

To estimate the optimal capacity of such a regenerative inverter, it is desirable to block regenerative power loss in an operating train, make a route for absorbing regenerative power and measure regenerative power, but because this requires additional regenerative power absorbing equipment and operation to prevent regenerative power loss, it is not easy to measure regenerative power using this method. There are other methods such as approximating based on variables related to substation, operating line, train condition and regenerative power in other lines and calculating using TPS and PFS. However, because the level of regenerative power varies according to the conditions of line on which the regenerative inverter is installed, train condition and operation condition, it is difficult to determine the accurate capacity through approximation based on these major variables. Accordingly, we need to calculate dump regenerative power in various train operation conditions by conducting TPS and PFS under different conditions of line, train and substation.

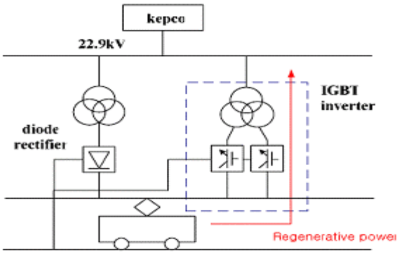


Figure 1: DC 1500V traction substation with a regenerative inverter.

3 Approximation method

Fig. 1 shows the layout of a substation for DC electric railway for calculating the capacity of a regenerative inverter, and conditions for the calculation are presented in table 1. As in fig. 1, a regenerative inverter in charge of a 12km-long regeneration section is installed at substation B, and the number of trains running in the section, n , is obtained by eqn. (1).

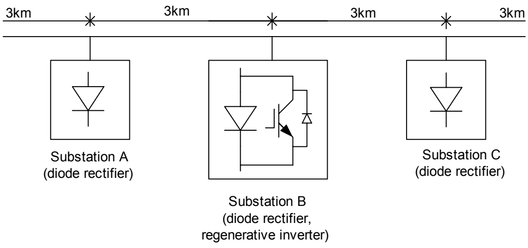


Figure 2: DC 1500V traction power system.

$$n = \frac{l}{v_s \cdot t_h} \qquad \text{[trains/h]} \qquad (1)$$

Maximum power consumption per hour, P_m , is calculated from train ton-kilo capacity as follows.

$$P_m = 2n \cdot s \cdot w \cdot l \cdot (1+a) \cdot k \quad \text{[kW]} \qquad (2)$$

Here, coefficient 2 means a double track section, and a is standard deviation of power variation according to DIA distribution. Capacity is calculated using power regeneration rate and regenerative braking efficiency rate obtained from existing substations with a regenerative inverter. Power regeneration rate, λ_1, means the ratio of absorbed regenerative power to P_m, the maximum power consumption of substations with a regenerative inverter, and regenerative braking efficiency rate means the ratio of absorbed regenerative power to the whole regenerative power generated within the section covered by a substation with a regenerative inverter. Here, the whole regenerative power includes regenerative power consumed by nearby powering trains and regenerative power loss in resistor bank. In general, power regeneration rate λ_1 range between 0.20 ~ 0.23, and regenerative braking efficiency rate λ_2 between 0.63 ~ 0.67 [2]. Using these data, the capacity of a regenerative inverter can be calculated by eqn. (3), where W is the whole regenerative power generated from the section covered by the regenerative inverter, which includes regenerative power consumed by nearby powering trains and regenerative power loss in resistor bank. Accordingly, the capacity of the regenerative inverter should be larger than W considering the operation condition of the line.

$$W = P_m \times \frac{\lambda_1}{\lambda_2} \text{ [kW]} \tag{3}$$

In order to calculate regenerative peak current I_b from mechanical energy absorbed at braking, consumed braking power P_b is calculated by eqn. (4), and braking electric power generated from a train at speed of v[km/h] is calculated by eqn. (5).

$$F_b = (31 \times \beta - r) \times s \times w \text{ [kgf]} \tag{4}$$

$$P_b = \frac{F_b \times v}{367} \times \eta \quad \text{[kW]} \tag{5}$$

Here, η is power delivery efficiency. Consumed braking power P_b is obtained from eqn. (4) and (5), and regenerative peak current can be calculated as follows.

$$I_b = \frac{P_b}{V_{inv}} \text{ [kA]} \tag{6}$$

In order to estimate the optimal capacity of a regenerative inverter, we calculated W regenerative power generable from the covered section, and I_b regenerative peak current. From the conditions in Table 1 were obtained W =1480[kW] and I_b =3.5[kA], and the capacity of a regenerative inverter approximated 1.5MVA, 350% 1 minute. Because the capacity of a regenerative inverter determined through the approximation method does not consider line conditions and train operation conditions, it can be used only to review the whole system capacity rather than as a specification to install a regenerative inverter.

Table 1: Calculation conditions.

Item	Value	Item	Value
Number of cars, s	8 (4M4T)	Running resistance, r	10kg/ton
Headway, t_h	2.5 min	Maximum speed, v_m	80km/h
Weight, w	48ton/car	Commercial speed, v_s	35km/h
Decelerating speed, β	3.5km/h/s	Regenerative operation voltage, V_{inv}	1650V
Train ton-kilo capacity, k	50kW/1000ton.km	Power regeneration rate, λ_1	0.20
Power delivery efficiency, η	0.85	Regenerative braking efficiency rate, λ_2	0.65

4 PFS method

This section explains how to determine the capacity of a regenerative inverter using TPS and PFS. After PFS is performed with changing the capacity and the number of regenerative inverters to be installed, the regenerative power loss of the line is calculated. Here, the loss ratio of regenerative power means the ratio of regenerative power consumed as heat in the cars to the whole regenerative power generated as shown in eqn. (7). After the optimal position and the number of regenerative inverters are determined in a way of reducing the calculated loss ratio of regenerative power to the maximum, the root mean square of regenerative power (RMS power) and peak power are calculated. The effective regenerative power per hour calculated by eqn. (8) determines the continuous rating of regenerative inverter, and is used to determine peak power rating based on the maximum regenerative power rate and the braking time of motor cars.

$$\begin{aligned}&\textit{regenerative power loss}\\&=\frac{\textit{regenerative power} - \textit{output power of regenerative inverter}}{\textit{regenerative power}}\end{aligned} \tag{7}$$

$$P = \sqrt{\frac{1}{T_s}\int_{t_1}^{t_2} p_{reg}(t)^2\,dt} \tag{8}$$

Here, P is the root mean square of regenerative power $P_{reg}(t)$, and T_s was 1 hour. The method of determining the position, number and capacity of regenerative inverters to be installed is shown in the block diagram in fig. 3, and its details are as follows.

1. Perform PFS for the case that regenerative inverters are installed in all substations on the line.
2. Calculate the mean square of regenerative power of each substation, and rank the substations according to regenerative power.

3. Perform PFS after removing regenerative inverters from the two substations with the lowest regenerative power.
4. Again calculate the root mean square of regenerative power of each station with a regenerative inverter, and calculate the loss ratio of regenerative power for the whole line.
5. Perform PFS while removing regenerative inverters one by one from substations with the lowest regenerative power.
6. Draw the curve of the loss ratio of regenerative power according to the number of regenerative inverters installed in substations, and selects the curve that shows the largest reduction in regenerative power loss.

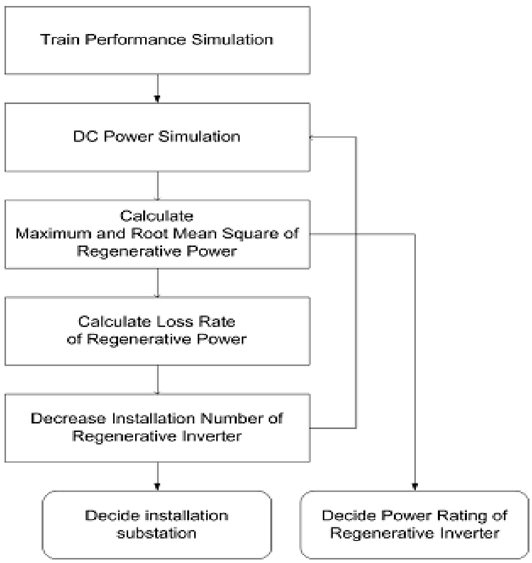


Figure 3: Flowchart for substation selection.

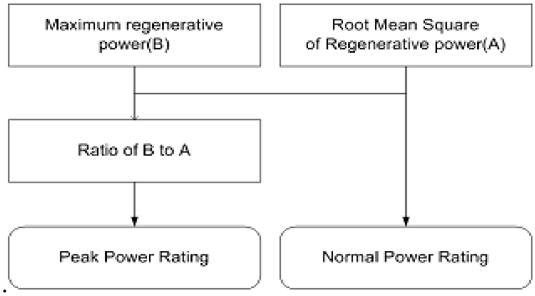


Figure 4: Flowchart for regenerative inverter capacity.

Once the position and number of regenerative inverters to be installed are determined, the rated capacity of regenerative inverter and the peak power capacity are calculated through the procedure in fig. 4. The rated capacity of a regenerative inverter sets the root mean square value of regenerative power obtained from substations, and peak power rating is determined by the ratio of the peak regenerative power to the root mean square value of regenerative power. In addition, because time for the rise of catenary line voltage caused by dump regenerative power of subway substations does not exceed 1 minute, peak power rating is assumed to continue for 1 minute.

We performed TPS and PFS using data on trains and lines of Seoul Subway Line 5 and 6. Figs. 5 and 6 show the catenary line voltage and the power consumption waveform of substations according to whether a regenerative inverter is installed or not. In the fig. 5, regenerative power generated by the power braking of motor cars is raising catenary line voltage instantaneously. Fig. 6 shows that regenerative power is absorbed by the substation and the variation of catenary line voltage is reduced.

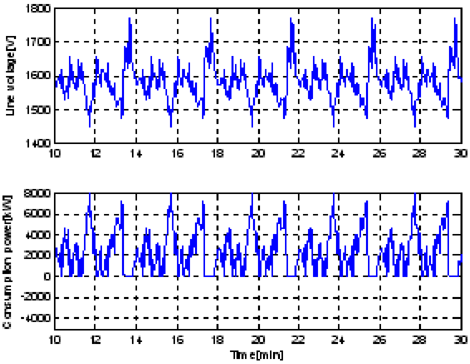


Figure 5: Seoul Line 6 Substation 8 without a regenerative inverter.

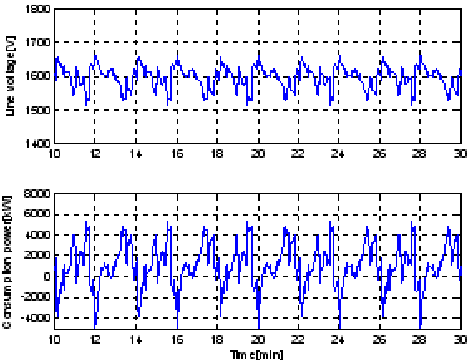
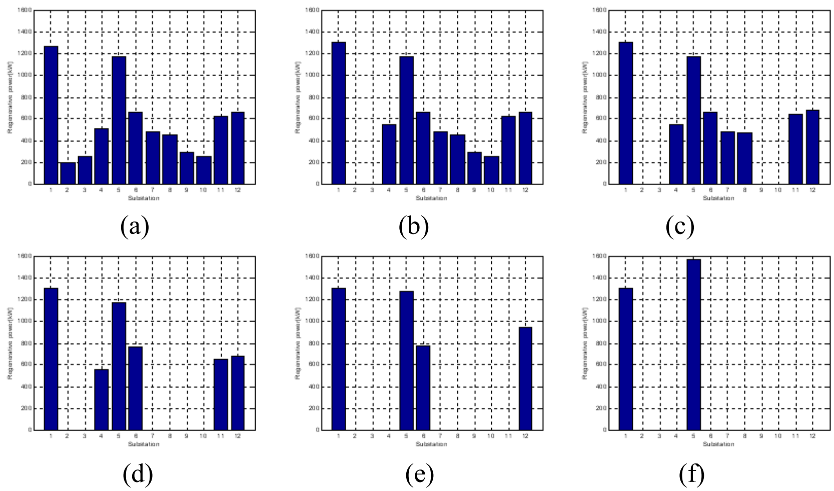


Figure 6: Seoul Line 6 Substation 12 with a regenerative inverter.

Fig. 7 shows absorbed regenerative power according to the number of substations with a regenerative inverter. Fig. 7 (a) is the case that regenerative inverters are installed in all substations. Regenerative power is different among substations because of differences in the gradient of line, distance between stations and training operation conditions. Figs. 7(b)~(f) show regenerative power of each substation while removing regenerative inverters one by one from the substation with the lowest regenerative power. As the number of substations with a regenerative inverter decreases, regenerative power at nearby substations with a regenerative inverter increases to some degree.



(a) (b) (c)

(d) (e) (f)

Figure 7: RMS of regenerative power in Seoul Line 6.

Because the unit price of a regenerative inverter and the initial cost of installation are high, it is economically inefficient to install regenerative inverters at all substations. Accordingly, we should find the position and number of substations to install regenerative inverters centering on substations with high regenerative power as shown in fig. 4, in a way of reducing the regenerative power loss of the whole line to the maximum.

Figs. 8 and 9 shows the curve of loss ratio of regenerative power changing according to the number of regenerative inverters in Seoul line 5 and 6. As a large-capacity regenerative inverter makes it possible to transmit more regenerative power to the supply grid, the loss ratio of regenerative power is reduced, and the curve of regenerative power loss goes down with the increase in the number of regenerative inverters installed. However, the reduction rate of regenerative power loss is not constant. It is because regenerative power is different among substations. As shown in figs. 8 and 9, reduction in the loss ratio of regenerative power decreases gradually with the increase in the number of substations with a regenerative inverter.

In case of Seoul Line 6, reduction in the loss ratio of regenerative power is largest when regenerative inverters installed at four substations. Because larger reduction in regenerative power loss is not expected from the installation of more regenerative inverters, it is desirable to install four regenerative inverters. As in fig. 7, the adequate capacity of regenerative inverter for Substation 1 and 5 is 1.5MVA and 1MVA for Substation 6 and 12. However, because Substation 5 and 6 are neighboring to each other, it is economically more efficient to install a regenerative inverter only at Substation 5 than at both.

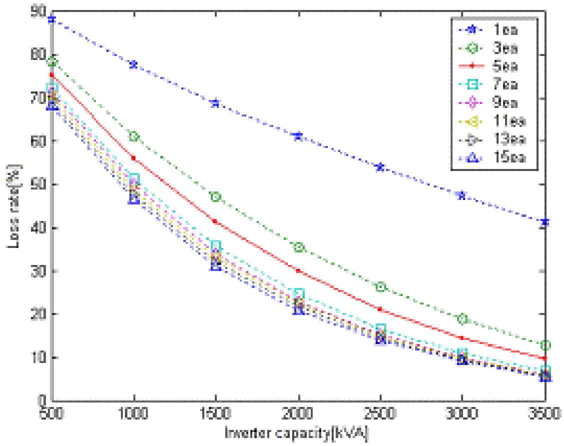


Figure 8: Loss rate of regenerative power in Seoul Line 5.

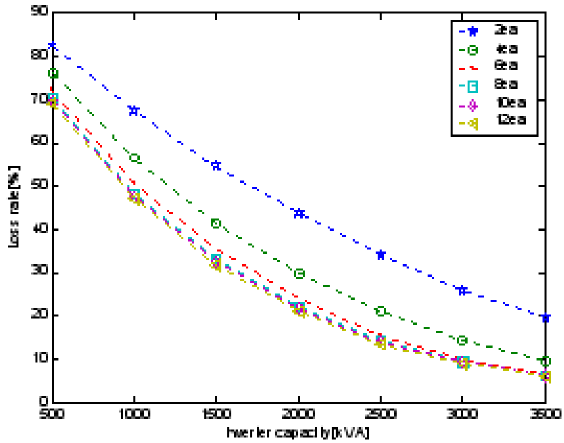


Figure 9: Loss rate of regenerative power in Seoul Line 6.

WIT Transactions on The Built Environment, Vol 88, © 2006 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)

We performed PFS for Seoul Subway line 5 and 6, and presented the results in table 2. The optimal capacity of regenerative inverter is determined by estimating rated capacity larger than the root mean square of regenerative power from each substation and determining peak power rating using the ratio of peak regenerative power to the rated capacity.

Table 2: Power simulation results of Seoul subways.

Line	Substation	RMS of regenerative power[kW]	Peak regenerative power[kW]	Ratio [%]
5	Euljiro 4-ga	1449	7102	490
	Haengdang	1284	5664	441
	Majang	1350	6554	485
6	Eungam	1305	6780	520
	Daeheung	1279	6481	507
	Samgakji	780	3827	491
	Shinnae	941	4833	514

5 Conclusions

The present study suggested a method of determining the position, number and optimal capacity of regenerative inverters that must be considered in installing regenerative inverters for DC 1500V electric railway system. We determined the capacity of regenerative inverter through simple calculation using the conditions of substations and train operation and the regeneration rate of other railway lines. We calculated the loss ratio of regenerative power and the root mean square of regenerative power for each substation by performing TPS and PFS, and determined the position and number of regenerative inverters considering change in the loss ratio of regenerative power. Applying TPS and PFS to Seoul Subway line 5and 6, we obtained the optimal position, number and capacity of regenerative inverters to be installed.

References

[1] S.K. Jung et al., “Right Rail transit system development”, Korea Railroad Research Institute, 2002.

[2] Electric Railway DC Power Supply System Investigation Committee, “Phenomena of Power Supply System Including Regenerative Cars and Future Directions”, Technological Report No. 296 of Japanese Institute of Electrical Engineers, 1989