

Experimental Study on Increasing Regenerative Power by Improving Regenerative Brake Control of Rail Vehicles in DC-electrified Railways

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In a DC-electrified railway system, the torque control of traction motors according to the input DC voltage of the traction inverter is generally applied during regeneration. It is effective in increasing the gain of this regenerative brake control for utilization of more regenerative brake power. In this article, the authors investigated the mechanism of increasing regenerative power when the regenerative brake control improved by theoretical analysis and an experimental on-track test.

Keywords: DC-electrified railway system, regenerative brake control, on-track test, regenerative power

1. Introduction

In DC-electrified railway system, the regenerative brake power must be consumed by the other powering train because the diode rectifier is generally utilized in substations. Therefore, motor torque control according to input voltage of traction inverter is commonly applied to railway vehicle for the purpose of control of regenerative power corresponding to load power. This control in regeneration is called as “light-load regenerative brake control⁽¹⁾. ” Figure 1 shows an overview of whole system of light-load regenerative brake control. In Fig. 1, $I_{q\max}$ is the maximum q-axis current. $V_{c\max}$ is fixed to avoid overvoltage of traction inverters. In terms of the control gain k_p , which is corresponding to V_{clim} , increasing k_p makes it possible to transmit regenerative power at high v_{creg} during regeneration. It is effective to keep higher Filter Capacitor (FC) voltage v_{creg} for the increase of regenerative power considering voltage drop of feeder resistance between regenerating train and powering train. However, ACR of the motor current, which is assumed as an one-order delay, is placed in the inner loop of the light-load regenerative brake controller. Therefore, excessive k_p makes the control system unstable since k_p equals to the feedback gain of the control system⁽²⁾.

Analytical method to design the gain of light-load regenerative brake control system has been proposed⁽³⁾. However, the effect on increasing regenerative power when k_p increased has not been considered before. Therefore, this article reveals the mechanism of increase of regenerative power when increasing k_p by both a theoretical analysis and an experimental on-track test.

2. Light-load Regenerative Brake Control System

In this analysis, loss of inverter isn't considered, and $v_{1d}i_{1d}$ is assumed small enough compared with $v_{1q}i_{1q}$. Then, (1) is established because the power of AC and DC of inverter should be equaled. Here, v_{1d} and i_{1d} are d-axis voltage and current, respectively. v_{1q} and i_{1q} are q-axis voltage and

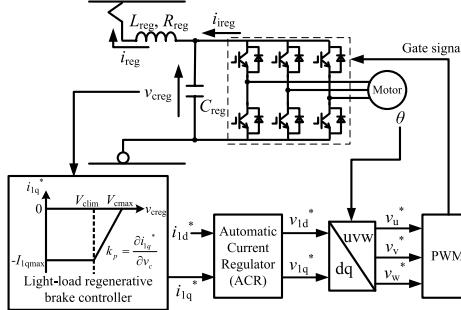


Fig. 1. Traction circuit of railway vehicle and light-load regenerative brake control system

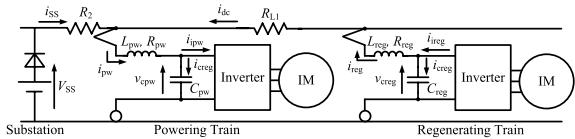


Fig. 2. Assumed DC-electrified railway system

current, respectively.

$$v_{creg}i_{reg} = v_{1q}i_{1q} \dots \dots \dots (1)$$

The light-load regenerative brake control which is shown in Fig. 1, is expressed by (2). In (2), positive value stands for regeneration.

$$i_{1q}^* = \begin{cases} I_{1q\max} & (v_{creg} < V_{clim}) \\ k_p(V_{c\max} - v_{creg}) & (V_{clim} \leq v_{creg} < V_{c\max}) \\ 0 & (V_{c\max} \leq v_{creg}) \end{cases} \dots \dots \dots (2)$$

Furthermore, if q-axis current is completely controlled as reference value, (3) is obtained by substituting (2) into (1).

$$i_{reg} = \begin{cases} v_{1q}I_{1q\max}v_{creg}^{-1} & (v_{creg} < V_{clim}) \\ k_p v_{1q}(V_{c\max}v_{creg}^{-1} - 1) & (V_{clim} \leq v_{creg} < V_{c\max}) \\ 0 & (V_{c\max} \leq v_{creg}) \end{cases} \dots \dots \dots (3)$$

Assumed DC-electrified railway system is shown in Fig. 2. This letter considers a state in which regenerative brake must be applied while allowing the FC voltage to rise because of

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Table 1. Parameters for theoretical analysis

Symbol	Quantity	Values
V_{clim}	Voltage to start to apply light-load regenerative brake control	1700 [V] (Pattern 1) 1781 [V] (Pattern 2)
V_{cmax}	Voltage to stop applying light-load regenerative brake control	1830 [V]
I_{1qmax}	Maximum q-axis current	225 [A]
v_{1q}	q-axis voltage	1474 [V]
R_1	Sum of feeder resistance R_{L1} and resistance of filter reactor (R_{pw} , R_{reg})	0.542 [Ω]
v_{cpw}	FC voltage of powering train	1620 [V]

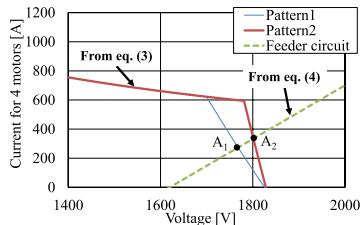


Fig. 3. Theoretical analysis on the static characteristics

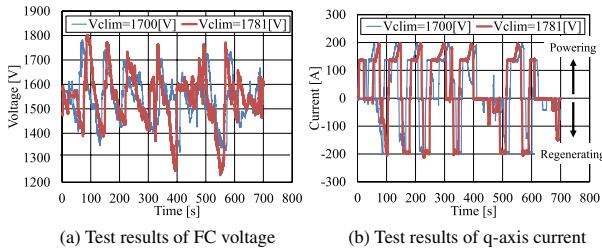


Fig. 4. Results of on-track test

the resistance between the regenerating train and the load. In this case, increase of regenerative power can be achieved by increasing the gain of light-load regenerative brake control k_p .

In Fig. 2, the constraint of the feeder circuit is expressed by (4).

$$i_{ireg} = R_1^{-1}(v_{creg} - v_{cpw}) \dots \dots \dots \quad (4)$$

Where, R_1 stands for the feeder resistance between regenerating train and powering train. Also, in the static analysis in this chapter, v_{cpw} is assumed as 1620 [V]. The static characteristics are shown in Fig. 5 based on Table 1, (3) and (4). Pattern 1 represents conventional case. On the other hand, k_p in pattern 2 is designed by utilizing the proposed method in Ref. (3). Figure 3 shows that the operating point moves to A_2 from A_1 by increasing k_p . From the coordinate of the operating point A_1 , the regenerative power in the case of pattern 1 is 494 kW. On the other hand, the regenerative power of pattern 2 is 608 kW from the coordinate of the operating point of A_2 .

3. Verification of Increase of Regenerative Power

3.1 Experimental Conditions In this chapter, the effect on increasing regenerative power by increasing k_p is verified by an experimental on-track test which is carried out in Odakyu Tama line. The test train consists in 6 cars. In the experimental on-track test, 2 patterns of the gain of light-load regenerative brake control, which are shown in Table 1, are utilized. V_{cmax} is set to 1830 V among all patterns.

3.2 Results of Experimental Test The experimental results of FC voltage and q-axis current are shown in Fig. 4. Where, q-axis current in Fig. 4(b) is for 1 motor.

Figure 4(a) shows that Pattern 2 keeps higher FC voltage

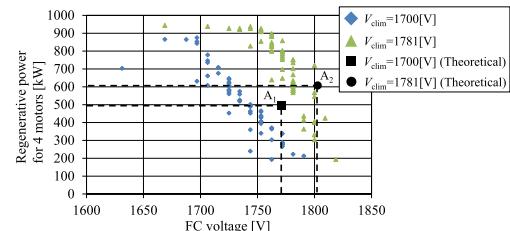


Fig. 5. Operating points at the experimental on-track test

Table 2. Results of the experimental on-track test

V_{clim} [V]	1700	1781
Powering energy [kWh]	1902	1911
Regenerative energy [kWh]	648	776

during regeneration than Pattern 1. Also, Fig. 4(b) shows that q-axis current in Pattern 2 is close to the maximum value during regeneration while that in Pattern 1 is much smaller than its maximum value especially in the high speed range.

In Fig. 5, the maximum FC voltage at each brake section and regenerative brake power at that time are plotted. Operating points in the theoretical analysis (A_1 , A_2) are also shown in Fig. 5. Figure 5 shows that the operating point moves to the direction away from the origin according to V_{clim} , that is, the region where both FC voltage and regenerative power are high. Figure 5 also shows that the tendency of increase of regenerative power and FC voltage is similar to that of theoretical analysis. Therefore, the result of the theoretical analysis is verified by the experimental on-track test.

The experimental results of regenerative energy, powering energy are shown in Table 2. Each value of the energy in Table 2 is for 1 train (6 cars) while running Odakyu Tama line 12 times. Table 2 shows that regenerative energy becomes higher in accordance with V_{clim} . This is because increasing V_{clim} makes it possible to transmit more regenerative power by keeping high FC voltage during regeneration. From Table 2, 19.8% increase of regenerative energy is verified by increasing V_{clim} from pattern 1 to pattern 2.

4. Conclusions

In this article, the mechanism of increasing regenerative power when the gain of light-load regenerative brake control k_p increased is considered by the theoretical analysis on the static state and the experimental on-track test. Results of the theoretical analysis revealed that regenerative power is increased in the case of higher k_p . Also, the effect on keeping higher FC voltage and increase of regenerative power by increasing k_p is verified by the on-track test. As a result of this effect, 19.8% increase of regenerative energy is revealed compared with the conventional system.

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