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A Study on Peak Power Reduction using Regenerative Energy in Railway Systems through DC Subsystem Interconnection

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Abstract – Owing to the consistent increase in energy efficiency issues, studies for improving regenerative energy utilization have been receiving attention in the Urban DC railway systems, where currently, the utilization of regenerative energy is low due to the lack of a specific plan for using this energy. The regenerative energy in railway systems has a low efficiency problem which results in the increase of the catenary voltage and a possibility to create problems to the electrical devices connected to the system. This paper deals with the power integration of large urban railway subsystems to improve regenerative energy utilization where the railway subsystems are integrated with other railway subsystems to improve the energy efficiency. Through the case studies, to find the realistic effect of integrated operation, the Seoul Metro subsystems, namely Line 5 and Line 7, has been applied. Also, evaluation for the electricity cost saving has been performed by using KEPCO electricity cost table.

Keywords: DC railway, Regenerative braking, Regenerative energy, Peak power reduction, Integrated system.

1. Introduction

The increase in the interest of energy conservation recently across industries implies to find reliable technical solution in order to reduce the energy consumption. In the field of power industries, many studies on high-efficiency issues and green power grid are under progress. Furthermore, the research on the realization of a more environmentally friendly and efficient urban railway system is required. The regeneration of braking energy is one of the most promising sources of energy savings to railway power system operators. Especially, railway vehicles have the unique characteristics of power consumption fluctuation which vary according to the location and time. This power variance means that the electric railway systems comprises of variable loads which consume huge positive power on acceleration and negative power on breaking [1-2]. A substation has to supply the power demanded when vehicles in the substation's range are in their starting phase, and this can momentarily lead to high power demand. This peak power is measured at each substation and used to calculate basic fees. For railway systems that are operated with relatively long headways, the basic rate measured in this way is close to 25% of the overall electricity cost.

To overcome this, several studies have been conducted recently to reduce peak power by the utilization of regenerative energy. In the current railway system, the regenerative energy is dissipated on board resistances or consumed by adjacent trains that are in the starting phase [3]. However, this energy is generally not utilized because at the moment of dissipation there are not many trains that are presently in the starting phase. In this context, in order to improve the regenerative energy utilization, comprehensive research has been done such as installing energy storage device or regenerative inverters [4-9].

In the case of research that improves efficiency through energy storage device; various studies have been done such as application of different types of storage device, control strategy, etc. In the case of research that applies the battery, the battery life when considering the cost is difficult to obtain economic feasibility; in addition, there is a problem with high initial investment costs. With respect to the installation site, installation on the vehicle or on the railway substation are being considered, but when considering the installation on the vehicle, sufficient space must be required, and high instantaneous capacity is needed. In the case of installation on the substations, there is a problem of high wiring losses in the process of charging and discharging. In the case of installing a regenerative inverter, high quality regenerative power cannot be supplied due to the harmonics generated from the inverter [10-12].

In this paper, the plan based on integrated operation of several railway subsystems, which has low initial investment cost and needs less maintenance, is proposed to improve the utilization of regenerative energy. DC linkages for integration systems have not been studied until now, and an algorithm for the selection of the connection point does not

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exist. Through the operation of the integrated railway system, more vehicles can consume the regenerative energy and consequently increase the utilization.

2. System Configuration for Integrated DC Railway Systems

2.1 Regenerative energy utilization

For nearby vehicles in the starting-phase to the front and rear directions at an appropriate braking moment of a specific vehicle, the utilization of the regenerative energy that occurs is facilitated, but if there is a significant distance from the vehicles in the starting-phase, the regenerative energy is not delivered, and is instead wasted as heat. Based on these characteristics of the railway system, the present paper is intended to facilitate the transfer of the regenerative energy of nearby vehicles at a connection point.

In an urban railway system, several lines are operated, and transfer stations exist at locations geographically close to each other. With a transfer station as the center, a system can transfer regenerative energy to another line by DC integration of multiple lines. Fig. 1 is the concept of the integrated system which proposed in this paper. Through the interconnected system located in transfer station, the surplus regenerative energy could be transferred to other railway power system.

2.2 Power flow analysis for DC railway system

By calculating the loop equations, the analysis of circuit for calculation of power flow is possible [13]. Fig. 2 shows the railway power system network. From this network, the node equation can be derived as follows:

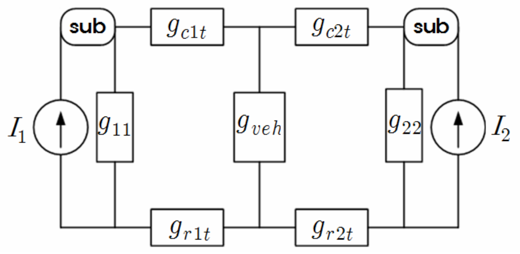

Fig. 2. Equivalent circuit of railway system

$$\begin{vmatrix} g_{11}+g_{c1t} & 0 & -g_{c1t} & 0 \\ 0 & g_{22}+g_{c2t} & -g_{c2t} & 0 \\ -g_{c1t} & -g_{c2t} & g_{c1t}+g_{c2t}+g_{veh} & -g_{veh} \\ 0 & 0 & -g_{veh} & g_{veh}+g_{r1t}+g_{r2t} \end{vmatrix} \begin{vmatrix} V_1 \\ V_2 \\ V_{c1} \\ V_{r1} \end{vmatrix} = \begin{vmatrix} I_1 \\ I_2 \\ 0 \\ 0 \end{vmatrix} \tag{1}$$

where g_{veh} is the equivalent admittance of the vehicle;
g_{ii} is the admittance of the substation;
g_{clt} is the admittance of the catenary between the vehicle and substation;
g_{rlt} is the admittance of the rail between the vehicle and substation;
V_i is the voltage of the vehicle's catenary;
V_{cl} is the voltage of the vehicle's rail;
I_i is the equivalent current source of the substation.

The relation of the voltage and equivalent impedance between both sides of the vehicle defined as;

$$g_{veh} = \frac{P_{veh1}}{(V_{c1}-V_{r1})^2} \tag{2}$$

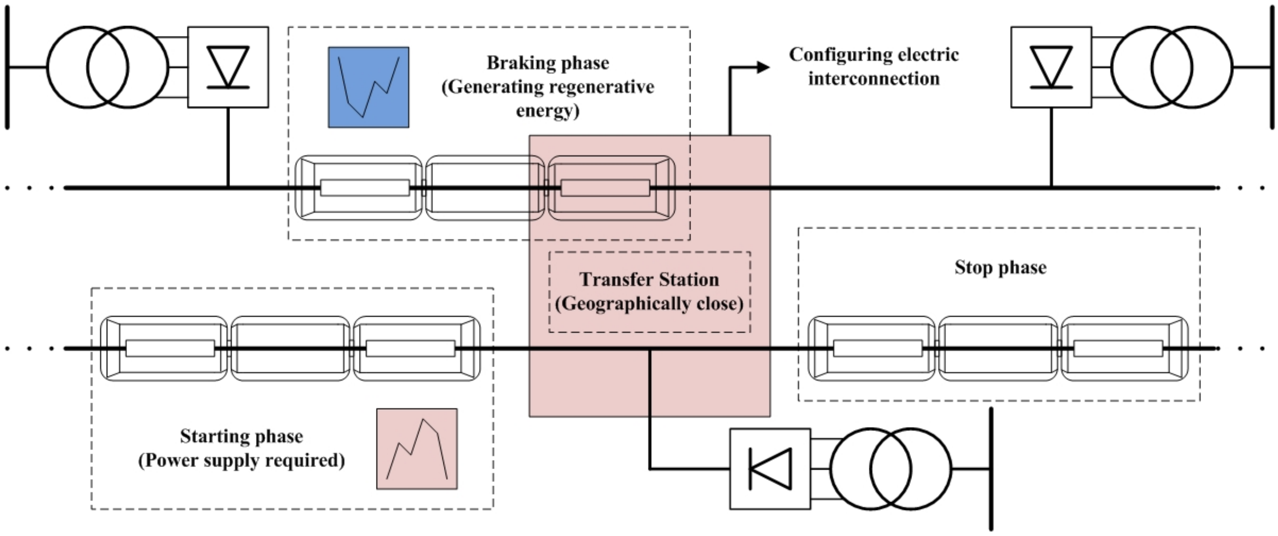

Fig. 1. Concept of integrated DC railway system

where P_{veh} is the active power of the vehicle.

Since I1 and I2 have been determined, the solution of the voltage at each node can be obtained by iteration. However, in the iterative process, since Eq. (2) which is a formula related to the square of voltage used to update gveh, there are some problems such as the rate of convergence or the number of iterations. To overcome the problem of divergence, the conversion process is required to modify Eq. (2) in the form of conductance matrix and voltage, current matrix. By utilizing Eq. (3), Eqs. (1) and (2) are transformed to Eqs. (4) and (5).

$$g_{veh}(V_{c1}-V_{r1}) = I_{veh} \tag{3}$$

where I_{veh} is the equivalent current of the vehicle;

$$\begin{vmatrix} g_{11}+g_{c1t} & 0 & -g_{c1t} & 0 \\ 0 & g_{22}+g_{c2t} & -g_{c2t} & 0 \\ -g_{c1t} & -g_{c2t} & g_{c1t}+g_{c2t} & 0 \\ 0 & 0 & 0 & g_{r1t}+g_{r2t} \end{vmatrix} \begin{vmatrix} V_1 \\ V_2 \\ V_{c1} \\ V_{r1} \end{vmatrix} = \begin{vmatrix} I_1 \\ I_2 \\ 0 \\ 0 \end{vmatrix} \tag{4}$$

$$I_{veh1} = \frac{P_{veh1}}{(V_{c1}-V_{r1})} \tag{5}$$

These improvements of the node equation makes the calculation process less sensitive in the initial state with voltage error when Iveh is updated during the iteration process due to the primary relationship between voltage and power consumption. This process reduces the calculation amount by increasing the rate of convergence of the iteration and reduces the number of iteration.

Fig. 3 represents the proposed flowchart of the power flow algorithm for the urban railway system. The proposed algorithm is configured by adding the integration process to the existing configuration. The highlighted sections are the integrated part, and by this process, existing algorithm enable to consider several line for integration. The algorithm is designed to perform calculations per second during headway based on the characteristics of the railway system. Before beginning to perform calculations, the location of the vehicle are determined based on a fixed location of the substation using the TPS(Train Performance Simulator) data.

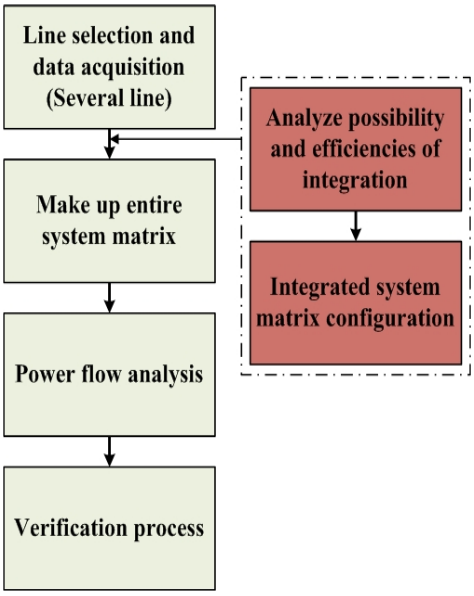

Fig. 3. Power flow flowchart of railway system

2.3 Analysis plan for integrated DC railway system

The configuration and size of the matrix are changed when the system is integrated. Particularly, the size of the system matrix would be almost double after the addition of an integrated line. Fig. 4 presents a flowchart of the proposed power flow algorithm for the system integration.

The node equations can be integrated using the process presented. If a substation exists at a connection point, the node equation is configured by adding admittance values between interconnection points. Otherwise, the progress would proceed by adding a dummy bus which is added to the calculation process. Eq. (6) is the integrated result of the proposed system integration process.

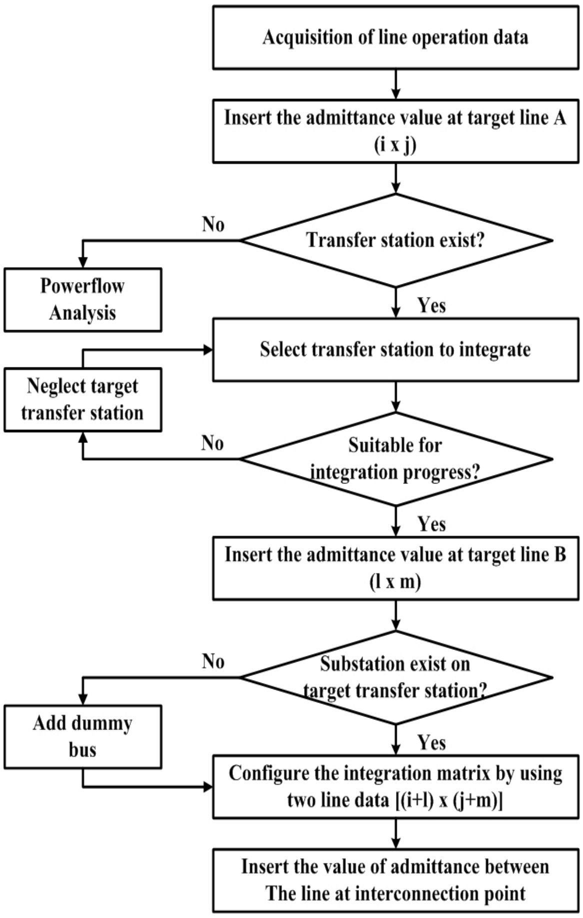

Fig. 4. Flowchart of system integration

$$\begin{vmatrix} \begin{matrix} a_{11} & \cdots & a_{1(nsub+2nveh)} \\ \vdots & \ddots & \\ a_{(nsub+2nveh)1} & & a_{(nsub+2nveh)(nsub+4nveh)} \end{matrix} & A \\ B & \begin{matrix} \alpha_{11} & \cdots & \alpha_{1(ksub+2kveh)} \\ \vdots & \ddots & \\ \alpha_{(ksub+2kveh)1} & & \alpha_{(ksub+2kveh)(ksub+4kveh)} \end{matrix} \end{vmatrix} \begin{vmatrix} V_{s1} \\ \vdots \\ V_{drnv} \\ V_{s1} \\ \vdots \\ V_{drkv} \end{vmatrix} = \begin{vmatrix} I_{s1} \\ \vdots \\ I_{drnv} \\ I_{s1} \\ \vdots \\ I_{drkv} \end{vmatrix} \tag{6}$$

where a_{xx} is the admittance value of Line 1;
α_{yy} is the admittance value of Line 2.

The integration matrix of each node equation is configured according to Eq. (6). The other parts of the node equation, represented as A and B, are sparse matrices, because each line has not any integration section excepting connection point. A mutual admittance value of the interconnection point is inserted at certain internal points of A and B, which are also symmetrical matrices.

3. Individual Operation

3.1 Target line information

Before simulating the integrated system, in order to confirm the efficiency improvement, the power supply and demand was simulated by selecting two 1500 V DC railway system. Seoul Subway Line 5 and Line 7 are geographically close and currently are not electrically connected. Tables 1-2 show the location data for the Seoul Subway Line 5 and 7(the black marked section indicates the location of the substation).

Table 1. Location data of station and substation. (Line 5)

Sta No.	Loca.	Sta No.	Loca.	Sta No.	Loca.	Sta No.	Loca.
510	2,900	521	14,706	532	25,764	543	36,444
511	3,611	522	16,497	533	56,975	544	38,350
512	4,839	523	16,497	534	28,339	545	39,046
513	6,178	524	17,508	535	29,200	546	40,400
514	7,201	525	18,216	536	30,030	547	42,235
515	8,392	526	19,764	537	30,913	548	43,519
516	9,479	527	20,484	538	31,816	549	44,318
517	10,584	528	22,184	539	32,826	550	45,119
518	11,676	529	23,084	540	33,585	551	45,976
519	12,979	530	24,202	541	34,325	552	46,903
520	13,805	531	25,084	542	35,235	553	47,993

Table 1. Location data of station and substation. (Line 7)

Sta No.	Loca.	Sta No.	Loca.	Sta No.	Loca.	Sta No.	Loca.
709	1,585	720	13,675	731	25,063	742	38,376
710	2,641	721	14,535	732	26,403	743	38,986
711	3,900	722	15,656	733	27,003	744	40,443
712	5,479	723	16,536	734	28,119	745	41,620
713	6,900	724	17,377	735	30,343	746	42,160
714	7,740	725	18,337	736	31,423	747	43,780
715	8,725	726	19,218	737	32,177	748	45,240
716	10,055	727	20,007	738	34,368	749	46,740
717	10,905	728	21,193	739	35,260	750	48,680
718	11,305	729	22,700	740	36,281		
719	12,705	730	23,150	741	37,352		

3.2 Energy efficiency analysis

The power flow algorithm for the urban railway system in this paper, receives the calculated position data and power consumption data every second from the TPS as input. Power flow calculation for the railway system should update the conductance matrix by considering the motion of the vehicle, and should change the power consumption according to the vehicle's operating mode. Table 3 is the line operating condition of the simulation.

3.3 Line 5 analysis

The power flow calculation for Seoul Subway Line 5 considered the conditions enlisted in Table 3 and takes into consideration 25 vehicles' operation each of northbound lane and southbound lane. Total load was 19133.6 kWh and total power supply was 29992.67 kWh.

3.4 Line 7 analysis

The power flow calculation for Seoul Subway Line 7 considered conditions enlisted in Table 3 and takes into consideration 24 vehicles' operation each of northbound lane and southbound lane. The total load was 18679.1 kWh and total power supply was 25164.08 kWh. Table 4 shows the total load and supply in individual operating condition. In this paper, the total supply is including regenerative energy produced by the regenerative braking process.

Table 3. Operation conditions of Simulation.

Simulated conditions		Seoul Subway	Line 5, Line 7
Operation data	Rated volt.	1,500	[V]
	Stop hours	30	[sec]
	Total operating time	4,162	[sec]
	Headway	180	[sec]
Substation data	No-load volt.	1,650	[V]
	Impedance	0.02956	[Ω]
Transmission data	Transmission line impedance	0.0203	[Ω/km]
	Rail impedance	0.000464	[Ω/km]

Table 4. Load supply status of Seoul Subway Line.

Case	Total load (kWh)	Total supply (kWh)
Line 5	19133.6	29992.67
Line 7	18679.1	25164.08
Total	37812.7	55156.75

4. Integrated Operation

4.1 Target line information

Geographically close interconnection of two lines has many advantages on construction cost. Additionally, if the substation is located at the expected connection point, the effect of these processes could be more feasible. To reflect these above conditions, the transfer station named Gun-ja between the Seoul Subway Line 5 and Line 7 were chosen. The interconnected station number is 544 at Line 5 and 725 at Line 7 in Tables 1-2. Fig. 5 is a flowchart of power flow calculation algorithm reflecting the two lines interconnection. When there is a case where the line is without the substation, it is assumed that the substation is installed by adding a dummy bus.

4.2 Analysis of energy efficiency

The power flow calculation for Seoul Subway Line 5 and 7 was performed at the same operating condition. The total load was 37812.7 kWh and total power supply was 54286.26 kWh. 870.46 kWh of power supply was reduced by the process of integration. Table 5 shows the total load and supply in integrated operating condition.

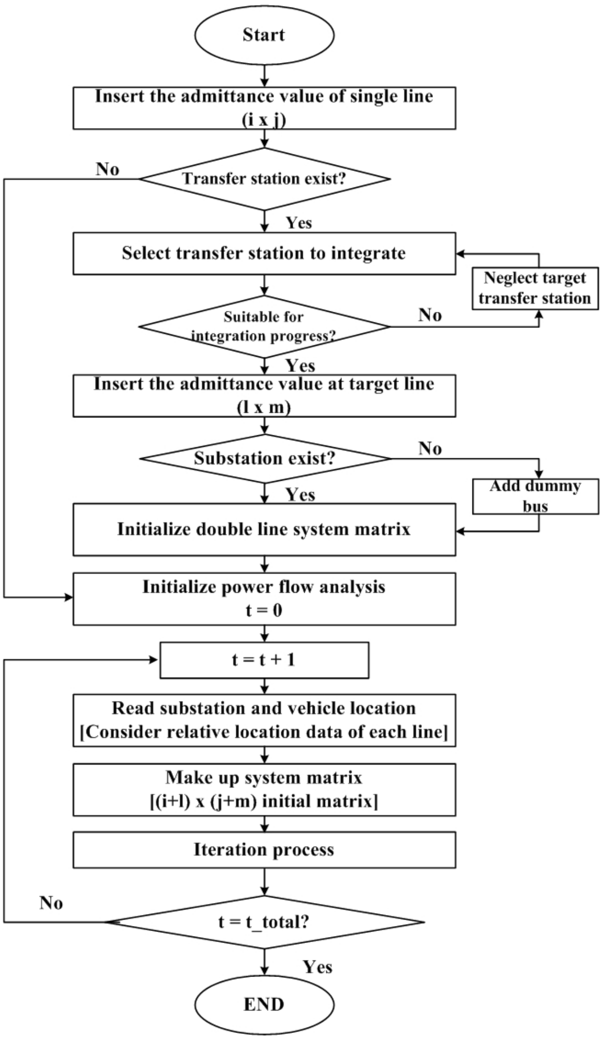

Fig. 5. Entire power flow analysis flowchart of integrated railway system

Table 5. Expectation of power supply in integrated system

Case	Total load (kWh)	Total supply (kWh)
Line 5	19133.6	29569.03
Line 7	18679.1	24717.25
Total	37812.7	54286.28

4.3 Analysis of peak power consumption

The subway substation in Korea measures the peak power every 15 minute to estimate the basic fee. Reducing peak power consumption by sharing regenerative energy between neighborhood vehicles through interconnection could save operating costs. Geographically distant location from interconnection point is not expected to change peak power significantly; regenerative energy utilization improvements also would be negligible. Figs. 6-9 shows the comparison of the power change curve before and after interconnection at the interconnection point and nearby substation (Kwang-na-ru station number is 546 in Table 1, Sang-bong and Chung-dam station number are 720, 729 in Table 2).

The peak power of Gun-ja substation was significantly decreased and substations in the neighborhood were also

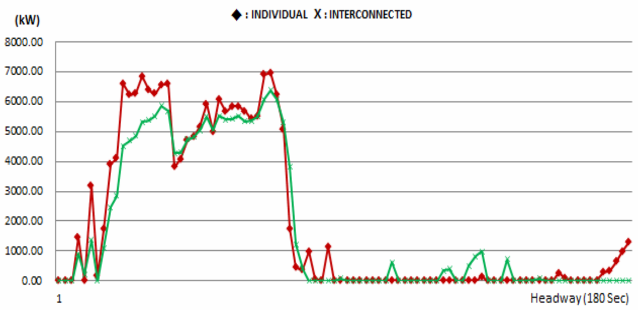

Fig. 6. Gun-ja substation power change curve

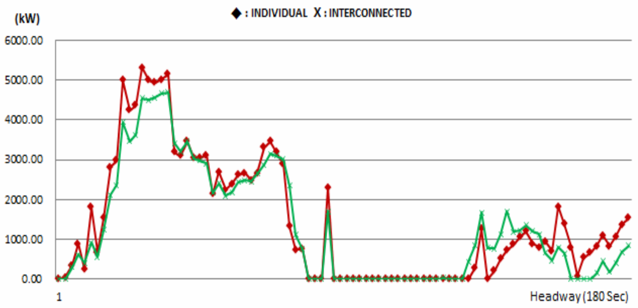

Fig. 7. Kwang-na-ru substation power change curve

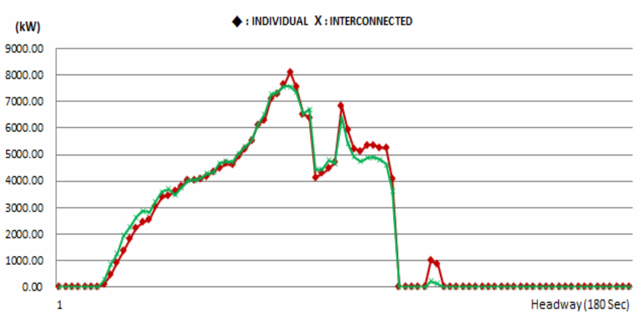

Fig. 8. Sang-bong substation power change curve

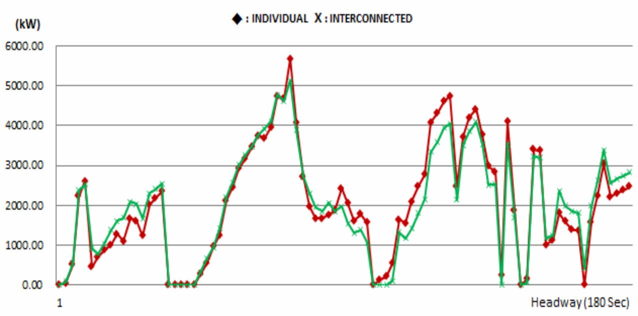

Fig. 9. Chung-dam substation power change curve

Table 6. Most effective substation and saving cost calculation (Line 5)

Substation	Ma-jang	**Gun-ja**	**Kwang-na-ru**	Gang-dong	Ko-duck
Peak (kW) [Individual]	11207.6	**6959.1**	**5315.1**	6022.2	8878.1
Peak (kW) [integrated]	11055.6	**6388.1**	**4699.4**	5780	8731.1
Cost saving (1,000₩ /month)	980	**3,680**	**3,970**	1,560	920

Table 7. Most effective substation and saving cost calculation (Line 7)

Substation	Tae-reung	**Sang-bong**	Kun-kuk Univ.	**Chung-dam**	Non-hyun
Peak (kW) [Individual]	6554.21	**8093.28**	5315.11	**5672.61**	8890.1
Peak (kW) [integrated]	6450.45	**7565.01**	4977.20	**5132.53**	8705.04
Cost saving (1,000₩ /month)	670	**3,410**	2,190	**3,480**	1,190

improved. The effect of the utilization of regenerative energy is expected to be limited due to the wiring loss problem. Saved costs by peak power reduction were calculated using KEPCO electricity cost table [15]. Table 6-7 represents the substation most effective in peak power reduction (Ma-jang, Gang-dong and Ko-duck station number are 541, 548, 552 in Table 1, Tae-reung, Kun-kuk Univ. and Non-hyun station number are 717, 727, 732 in Table 2).

In Line 5, interconnection point and nearby substation were significantly reduced at peak power. In the case of Kwang-na-ru substation, a 615.62 kW decrease at peak power could be observed. In Line 7, Sang-bong substation and Chung-dam substation were significantly decreased at peak power, including saving cost.

5. Conclusion

In this paper, the system integration between electrically separated railway systems was proposed. To interpret the effect of improvement about efficiency in the integrated system, the urban railway system and analysis algorithm were simulated using Compaq Visual Fortran. The peak power reduction of the integrated system could be confirmed through case studies. In terms of energy supply, due to the wiring loss, regenerative energy delivery is limited to a certain area and entire power supply improvement is relatively small due to this factor. When analyzed in a particular region, the energy utilization shows positive effects on voltage stability [14]. In addition, peak power reduction of nearby substation was confirmed through simulation. To investigate the effects of the reduced operating costs, the reduction in electricity prices has been calculated by using KEPCO electricity cost table [15].

Acknowledgements

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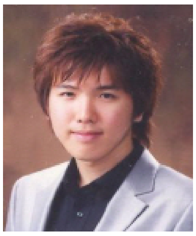

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