Journal of Energy and Power Engineering 15 (2021) 243-252
doi: 10.17265/1934-8975/2021.07.002

A Study on the Analysis of Load Flow for Railway DC System

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Abstract: Urban railway systems differ greatly from general power systems in that they use direct current (DC) power supply and that the location and power requirements of the loads change. The position and power consumption of the load shall be interpreted continuously every second, or in a fixed unit of time, for a specific period of time during which the operating conditions are repeated. The additional analysis of energy-saving systems being considered as energy efficiency improvement methods requires more complex load flow analysis algorithms. Simulations are performed load flow every time step. The power of an electric railway power feeding system is the power consumed or produced by a train. Because the amount and position of the load change rapidly over time, load flow analysis continues over time. Therefore, based on the method of obtaining solutions by constructing node equations for load flow analysis in this study, load flow analysis was performed through algorithms with energy-saving systems applied.Both thetrain performance simulation (TPS) and power simulation results show that the actual measurement data are estimated almost equally.

Key words: Load flow, railway, TPS, power simulation, energy storage system (ESS).

1. Introduction

Urban railway systems differ greatly from general power systems in that they usedirect current(DC) power supply and that the location and power requirements of the loads change. The position and power consumption of the load shall be interpreted continuously every second, or in a fixed unit of time, for a specific period of time during which the operating conditions are repeated[1].

The substation of the DC urban railway is a forward diode system. Electric trains are characterized by fluctuating loads and moving loads at the same time. The voltage supply method of the DC urban railway is to supply the alternating current (AC) voltage supplied by KEPCO by rectifying it through a rectifier and converting it into DC voltage. The rectifier is connected in a forward diodemanner, so the regenerative power of the train is not returned to the power source. If the regenerative power of the train is returned to the contact wire, the instantaneous power generated during regeneration will raise the contact wire voltage, destabilizing the system and causing the train to fail. In addition, if the surrounding train fails to accommodate that voltage, the regenerative power generated is converted into thermal energy by the resistance of the contact wire[2].

Each component of the power supply system (substation, contact wire, rail and train) is converted into an electrical equivalent circuit for the interpretation of moving loads such as trains and energy saving systems for energy efficiency improvement. With each parameter, the equivalent circuit is constructed, and the equivalent circuit is interpreted using a formula. The calculation of electricity in a train is the power required by the train to obtain the acceleration required by the train at a given position in the train. The operating curve of the train suitable for the DC feeding system analysis uses the characteristics of power calculated by location through Train Performance Simulation(TPS).

The additional analysis of energy-saving systems being considered as energy efficiency improvement methods requires more complex load flow

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2. Train Performance Simulation(TPS)

TPS is a program that simulates the driving performance of a train by creating a model that reflects existing railway or planned route information. It is used to evaluate train operation efficiency and operation performance, such as operation time and energy consumption by route, almost similar to actual opening, to determine the adequacy of new routes, including ground facilities such as track, power, and signal.

TPS is developed to provide various train operation performance curves through input data (electric vehicle information, track information, operating conditions information, etc.) as shown in Fig. 1. Various train options such as traction, output, acceleration, etc. and track options such as branching and isolation periods were configured to allow simulation to be suitable for the latest railway environment.

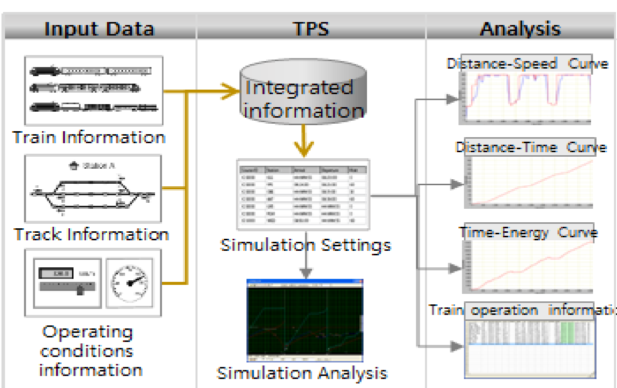


Fig. 1 TPSconfiguration diagram.

3. DC Feeding Power Simulation

Information about load changing over time is calculated by TPS, and power simulations bring information calculated from outside into the data format that the program needs. In addition, information on the power supply system is needed to prepare the equivalent circuit of the system. In other words, data such as the location, capacity, and resistance of the substation are needed. Fig. 2 summarizes the inputs and key functions of information on DC feeding power simulations.

The main functions of DC feeding power simulation are as follows.

(1) Power Supplied by Substation

During the simulation, the maximum load, average load, and maximum current of each substation are analyzed.

(2) Analysis of Contact Wire Current and Voltage

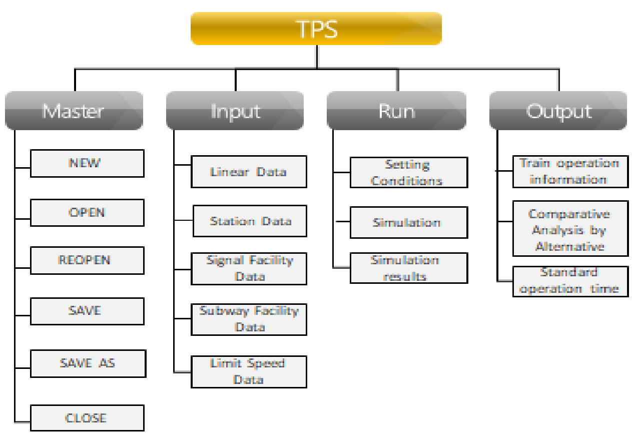
During the simulation, the current and voltage of the contact wire at the substation and vehicle position are analyzed for each time step.

(3) Analysis of the Maximum and Minimum Voltages of a Train

The maximum and minimum voltages of the vehicle are analyzed during the simulation.

(4) Analysis of Energy Storage System (ESS)Charge/Discharge Power and Energy Savings

During the simulation, the power charged and discharged by the ESS is analyzed.



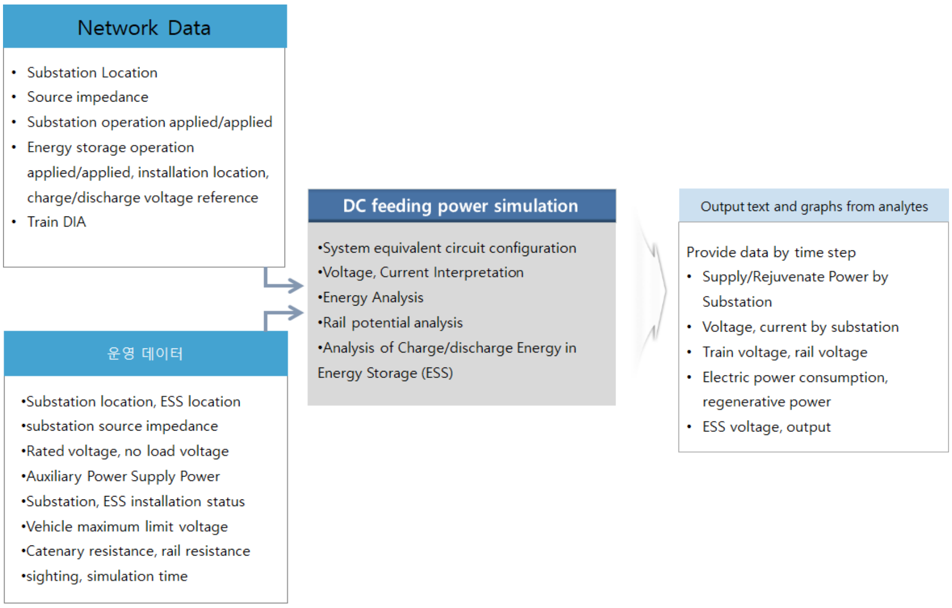


Fig. 2 Key features of DC feeding power simulation.

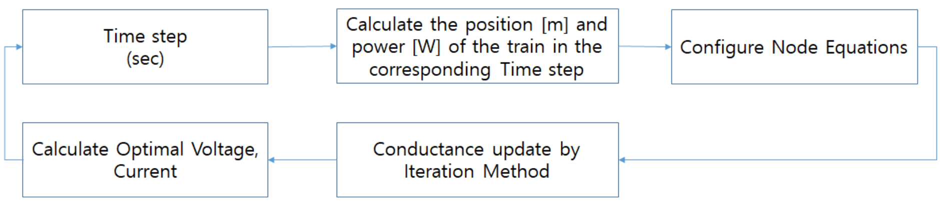


Fig. 3 DC feeding power simulation algorithm.

DC feeding power simulation is performed at each time step in conjunction with the TPS. The voltage ofthe substation and each train varies with the progression of time or the progression of the train. The DC feeding power simulation consists of three stages, as shown in Fig. 3.

3.1 Load Flow Analysis

Based on the requirements at loads consuming electrical energy, a series of processes to interpret the supply of energy and the flow of power through the power system are defined as load flow analysis. The analysis of load flow is based on various purposes such as addition of facilities, system planning, diagnosis, etc. from the design stage of the power system. In particular, for the purpose of adding facilities, load flow analysis is very important in terms of verifying the effectiveness of additional facilities on existing systems, in terms of system management, and determining facility specifications considering the capacity and reliability of the systems.

In particular, for urban railway systems, there is a very big difference in that DC power supply is used, unlike general power systems, and the location and power requirements of the load change. Changes in load location and power consumption mean that a continuous interpretation must be performed every second or on a constant basis during a specifictime period in which the operating conditions are repeated, rather than just calculating states at a specific time snapshot, as in the existing AC system. Furthermore, the additional interpretation of ESSs considered as energy efficiency improvement measures for electrical railway systems requires more complex load flow analysis algorithms. Fig. 4 shows a flow chart of the DC electric railway system.

As shown in Fig. 5, the developed load flow is based on an algorithm that constructs a node equation to

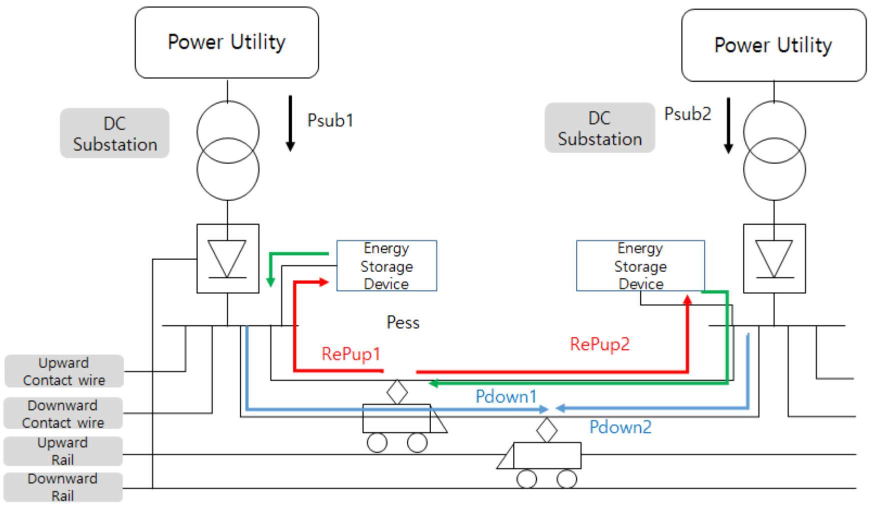


Fig. 4 Flow chart of the DC electric railway system.

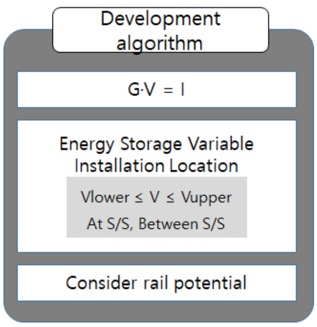


Fig. 5 Developed load flow algorithm.

obtain a solution [3]. The algorithm in this paper considered the rail voltage. The ESS can be installed between the substation and the substation.

Circuit network interpretation for load flow calculation is possible by obtaining a solution to the node equation. Fig. 6 shows a simple DC urban railway system, including two railway substations and one vehicle. Fig. 7 shows the equivalent circuit.

The node equation for Fig. 7 is shown in Eq. (1). Eq. (2) shows the relationship between the voltage at both ends of the train and the equivalent impedance.

$$\begin{vmatrix} g_{11}+g_{13} & 0 & -g_{13} & 0 \\ 0 & g_{22}+g_{23} & -g_{23} & 0 \\ -g_{13} & -g_{23} & g_{33}+g_{13}+g_{23} & -g_{33} \\ 0 & 0 & -g_{33} & g_{33}+g_{14}+g_{24} \end{vmatrix} \begin{vmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{vmatrix} = \begin{vmatrix} I_1 \\ I_2 \\ 0 \\ 0 \end{vmatrix} \quad (1)$$

$$g_{33} = \frac{P_3}{(V_3 - V_4)^2} \quad (2)$$

Load P_3 is given a value corresponding to the vehicle position which is the resulting value of the TPS. Since I_1 and I_2 are determined, a solution to the voltage of each node can be obtained using the iterative calculation method.

To solve Eq.(1), obtain g_{33} by Eq.(2). Since we do not know the value of V_3, we initially calculate g_{33} by assuming a DC no-load voltage of 1,500 V (or 750 V), and obtain [V] by solving Eq.(1).

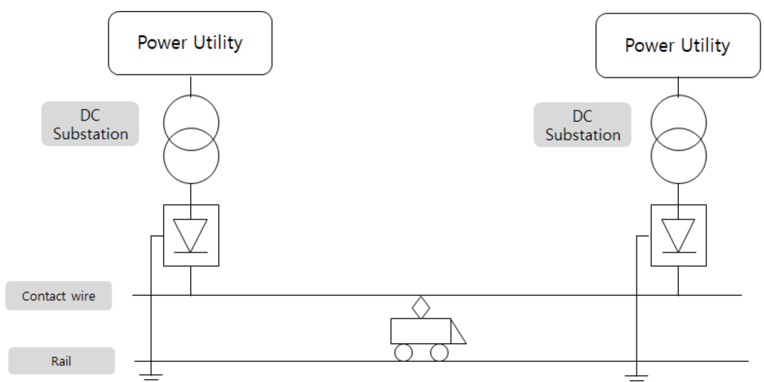


Fig. 6 DC urban railway system.

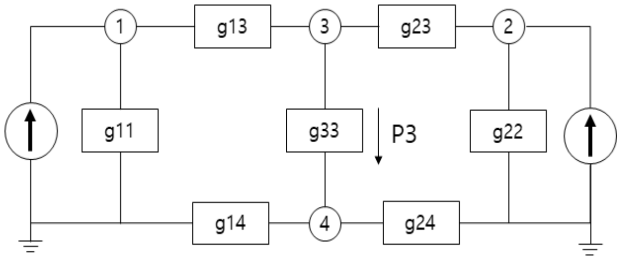


Fig. 7 Equivalent circuit of DC urban railway system.

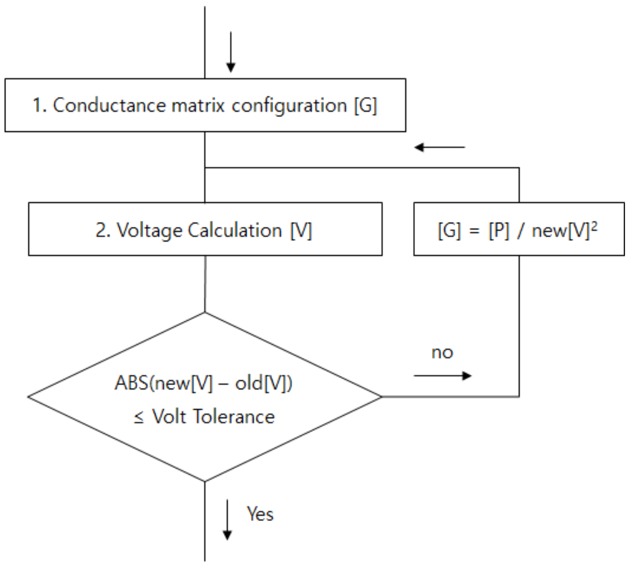


Fig. 8 Algorithm for load flow calculation by conductance matrix repeating method.

With the new $[V]$ obtained like this, g_{33} is calculated again. After modifying $[G]$, Eq.(1) is released again. If the difference between the old $[V]$ and new $[V]$ values falls within the allowable range, then the repeat calculation is finished. The algorithm using this method is shown in Fig.8.

3.2 Load Flow Calculation ConsideringESS

Considering the installation of the ESS in the substation, Fig. 9 shows the equivalent circuit additionally installed in the equivalent circuit in Fig. 7.

The current I_{ess} of the ESS and the internal resistance g_{ess} of the storage system are added in parallel to the substation with Norton equivalent current sources. The system matrix is constructed anew as shown in Eq.(3).

$$\begin{vmatrix} g_{11}+g_{13}+g_{ess1} & 0 & -g_{13} & 0 \\ 0 & g_{22}+g_{23}+g_{ess2} & -g_{23} & 0 \\ -g_{13} & -g_{23} & g_{13}+g_{23} & 0 \\ 0 & 0 & 0 & g_{14}+g_{24} \end{vmatrix} \begin{vmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{vmatrix} = \begin{vmatrix} I_1+I_{ess1} \\ I_2+I_{ess2} \\ -I_{33} \\ I_{33} \end{vmatrix} \quad (3)$$

When considering the ESS, load flow analysis of the location and operation mode ofthe train is performed first every second. It is checked whether the voltage result figures for each substation are outside the input voltage limit. When there is an event, a method of recalculating through matrix deformation is adopted, such as the above expression.That is, in order to fix the V_1 voltage, $g_{11}+g_{13}+g_{ess1}$ and I_1+I_{ess1} are set close to an infinite value, a matrix is calculated, and then a new I_{1_new} ($=I_1+I_{ess1}$) value is calculated with a fixed V_1 value. Thereafter, the I_{ess1} value is calculated by subtracting I_{1_new} from the existing I_1.Fig. 10 shows the load flow to which an ESSvoltage control range optimization algorithm has been added.

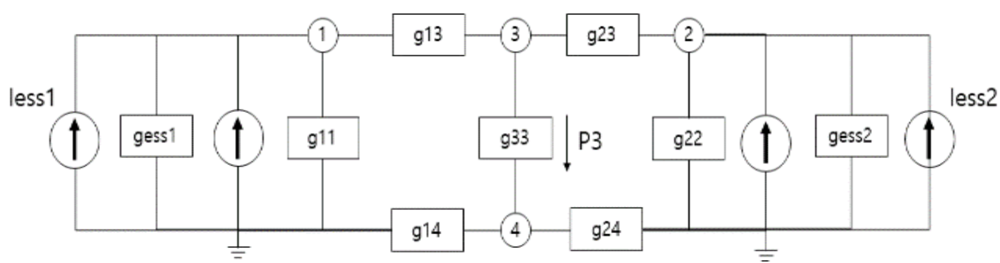


Fig. 9 Equivalent circuitry for railway systems with ESS installed.

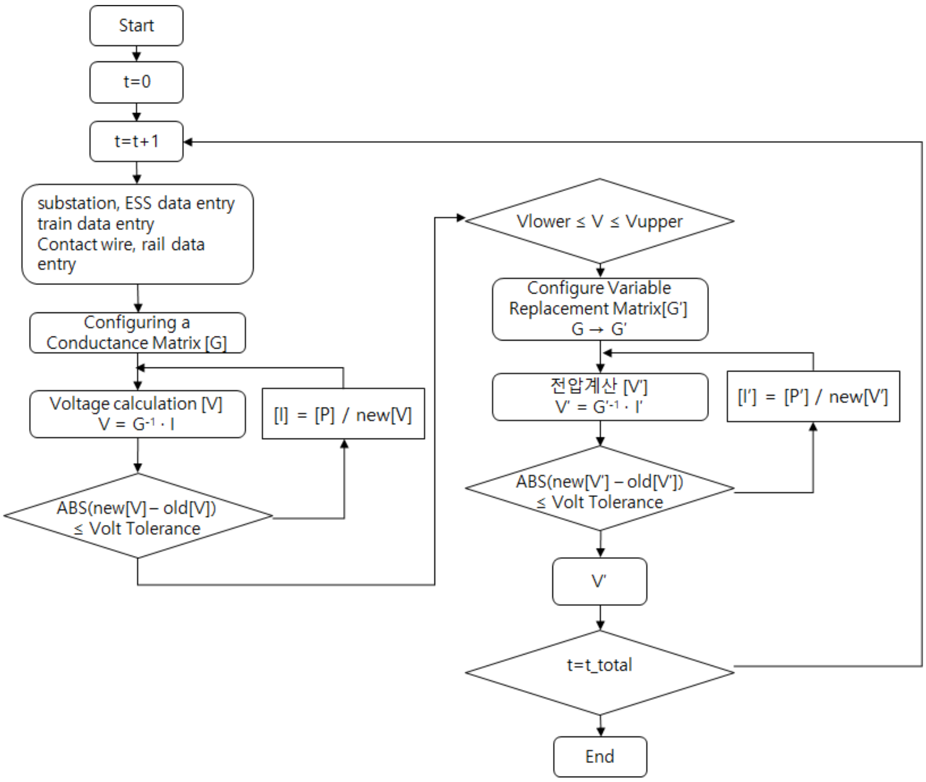


Fig. 10 ESSvoltage control range optimization algorithm.

4. Simulation Results Analysis

A simulation was performed on the section of Seoul Line 2 in Fig. 13.The measured systems and trains measured the actual power of the Seoul Line 2 trains during operation. The consumption pattern of electric power was measured and analyzed, and the feeder of Nakseongdae substation on Line 2 of Seoul was measured to measure the actual power supplied to electric wires [4, 5].

4.1 Electric Power Measurement of Train

(1) Measurement Route

- Seoul Line 2.

(2) Measuring Equipment

- Monitoring control device: analog input 8 channels, digital input 12 channels;
- 1 laptop: equipment for monitoring measured data values;
- 4 CTs: current sensors (3,000A/10V) for measuring wire current and inverter output current;
- 1 PT: voltage sensor for wire voltage measurement (2,000V/10V).

(3) Measuring Location of the Train

- Channel 1: resistor consumption current (scale: 3,000A/10V) 50509A;
- Channel 2: contact wire voltage (scale: 2,000V/10V) 50509 wires—500A;
- Channel 3: inverter input current (scale: 3,000A/10V) 9509;
- Channel 4, 5: inverter output current (scale: 3,000A/10V) 55 551U, 551W.

4.2 Power Measurement for Substation

(1) Measuring Location

- Nakseongdae substation.

(2) Measuring Equipment

- One power analyzer (RPM): AC 22.9 kV voltage, current measurement;
- One PXI: measurement of CT current and PT voltage of 50F relay;
- Two laptops: equipment for monitoring measured

data values.

(3) Measuring Location

- Nakseongdae substation: contact wire voltage, current.

4.3 Simulation Results

4.3.1 Power Simulation and Analysis of Trains

The situation in which trains run between Euljiro Station and City Hall Station was considered. Train data and track data were used to simulate train driving. The simulation results are as follows.

TPS was carried out for Seoul Line 2. As TPS input data, train, route characteristics and station locations are shown in Tables 1 and 2.

- Train and route characteristics;
- Station location.

The simulated results are shown in Figs. 11 and 12. The measurement was carried out three times, and it was verified that the value may vary even if the measurement is made according to the driver's operation pattern. However, the overall pattern was found to be similar. Therefore, the simulation results are also confirmed to be similar to actual power consumption and regenerative power consumption patterns.

As a result of three measurements of power consumption and regenerative power consumption for Seoul Line 2 trains, the actual measurement value was

Table 1 Vehicle and line characteristics.

	Characteristic
Electric train	10 coach (5M5T)
Tare Weight	359ton
Voltage	DC 1500V
Max Speed	80km/h
Acceleration	3.0km/h/s
Deceleration	3.5km/h/s
Motor Power	200kW

Table 2 Station locations.

Name	Location (m)	Name	Location (m)
Euljiro1-ga	0	Seocho	23,178
Euljiro3-ga	755	Bangbae	24,821
Euljiro4-ga	1,405	Sadang	26,380
Dongdaemun	2,415	Nakseongdae	28,049
Sindang	3,295	Seoul Univ	29,098
Sangwangsimni	4,230	Bongcheon	30,080
Wangsimni	5,070	Sillim	31,229
Hanyang Univ	6,061	Sindaebang	32,998
Ttukseom	7,145	Guro Digit	34,102
Seongsu	7,970	Daerim	35,225
Konkuk Univ	9,218	Sindorim	36,989
Guui	10,795	Mulae	38,216
Gangbyeon	11,719	Yeongdeungpo-gu Office	39,081
Sungnae	13,516	Dangsan	40,237
Jamsil	14,557	Hapjeong	42,260
Sincheon	15,773	Hongik Univ	43,340
Sports Complex	16,953	Sinchon	44,650
Samseong	17,931	Ewha Univ	45,482
Seolleung	19,257	Ahyeon	46,400
Yeoksam	20,461	Chungjeongno	47,202
Gangnam	21,236	City Hall	48,263
Seoul Edu Univ	22,461		

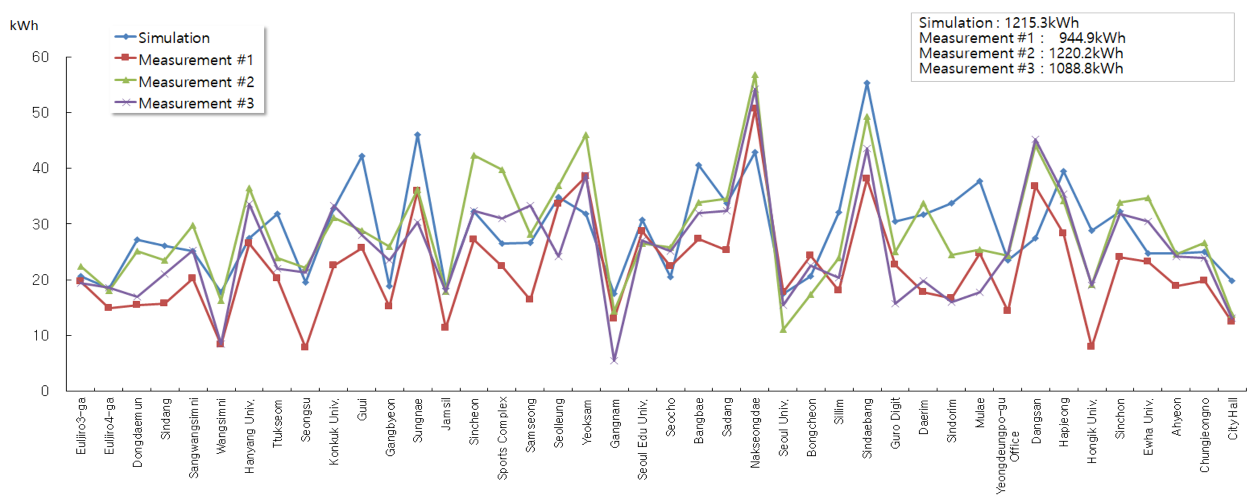


Fig. 11 Powering energy(measurement & simulation).

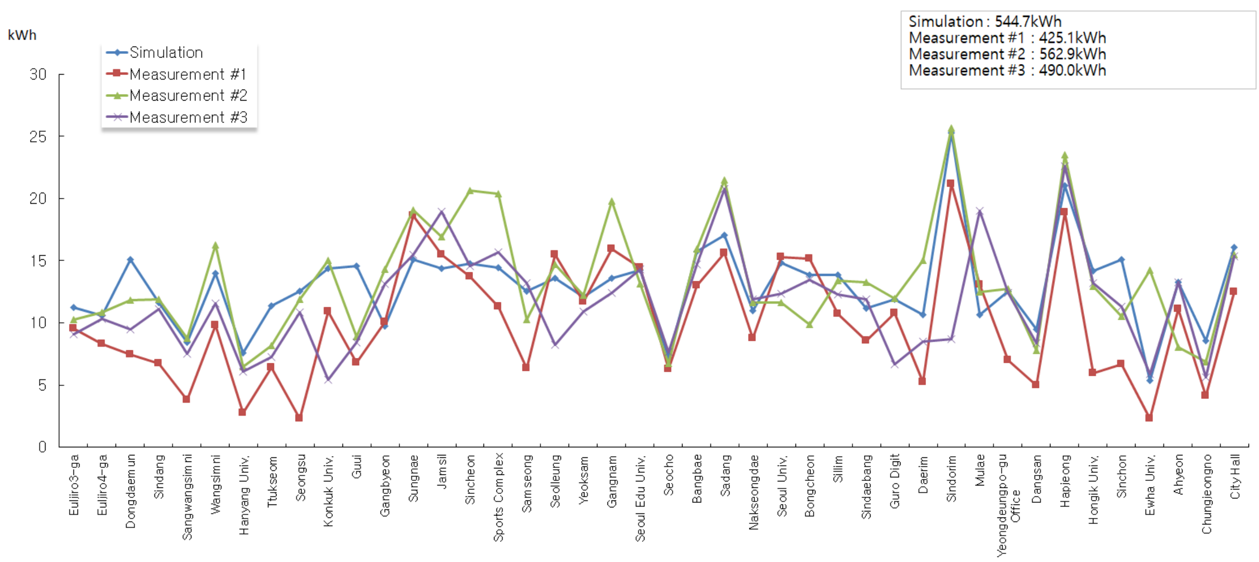


Fig. 12 Regenerative energy(measurement & simulation).

944.9 to 1,220.2 kWh compared to the simulation value of 1,215.3 kWh. The regenerative power was shown to be between 425.1 and 562.9 kWh compared to the simulated value of 544.7 kWh. The error rate between the measured average value and the simulation value was 12.0% for power consumption and 10.6% for regenerative power.It was confirmed that the simulation results fit the measured values well.

4.3.2 Simulation and Analysis of Substation Supply

Power simulations are performed by weekday and weekend operations through the results of train consumption and regenerative energy simulation. Input conditions for power simulation are as follows.

Route: Seoul Metro Line 2

Electric car: 10 volume 1 unit

Station: 43 stations

Dwell time: 30 s

Substation: 13 substations on Line 2

Headway

-Weekdays: rush hour (2 min and 30 s), non-rush hour (5 min and 30 s)

-Saturday and holidays: 5 min and 30 s

(1) Measurement Data

- Nakseongdae substation (once);
- Nakseongdae substation (2 times).

(2) Comparison of Power Consumption Simulation and Measurement Results of Substation

The results of the two measurements are shown in Tables 3 and 4. The results of two measurements and simulations were compared for Nakseongdae substation on Seoul Line 2. As a first result, the result of measuring power on the Rush Hour was 4,931 kWh, and the simulation result was 5,250 kWh with an error rate of 6.5%.

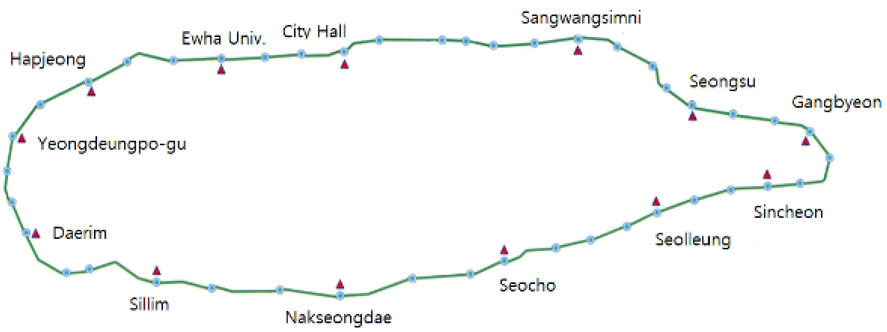


Fig. 13 Substation locations on line 2.

Table 3 Substation measurement data #1.

Time	Power Consumption	
	Rush Hour	Non-Rush Hour
12:00		2,234
13:00		2,480
14:00		2,516
15:00		2,426
16:00		2,470
17:00		2,368
18:00	5,172	
19:00	4,596	
20:00	5,026	
21:00		2,398
22:00		2,226
23:00		1,254
Average	4,931	2,264

Table 4 Substation measurement data #2.

Time	Power Consumption	
	Rush Hour	Non-Rush Hour
15:00		2,492
16:00		2,252
17:00	4,566	
18:00	5,168	
19:00	5,132	
20:00		2,672
21:00		2,322
22:00		1,820
23:00		1,450
5:00		1,878
6:00		2,696
7:00	5,288	
8:00	4960	
9:00		2698
10:00		2610
Average	5,023	2,289

The power measurement of Non-Rush Hour was 2,264 kWh, and the simulation result was 2,291 kWh with a 1.2% error rate. As a second result, the result of measuring power on the Rush Hour was 5,023 kWh, and the simulation result was 5,250 kWh with an error rate of 4.5%. The power measurement of Non-Rush Hour was 2,289 kWh, and the simulation result was 2,291 kWh with a 0.1% error rate. The power simulation results show that the measurement data are estimated almost equally.

Table 5 summarizes the measurement results and simulation results.

4.3.3 Power Simulation and Analysis with ESS

(1) Measurement Data

Table 6 shows the power measurement results of the substation in Line 2 to which the ESS was applied. Power consumption and regenerative power consumption were calculated and accumulated over time.

(2) Comparison of ESSApplication Simulation and Measurement Results

The power simulation was simulated on the assumption that it would reduce regenerative power by 100%. In addition, the simulation is performed by installing the ESS in only one substation. As a result, installing an ESS at the substation on Line 2 in Seoul can save 6,021.43 kWh (856.84kWh + 5,164.59kWh)on weekdays and 6,541.81 kWh on weekends, saving an average of 6,281.62 kWh.

Table 5 Comparison of the measured value and the simulation result.

Substation Name	Rush Hour			Non-Rush Hour		
	Measurement	Simulation	error rate	Measurement	Simulation	error rate
Nakseongdae	4,931	5,250	6.50%	2,264	2,291	1.20%
	5,023	5,250	4.50%	2,289	2,291	0.10%

Table 6 Saving energyby the measurement.

	Power consumption (kWh/day)	Saving energy (kWh/day)
Weekday	32,957.15	6,849.70
	34,709.95	6,363.85
	35,255.65	6,498.60
	34,443.75	6,793.30
Weekend	31,819.05	5,837.50
	25,400.85	6,340.70
Average	32,431.07	6,447.28

Table 7 Saving energyby the simulation.

Saving energy (kWh/day)		
Weekday	Rush hour	856.84
	Non-rush hour	5,164.59
Weekend	6,542.81	
Average	6,281.62	

The average energy-saving regenerative power value of the actual measurement results was measured at 6,447.28 kWh/day, and the simulation results were shown at 6,281.62 kWh/day. The error rate is 4.3%, indicating that the results of the measurement and the simulation are almost identical.

5. Conclusion

As a result of three measurements of power consumption and renewable power consumption on Seoul Line 2, the error rate of the measured average and simulation values was 12.0% of power consumption and 10.6% of renewable power. It was confirmed that the simulation results fit well with the measured values.

The substation on Seoul Line 2 compared the simulation results with two measurements. The error rate was found to be 0.1% to 6.5%. Power simulation results also show that the measurement data are estimated to be almost the same.

The simulation and measurement results to which the ESS was applied were compared.The error rate is 4.3%, indicating that the measurement and simulation results are almost identical.

In this study, we conducted a study based on algorithms that constructed node equations to obtain solutions. As previously described, both the train performance simulation and power simulation results show that the actual measurement data are estimated almost equally. The proposed algorithm is expected to be useful for analyzing DC railway power.

Acknowledgments

This study was conducted by the Ministry of Land, Infrastructure and Transport’s Research Project on Railway Technology-Projects (21RTRP-B146034-04).

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