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직류 전기철도 시스템의 변전소 설계 및 평가

(Design and Assessment of DC Traction Power Supply System for Light Rail Transit)

백병산* · 김재철** · 문종필 · 최준호
(Byung-San Baek · Jae-Chul Kim · Jong-Fil Moon · Joon-Ho Choi)

요 약

전기철도 급전시스템의 설계와 평가에 관련하여 어려운 점은 고려해야 할 요소들이 많고, 시스템적 접근이 요구되나 단편적인 논문과 엔지니어링 측면의 접근이 대부분이다. 본 논문에서는 전기철도 시스템 중 국내외에서 최근 활발히 추진되고 있는 경량전철을 위한 직류 급전시스템의 설계 및 그의 적정성을 평가하는 기법을 체계화하였다. 먼저, 급전 시스템의 구성요소인 급전 변전소와 부하인 차량과 그리고 전력선을 포함한 전체 시스템의 특성파악하고 분석하였다. 실제 계통과 동일하게 모델링하기 위하여 축약 및 등가화를 하였으며, 등가화한 시스템을 해석하기 위한 방안으로 노드방정식과 반복접근법을 적용하였으며, 이를 체계화하여 모의절차, 평가 및 설계방법을 제시하였다. 제시한 알고리즘 및 설계절차에 따라 프로그램을 개발하였으며 사례연구를 통하여 그 유효성을 입증하였다.

Abstract

For the design of DC traction power supply system at new Light Rail Transit(LRT) construction, it is very important to determine system configuration, location and power capacity of substation. However, a LRT system consists of a number of subsystems such as train movement, power supply and traction drives, which inevitably contains many complexities and diversities. The objective of this paper is to clarify and systematize the design procedure and its assessment for the electrification system of a LRT line. This paper discusses in detail our approach to system design and its assessment. The whole DC-feeding network configuration, characteristics of a train, and design method of substation arrangements is thoroughly investigated for the design. As a result of the investigations, the design procedure is clarified and systematized, and a computer program for the design and evaluation of the system is developed using the most suitable iterative method with nodal equation. To verify the proposed design and its assessment procedure, case studies for the DC traction power supply system of a planed Korean LRT line are performed.

Key Words : DC-feeding-traction system, nodal equation, iterative method, computer-based simulation, Light Rail Transit

* 주저자 : 현대중공업 기계전기연구소 수석연구원
**교신저자 : 숭실대학교 전기공학부 교수
Tel : 031-289-5152, Fax : 031-289-5027, E-mail : bsbaek@hhi.co.kr
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1. Introduction

As a result of modernization and industrialization, many constructions have been made at a field of an electric railway system. The electric railway system is a unique public transportation which can solve the traffic problems such as the space limitation and the environmental problems caused by exhausted petroleum and gas, and noise.

Recently, many LRT constructions have been on progress according to the Ministry of Construction and Transportation (MOCT) policy as the demand of traffic increases in Korea. Thus the design method of the system is also needed for the stable and efficient operation of LRT. Power engineers should carry out a feasibility study to decide the cost-effective ratings of equipment in a design using hand calculations or simulation techniques with predicted traffic patterns and passenger loads[1-3].

For an electric railway system, not only the safe and efficient operation, but the system design is required for the passenger transportation and the energy efficiency. There have been some difficulties for the design and its assessment such as checking the many parameters and systematic approach. However, most papers or studies have been focused on the fragmentary research and the engineering side. Only some advanced companies have itself program for the design, those contents also are not exhibiting. The objective of this paper is to clarify and systematize the design procedure and its assessment for the electrification system of an electric railway. This paper will discuss in detail our approach to system design and its assessment.

In order to get the design, basic theory of traction power supply system is described and the characteristics of train as a dynamic load are investigated. The nature of the load flow problem is analyzed using a simplified DC circuit. The most important part for the design of power supply system is the DC power flow calculation. Because the power and voltage constraints make the problem nonlinear, the iterative numerical solution should be needed. The detailed investigation is given to select the most efficient circuit solution method for the simulation of DC-fed complex traction-power systems. Many iterative techniques have been reported in technical literature on the solution of complex DC-rail-traction systems[4-6] and current-vector iterative method is assessed the best way of them in this paper. The method is applied to the proposed simulation program. This paper also describes how to evaluate and design the system from simulation results. Through the suitable case studies, we verified that the proposed design procedure with the developed program is effective.

2. Basic Design of Traction Power Supply System

Railway traction power system consists of substation facility, catenary, train and return rail. Usually substation facilities of them can be classified into AC high voltage switchgear, rectifier transformer, rectifier, DC switchgear, inverter (or resistor bank) and SCADA system. The electrical power can be divided into traction power and station auxiliary power. The traction power circuit is usually designed into two banks for redundancy. In the DC traction power system, current from the traction power substation is delivered to the moving trains through either the third rail or the overhead contact system and returned to the substations through the track running rails or negative conductors.

To illustrate the power simulation of DC railway traction power network, the overall power flow scheme can be represented by each substation with transformer and rectifier, power cables, passenger stations according to train moving in Fig. 1.

3. Network analysis and power calculations

3.1 Network Analysis

With a train represented by a voltage source and a series conductance, a simple plain network is shown schematically for power analysis in Fig. 2. The DC voltage source, Vs, feeds a train load which draws power Pt through the catenary or the third rail with conductance G. It is assumed that Pt is fixed, although in reality it varies with different pantograph or collector-shoe voltages and train speeds according to a series of curves which are not necessarily linear[5, 6].

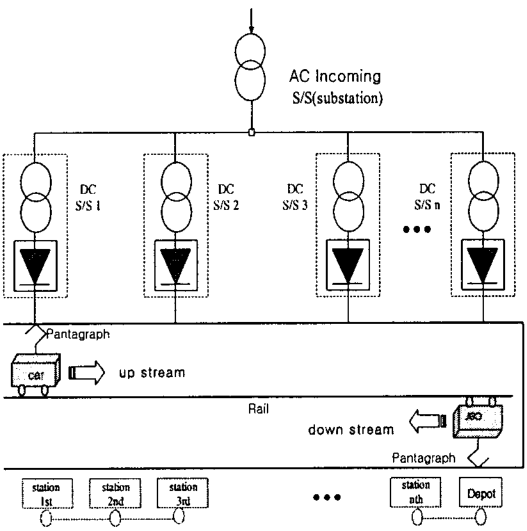


Fig. 1. DC-fed traction power system

The desired results are the train voltage and current, which are not obvious without algebraic manipulation because of an unknown train conductance Gt.

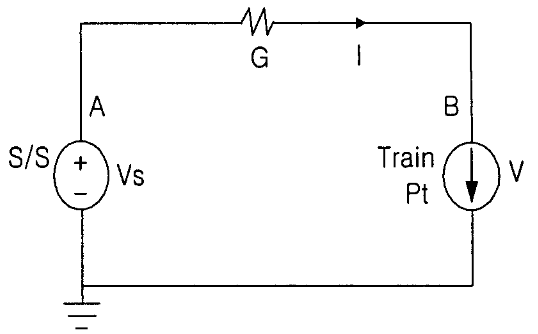


Fig. 2. Simplified DC feeding circuit

The train power Pt is the only known variable in eq. (1).

$$P_t = G_t \times V^2 \tag{1}$$

where V is a pantograph or collector-shoe voltage at node B.

The train demanded power is established as a function of conductance in form of a quadratic equation. If the power is assumed to the power delivered through the circuit at node B, power transporting to train node B can be represented by eq. (2) from Fig. 2, where, I is a current flowing from the S/S (A) to train (B).

$$P = V \times I \tag{2}$$

$$I = G(V_s \times V) \tag{3}$$

where G is power cable conductance.

Combining equations (2) and (3) yields eq. (4).

$$P = GV_sV - GV^2 \tag{4}$$

The power can be determined by the quadratic formula for voltage V. Since the power at bus B transferred by the feeding circuit should match the train demanded power, the intersection points of two quadratic curves described by eq. (1) and (4) should be found to solve the DC-power-flow problem.

It is important to note that the quadratic formula yields two values of voltage which will fulfill the specified condition. To find the load flow for dynamic power distribution, nodes and branches for all DC network can be represented in matrix form of equations using Ohm's law, KCL and KVL.

The matrix equation describing the performance of a DC-traction power system in conductance form is as eq. (5)

$$[G][V]=[J] \tag{5}$$

where $[G]$ is an symmetrical nodal conductance matrix and is defined as the number of nodes. The nodal currents in the right-hand-side vector $[J]$ are all zero except the substation positive- and negative-busbar nodes. In the current-vector iterative method, the train model is converted into an ideal current source instead of a conductance. This current source is connected between train pantograph or collector-shoe node and train node at the train position. The nodal current of these nodes in the right-hand side vector $[J]$ is replaced by either positive or negative train current. The solution is initiated by assuming that train voltages are all at the system-voltage level. Then, the train current is derived from the loading condition.

$$I_{kt}=\frac{P_{kt}}{V}(kt=1,2,\ldots,kn) \tag{6}$$

where, *kt* refers to the train number and *kn* is the total number of trains in the system. The train current calculated from eq. (6) are substituted into eq. (5) to obtain a new set of train voltages. These new voltages are used in eq. (6) to recalculate train currents for a subsequence solution of eq. (5). The process will be carried out until a desired voltage tolerance is achieved.

Fig. 3 geometrically represents a convergence process of the current-vector iterative method. In Fig. 3, the lines (①, ②, ③) indicate the load condition and the arch shows the transport power. As shown in figure, the moving from line ① move to line ③ means that satisfy the load condition.

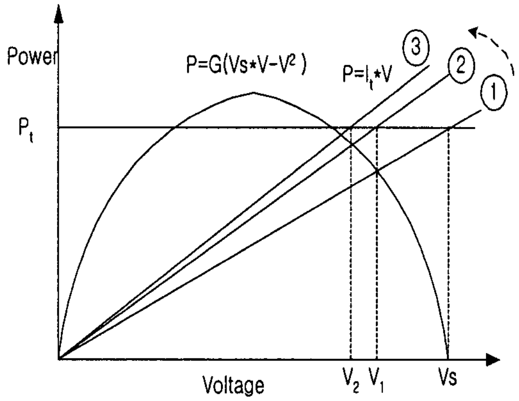


Fig. 3. Applied iteration method

In order to easily apply nodal equation to the system, voltage source converted into current source using superposition theory. Fig. 4 shows the detailed electrical equivalent circuit of substation. The power at substation node can be decided by following equation.

$$V=V_{so}-R_i\times I \tag{7}$$

where, V is the substation output voltage, $V_{so}(=J\times R_i)$ is the substation no load output voltage. R_i is the substation inner impedance, I is the substation output current, and J is the current source.

DC-fed traction power system in Fig. 1 can be represented by equivalent circuit with nodes(substations, trains) in Fig. 5. Note that the status of trains are described using powering (⇩) or regenerative breaking (⇧) mode.

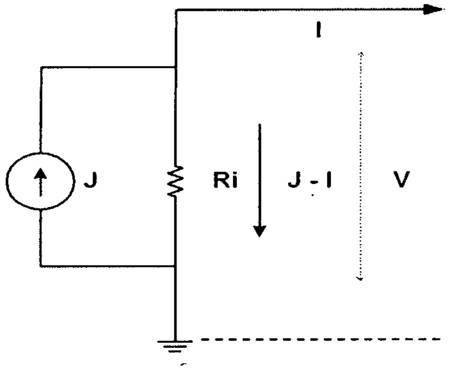


Fig. 4. Electrical equivalent circuit of substation

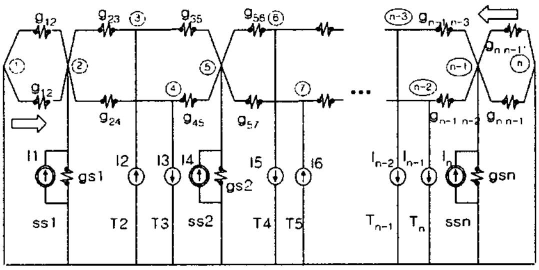


Fig. 5. Equivalent circuit of DC-feeding traction system

Applying nodal equation to Fig. 5, Eq. (5) can be rewritten in a matrix form:

$$\begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1n-1} & G_{1n} \\ G_{21} & G_{22} & \cdots & G_{2n-1} & G_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ G_{n-11} & G_{n-12} & \cdots & G_{n-1n-1} & G_{n-1n} \\ G_{n1} & G_{n2} & \cdots & G_{nn-1} & G_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_{n-1} \\ V_n \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_{n-1} \\ I_n \end{bmatrix} \quad (8)$$

where $[G_{ij}]$ is a conductance between node i and j, $[V_j]$ is a node (substation, train, tie-post) voltage, and $[I_j]$ is a node (substation, train, tie-post) current.

3.2 Proposed Simulation Algorithm

Fig. 6 shows the simulation configuration for the overall traction power system in Fig. 5. It makes a digital train ride simulation including the entire electrical network possible. There are two steps of calculations in the simulation process. The first one is on the train movement (TPS), the second one is on the electrical power supply network. TPS is not the intent of this article, which have been developed a few years ago. The interested reader should find the appropriate document for further details.

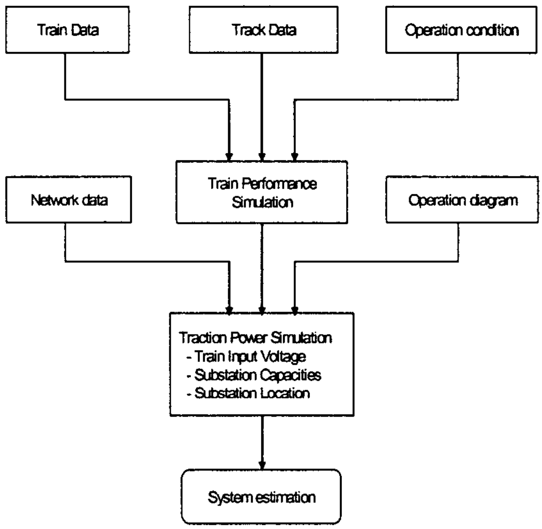


Fig. 6. Traction power system simulation structure

In eq. (8) conductance matrix are decided by the connection of each node. Most of values are zero except the related connect nodes. Voltage matrices are unknown values obtained by the iterative method in power simulation and current matrices are node injection current values which derive from TPS.

Fig. 7 shows the flowchart of proposed algorithm. Using eq. (6) and (8), the system basic value such as node voltage and current are estimated per every time step. The iteration stops when voltage value converges into the tolerance value.

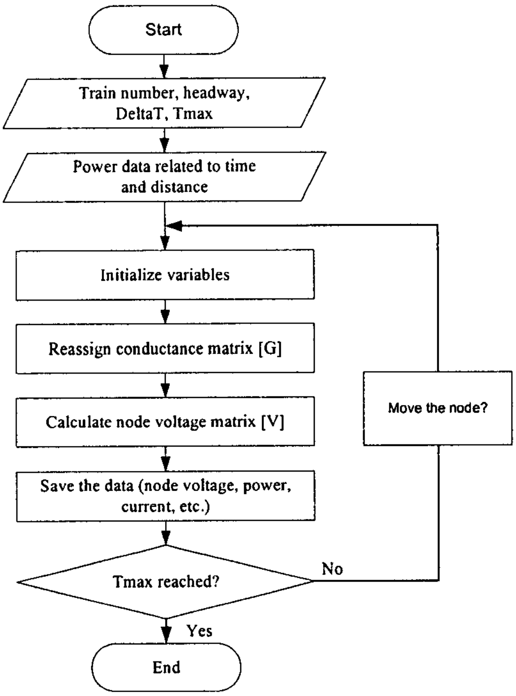


Fig. 7. Simulation algorithm flowchart

3.3 Proposed system design procedures

The proposed design procedures for the electrification system of a LRT line are summarized as follows[7].

Step 1) The most suitable position of substations are chosen from candidate group (substation, station and depot). Also, the candidates being easy to connect to power grid are more economic.

Step 2) The specialist considers voltage drop, economic performance, etc. from this candidate group and choose some cases which shall be arranged from candidates for substation position again.

Step 3) Each selected case conducts power simulation to decide most suitable position and capacity.

Step 4) Check the voltages at the pantograph from simulation result by considering the voltage drop to supply voltage magnitude more than smallest input voltage of VVVF inverter for traction motor. This voltage should always be in the range of 500~900[V] for a nominal voltage of 750[V] system.

Step 5) Examine the overload requirement and peak power from simulation result. Rectifier capacity shall be required to endure 100[%] load continuously, 200[%] for 2 hours, 300[%] for 1 min.

Step 6) Decide the most suitable locations of the substation and their capacities. And decide the capacity regenerative inverter if it is required.

4. Case Studies

To illustrate the design procedure and demonstrate the developed program, the suitable LRT line which has 4 substations, 1 depot and 9 stations with a double track was selected. Table 1 shows data of line and stations.

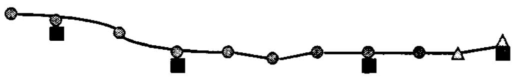
Table 1. Data of line and stations

Identification	Position [km]	Designation	Distance between stations[km]
Start	0.000	Start	0.000
ST_01	0.040	Station 1	0.040
ST_02	0.815	Station 2	0.775
ST_03	2.180	Station 3	1.365
ST_04	3.225	Station 4	1.045
ST_05	3.960	Station 5	0.735
ST_06	4.540	Station 6	0.580
ST_07	5.200	Station 7	0.660
ST_08	5.775	Station 8	0.575
ST_09	6.290	Station 9	0.515
End_S	6.330	End of service	0.040
D_01	6.720	Depot	0.390
D_02	7.020	Car Depot	0.300
End	7.800	End	0.780

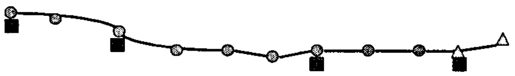
In this study, three cases are decided considering the voltage drop and economic point of view in Table 1 according to the proposed system design procedures.

The running condition of trains and operation condition of substation are applied equally for all cases and power simulation is conducted to decide the most suitable system for best solution respectively.

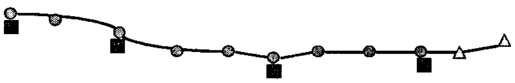
- Case 1(substation locations: 0.815, 3.225, 5.775 and 7.020[km])



- Case 2(substation locations: 0.040, 2.180, 5.200 and 6.720[km])



- Case 3(substation locations: 0.040, 2.180, 4.540 and 6.290[km])



4.1 System data

The exact input data are needed to get the good results of power simulation. All input data applied for power simulation are investigated from each facility maker and related company. Table 2 and 3 shows train data and its characteristics, running condition and network data.

Table 2. Train data and characteristic

Item	Type	Unit
Type of Vehicle	Steel tire LRT/3rd Rail	
Train formation	2	unit
Tare weight	43.2	[Ton/Car]
Passenger load	20	[Ton/Car]
Design max. speed	80	[km/h]
Max. operation speed	70	[km/h]
Running resistance	4.058	KN/formation
Max acceleration	3.96	[km/h/s]
Max deceleration	4.68	[km/h/s]
Gear ratio	8.48	
Gear efficiency	97	[%]
Motor efficiency	91	[%]
VVVF Inverter efficiency	98.5	[%]
Motor Power factor	84	[%]
Number of Inverter	4	ea/formation
Number of motor	8	ea/formation
Auxiliaries	55	kW/formation

Table 3. Running condition and network data

Item	Value	Unit
Minimum headway	2.0	[min]
Dwell time	20	[sec]
Turnaround time	30	[sec]
Rectifier rated/no load voltage	750/810	[V]
Substation inner resistance	22.5	[mΩ]
Power rail resistance	17.1	[mΩ/km]
Running rail resistance	12.55	[mΩ/km]
Feeder cable resistance	40.65	[mΩ/km]
Return feeder cable resistance	27.1	[mΩ/km]

4.2 Train performance simulation (TPS) result

At the first step, using the system data enumerated above, current values in time domain with TPS are estimated to design the traction electrical power system. Fig. 8 and 9 are the characteristics of powering and breaking performance, respectively.

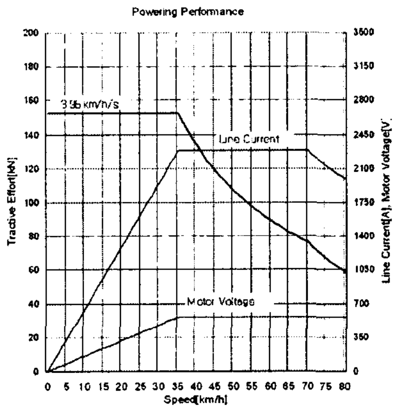


Fig. 8. Powering performance curve

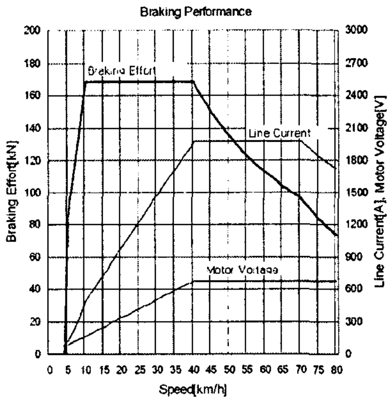


Fig. 9. Breaking performance curve

TPS was conducted under the schedule speed of 29[km/h] and train resistance formula for a 4-car train is as follows.

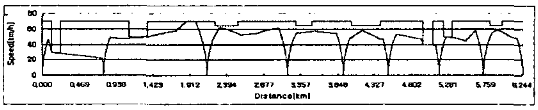
$$R_t = (1.65 + 0.0247V)W_m + (0.78 + 0.0028V)W_t + (0.0028 + 0.0078(kmc - 1))V^2 \quad (9)$$

Where, V is a train speed[km/h], W_m is a axial load of motor car[ton], W_t is a axial load of trailer car[ton], and kmc is a car number of train formation

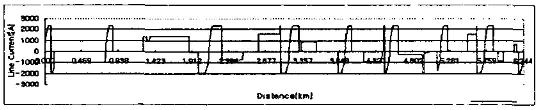
Table 4 is TPS results for up line. Fig. 10 shows the train speed and pantograph current value when train runs under the schedule speed of 29[km/h].

Table 4. Station to station (1 → 9) data at schedule operation

Station No.		Distance [km]	Time [min]		RMS Current [A]		Energy Consumption[kWh]	
From	To		Run	Stop	Im	Idc	Powering	Braking
1	2	0.78	1.34	0.33	82.6	131.5	3.9	-1.5
2	3	1.36	1.49	0.33	114	257.1	5.6	-9.2
3	4	1.05	1.23	0.33	144.7	326.4	10.7	-6.3
4	5	0.73	0.84	0.33	154.8	330.4	9	-3.3
5	6	0.58	0.92	0.33	136.3	303.9	4.4	-7.7
6	7	0.66	0.93	0.33	129.5	272.9	5.7	-4.4
7	8	0.58	0.79	0.33	149.3	312.3	6.1	-3.1
8	9	0.51	0.76		154	327.7	5.9	-4
Total		6.20	8.28	2.31	114	244.7	51.3	-39.4
			10.59				11.9	



a) Train speed and limit



b) Pantagraph current

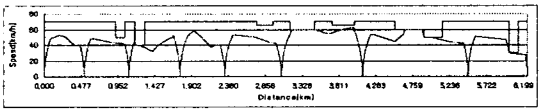
Fig. 10. TPS result of up line (1 → 9)

Table 5 is TPS results for down line. Fig. 11 shows the train speed and pantograph current value when train runs under the schedule speed of 29[km/h].

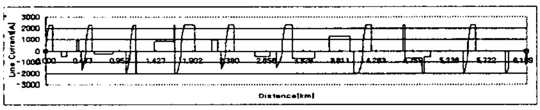
Table 5. Station to station (9 → 1) data at schedule operation

Station No.		Distance [km]	Time [min]		RMS Current [A]		Energy Consumption[kWh]	
From	To		Run	Stop	Im	Idc	Powering	Braking
9	8	0.51	1.76	0.33	125.2	264.7	13	-3.1
8	7	0.58	0.77	0.33	149.5	315.3	5.6	-4

Station No.		Distance [km]	Time [min]		RMS Current [A]		Energy Consumption[kWh]	
From	To		Run	Stop	Im	Idc	Powering	Braking
7	6	0.66	0.98	0.33	128.2	264.5	7.1	-3
6	5	0.58	0.94	0.33	160.6	346	10.7	-3.1
5	4	0.73	0.85	0.33	144.3	314.7	5.4	-5.9
4	3	1.05	1.22	0.33	140.5	315.2	10.2	-6
3	2	1.36	1.51	0.33	144.6	324	17.1	-4.4
2	1	0.78	1.12		112.6	233	5.8	-4
Total		6.25	9.16	2.31	120.9	261.1	74.9	-33.4
			11.47				41.5	



a) Train speed and limit



b) Pantagraph current

Fig. 11. TPS result of down line(9 → 1)

4.3 Power Simulation Result

Using the TPS results, power simulation was performed with total system condition for each case according to the flow chart in Fig. 7.

In a case of that there are multi substation operating in section, substation outage must be considered when pantograph voltage is estimated. Trains were operated the headway with 120sec for designing of electrification system.

4.3.1 Results for Case 1

Table 6 shows the substation power simulation result for Case 1. Minimum voltage of pantograph was 721[V] in normal feeding. In case of the failure of one substation, minimum voltage of pantograph was 482[V]. The lowest permanent voltage according to IEC-Standard 60850 is given by 500[V]. Therefore it means that operation of trains is not available. Substation arrangements of Case 1 are no good.

Fig. 12 shows Pantograph voltage profile of Case 1 in the worst case (SS1 not in service).

4.3.2 Results for Case 2

Table 7 shows the substation power simulation result for Case 2. Minimum voltage of pantograph was 711[V] in normal feeding. In case of the failure of one substation, minimum voltage of pantograph was 613[V]. The position is at 65m from up stream. Based on IEC 60850, any voltage does not violate the limit voltage. It means all the trains are operable. Therefore, substation arrangements of Case 2 are good.

Fig. 13 shows pantograph voltage profile of Case 2 in the worst case (SS1 not in service).

4.3.3 Results for Case 3

Table 8 shows the substation power simulation result for Case 3. Minimum voltage of pantograph was 713[V] in normal feeding. In case of the failure of one substation, minimum voltage of pantograph was 601[V]. The position is at 235m from down stream.

Based on IEC 60850, any voltage does not violate the limit voltage. Therefore, substation arrangements of Case 3 are good.

Fig. 14 shows Pantograph voltage profile of Case 3 in the worst case(SS4 not in service).

Table 6. Substation power simulation result for Case 1

SS	Eff. Power[kW]				Max. Power[kW] for S/S	Min. Panto Voltage[V]
	SS1	SS2	SS3	SS4		
All SS in service	1060	1006	815	529	2391	721

SS	Eff. Power[kW]				Max. Power[kW] for S/S	Min. Panto Voltage[V]
	SS1	SS2	SS3	SS4		
SS1 not in service	Fail	1927	1002	491	4376	482
SS2 not in service	1610	Fail	1235	571	3699	642
SS3 not in service	1186	1341	Fail	1017	2920	707
SS4 not in service	1157	1168	1261	Fail	3797	729

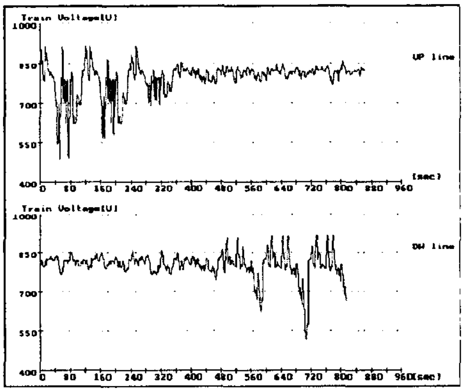


Fig. 12. Pantograph voltage profile of Case 1 (SS1 not in service)

Table 7. Substation power simulation result for Case 2

SS	Eff. Power[kW]				Max. Power[kW] for S/S	Min. Panto Voltage[V]
	SS1	SS2	SS3	SS4		
All SS in service	791	1014	931	689	2258	711
SS1 not in service	Fail	1714	1091	673	4032	613
SS2 not in service	1360	Fail	1347	739	3073	656
SS3 not in service	848	1402	Fail	1257	3548	667
SS4 not in service	795	1177	1523	Fail	4254	675

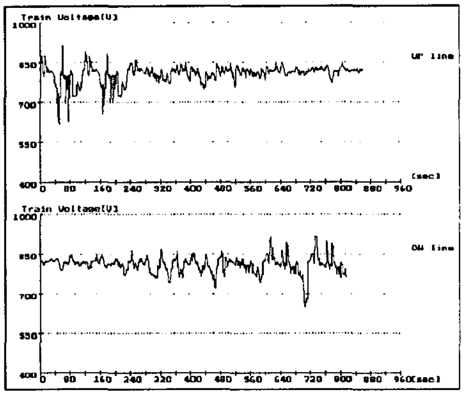


Fig. 13. Pantograph voltage profile of Case 2 (SS1 not in service)

Table 8. Substation power simulation result for Case 3

SS	Eff. Power[kW]				Max. Power[kW] for S/S	Min. Panto Voltage[V]
	SS1	SS2	SS3	SS4		
All SS in service	777	923	871	815	2474	713
SS1 not in service	Fail	1603	1024	869	3677	638
SS2 not in service	1261	Fail	1284	920	2896	679
SS3 not in service	836	1321	Fail	1337	3846	707
SS4 not in service	785	1101	1602	Fail	4490	601

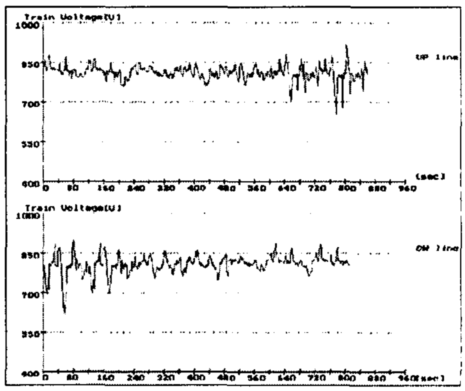


Fig. 14. Pantograph voltage profile of Case 3 (SS4 not in service)

4.4 Power system design

We can decide most suitable locations and capacity from above simulation result according to the proposed design procedures.

First, the voltage of case 1, 482[V], violated the pantograph's standard voltage but case 2 and 3 does not. Therefore, we can think that substation arrangement of both case 2 and 3 is good, but case 2 is more desirable because voltage drops are less than case 3.

Second, instantaneous peak power of substationshould be examined. The instantaneous peak power is 4254[kW] at case 2, and 4490[kW] at case 3. Therefore, case 2 becomes the most suitable alternative synthetically.

Third, the substation capacity design results for 750[V] system of case 2 are shown at Table 9. This design values are almost same as that of conventional simple calculations. The interested readers refer to reference[8]. Substation arrangements as case 2 shall be decided 0.040, 2.180, 5.200 and 6.720[km], respectively.

Table 9. Substation capacity design

	Rectifier power[kW]				Transformer Cap.[kVA]
Substation No	SS1	SS2	SS3	SS4	-
1 bank Cap.	1500	1500	1500	1500	2000
Substation Cap.	3000	3000	3000	3000	2000 x 2

Finally, regenerative inverter unit should be satisfied with the simulation result in Table 9. Regenerative power was simulated and gotten in a case with 3 different headways for future passengers. Table 10 shows the results of regenerative power simulation.

Table 10. Regenerative power [kW]

Headway	SS1		SS2		SS3		SS4		Note
	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	
120 sec	103	1412	87	923	91	1252	64	900	Design
210 sec	104	1265	115	1216	70	665	53	530	2016year
300 sec	64	1399	90	1269	99	1231	58	586	2006

Considering the margin and economical point, the design results of regenerative inverter unit are as shown in Table 11.

Table 11. Regenerative inverter capacity design

	Power	Value	%	Design
SS1	Eff.	314	157	Inverter : 200[kW] (100% cont., 500% 30sec) Transformer : 400[kVA]
	Avg.	104	52	
	Max.	1412	706	
SS2	Eff.	246	123	Inverter : 200[kW] (100% cont., 500% 30sec) Transformer : 400[kVA]
	Avg.	115	57	
	Max.	1269	635	
SS3	Eff.	255	127	Inverter : 200[kW] (100% cont., 500% 30sec) Transformer : 400[kVA]
	Avg.	99	49	
	Max.	1252	626	
SS4	Eff.	173	86	Inverter : 200[kW] (100% cont., 500% 30sec) Transformer : 400[kVA]
	Avg.	64	32	
	Max.	900	450	

5. Conclusions

In this paper, we clarified and systematized the design procedure and its assessment for DC traction power supply system of a LRT line, which is being most important in case of introduction and operation of the system. The main conclusions in this paper are summarized as follows.

1) For the analysis and design of the system, characteristics of a train, feeding network

configuration, and design method of substation arrangements have been clarified.

2) The development of a computer program for the design and its assessment of the system has been made using the most suitable iterative method with nodal equation at network analysis and power calculations.

3) In order to evaluate and design the system from computer simulation results the procedure was proposed.

4) To verify the proposed design procedure and effectiveness of the developed program, the design of DC traction system for a planed Korean Light Rail Transit(LRT) line was conducted. Therefore, most suitable locations of the substation and their capacities were determined using the result of simulation according to the proposed procedure based on the IEC and the EN50163.

The systematized design process together with the program developed at this study is expected to be used as a reference to determine the capacity for the DC feeding electrification systems in the electric railway.

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◇ 저자소개 ◇

백병산(白秉山)

1963년 6월 16일생. 1987년 부경대학교 전기공학과 졸업. 1991년 부산대학교 대학원 전기공학과 졸업(석사). 2005년 숭실대학교 대학원 전기공학과 졸업(박사). 현재 현대중공업(주) 기계전기연구소 수석연구원.

김재철(金哉哲)

1955년 7월 12일생. 1979년 숭실대학교 전기공학과 졸업. 1983년 서울대학교 대학원 전기공학과 졸업(석사). 1987년 동 대학원 전기공학과 졸업(박사). 현재 숭실대학교 전기공학부 교수.

문종필(文鍾必)

1977년 5월 27일생. 2000년 숭실대학교 전기공학과 졸업. 2002년 숭실대학교 대학원 전기공학과 졸업(석사). 2004년 동 대학원 전기공학과 박사수료. 현재 기초전력연구원 선임연구원.

최준호(崔峻豪)

1970년 7월 30일생. 1996년 숭실대학교 전기공학과 졸업. 1998년 동 대학원 전기공학과 졸업(석사). 2002년 동 대학원 전기공학과 졸업(박사). 2002년 서울대학교 BK21박사후연구원. 현재 전남대학교 전기공학과 조교수.