A Novel Fault Location Scheme on Korean Electric Railway System Using the 9-Conductor Representation

Hansang Lee, Changmu Lee, Hanmin Lee, Gilsoo Jang, and Sanghoon Chang

Abstract— **This paper presents a novel fault location scheme on Korean AC electric railway systems. On AC railway system, because there is a long distance, 40 km or longer, between two railway substations, a fault location technique is very important. Since the fault current flows through the catenary system, the catenary system must be modeled exactly to analyze fault current magnitude and fault location. In this paper, before suggestion for the novel scheme of fault location, a 9-conductor modeling technique that includes boost wires and impedance bonds is introduced, based on the characteristics of Korean AC electric railway. After obtaining a 9-conductor modeling, the railway system is constructed for computer simulation by using PSCAD/EMTDC. By case studies, we can verify superiority of a new fault location scheme and suggest a powerful model for fault analysis on electric railway systems.**

***Index Terms*—Fault analysis, Boost wire, Korean AC electric railway system, Fault current ratio**

I. INTRODUCTION

An electric railway system has a number of advantages in terms of traffic capability, energy efficiency, operational cost and environmental friendliness in comparison with other transportation systems[1]. However, the faults that threaten safety of passengers or proper operations of electrical signal equipments are inevitable phenomena on electric railway system. Especially, because the electric railway systems are combined systems by static and dynamic electrical system, the probability of fault occurrence is much higher than general electric power systems[2]. Actually, railway vehicles supply electric power through pantographs that play roles as junction between static and dynamic electrical system. As the vehicles run, the catenary systems experience frictional wear and snapping finally. Because of this reason, the fault analysis on electric railway system has been a main research theme.

Before performing fault analysis, first of all, it is important to model Korean AC electric railway system. The existing model which has been used on fault analysis is 5-conductor reduced equivalent modeling [3] by using reduced equivalent method [4]. However, this 5-conductor reduced equivalent model does not consider boost wires and impedance bonds. The boost wires are connections between protection wires and rail to absorb the current flowing on rail [5] and the impedance bonds are connections of two protection wires, two rails, and buried earth wires to reduced total impedance of these 5 conductors by placing them parallel. The 5-conductor reduced equivalent model is not suitable for a novel fault location scheme in this paper because the model does not express the boost wires and impedance bonds. To make the model appropriate for a novel scheme, the 9-conductor reduced equivalent model is suggested by using PSCAD/EMTDC[6].

An existing fault location scheme is to calculate current ratio by estimating fault current on two autotransformers[7]. However, in Korean electric railway system, railway substations are located per about 40km, and 3 auto-transformers are placed as sectioning post and parallel post between two substations. That is, the distance between two autotransformers is about 10km. Although this scheme is very accurate and its locating error rate is 1~2%, the actual locating error becomes 100~200m because the distance between two fault current detectors is about 10km.

Because the faulted catenary system may cause railway vehicles operation interrupted, they should be restored as soon as possible. Moreover, since unmanned automation technique on railway substation is one of the electrical technique trends, needed time for restoring gets higher. By these reasons, the railway system operators need to bring down restoring time. There is only way not to reduce the locating error rate but to reduce the locating error. Therefore, in the novel fault location scheme, fault current detectors are installed on boost wires which are placed per 1.2km. The location error can be reduced significantly by installing detectors closely. If the novel scheme has same location error rate with conservative scheme, the location error becomes 12~24m.

II. KOREAN AC ELECTRIC RAILWAY SYSTEMS

The Korean AC electric railway systems are based on single-phase 55/27.5kV AC feeding circuits supply electric trains with electric power via three-to-two-phase Scott transformers, feeders, contact wires, and rails. The auto-transformer is designed with a turn ratio of 1:1. The parallel

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post(PP) is located at approximately every 10 km. Substations (SS) are located at about every 40~50 km, and a sectioning post (SP) is located between two substations, The SP has circuit breakers which enable one feeding circuit to electrically separate from the other. They may be closed in case the adjacent SS is out of service. General electric railway system in Korea is illustrated on Figure 1.

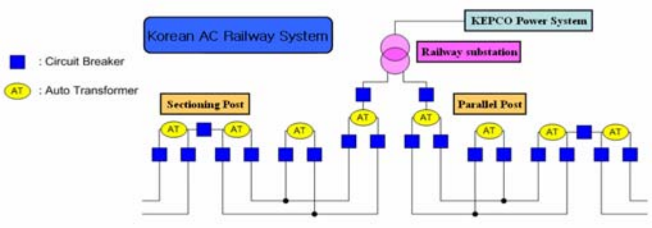

Fig 1. Configuraion of Korean AC Railway System

To make a reasonable model for AC railway system, it is the most important to construct a definite model for catenary system, because the fault current flows on the catenary system by impedance ratio.

Defining the methodology for catenary system equivalence, other parts should be constructed exactly. Models for KEPCO power system, Scott transformer, and autotransformer are followed.

A. KEPCO power system

Korean AC railway systems are supplied electric power from KEPCO power system by 154kV. In this paper, the electric source model is modeled by voltage source and source impedance. The voltage magnitude of the voltage source is 154kV for line-to-line rms value. The source impedance parameters can be obtained from sequence data of the KEPCO power system. The impedance parameters can be seen as below.

Table 2. Source impedance parameters

Sequence	Percent impedance	Base value
Positive	0.105+j1.645	100 MVA 154 kV
Negative	0.105+j1.645	
Zero	0.294+j3.372	

B. Scott transformer

Since general generator configuration, electric power systems generate and transmit electric power based on 3 phase circuits. However, the railway systems just need two single phases for up-line rail and down-line rail. If the railway systems are supplied without any appropriate transformation, severe unbalance may be caused. To prevent the unbalance on the electric power system, the Scott transformer should be applied on railway substation.

Simply to say, the Scott transformers are to balance 3-phase source circuit by transformation from 3-phase circuit to two single phase circuits by using two single-phase transformers. Winding configurations can be seen on Figure 2.

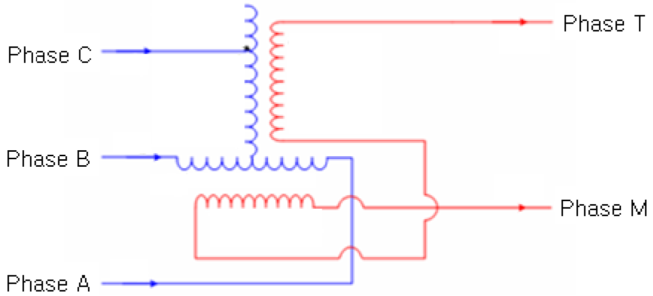

Fig 2. Scott transformer windings

Because the Scott transformers converse 3-phase circuit to two single phase circuits, single phase MVA capacity of secondary winding becomes half of 3-phase capacity. Therefore, impedances Z_{TR} of phase M or T are calculated by following equation 1.

$$Z_{TR} = \%Z_{TR} \frac{10 \cdot V^2}{P_{TR}/2} \; [\Omega] \tag{1}$$

Here, Z_{TR} : Impedance of phase M or T

$\%Z_{TR}$: Percent impedance of Scott transformer

V : Voltage (55kV)

P_{TR} : 3-phase capacity of Scott transformer [kVA]

C. Autotransformer

Because distances between two railway substations are about 40~50km, it is important to keep AC voltage rated value. Also, since communication lines are installed parallel with feeders and the current on feeder fluctuates sharply with electric vehicle drive mode, the inductive interference may cause communication error severely. Therefore, the Korean AC railway systems employ autotransformers to mitigate AC voltage drop and inductive interference. Two terminals and neutral lines of Scott transformers are connected to feeders, contact wires, and rails.

D. EMTDC models construction

To make railway system on EMTDC, the source system and Scott transformer are constructed as figure 3. Since the source system is modeled by using 345/154 substation, transmission line module is added.

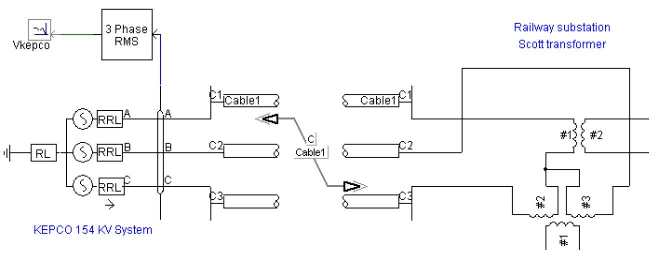

Fig 3. KEPCO power system and Scott transformer

Figure 4 illustrates autotransformer model and connection with railway catenary system.

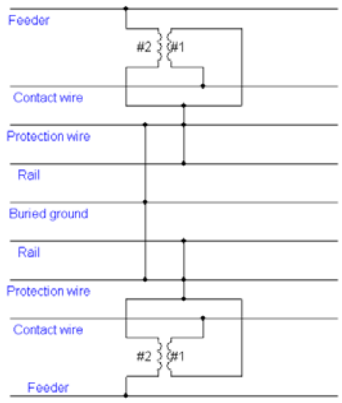

Fig 4. Autotransformer and catenary system

III. CATENARY SYSTEMS

Korean railway catenary system which is located between two autotransformers has 14 parallel conductors. Figure 5 illustrates catenary system which is composed of feeder, contact wire, protect wire, messenger wire, earth wire, and two rails for up-line and down-line each. Actually, these conductors are not electrically separated. That is, there are some equi-potential conductors.

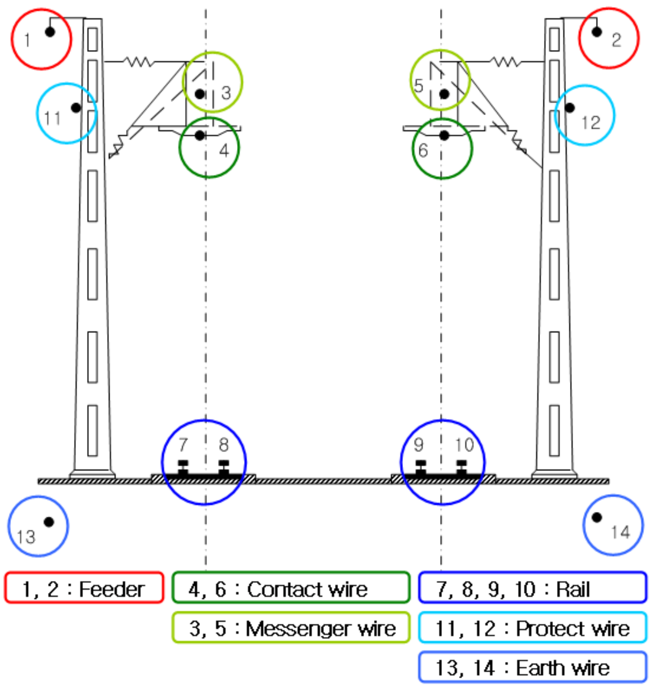

Fig 5. Catenary system : actual conductor configuration

The mainstream for analyzing the railway system is to model the catenary system to 5-conductors group. Conductor grouping is illustrated on figure 5[5]. In other words, the reduced equivalent model is composed of two feeders, two contact wire conductors groups, and one rail conductors group. However, because this paper suggests a novel fault location technique by sensing boost wire current, rail conductors group is equivalently reduced for five separate conductors. The conductor grouping methodology is explained below.

A. *Self-impedance of virtual conductor*

Two conductors which are equi-potential can be reduced as figure 6. On figure 6, assuming V_a and V_b are same, Z_1 can be calculated as equation 2.

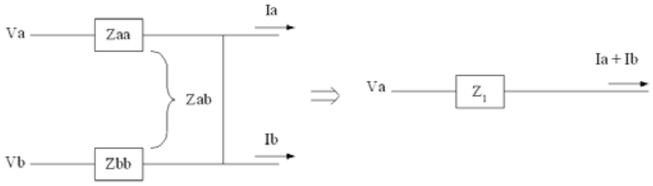

Fig 6. Self-impedance of virtual conductor

$$Z_1 = \frac{Z_{aa} \cdot Z_{bb} - Z_{ab}^2}{Z_{aa} + Z_{bb} - 2Z_{ab}} \qquad (2)$$

Here, Z_{aa} : Self-impedance of conductor a

Z_{bb} : Self-impedance of conductor b

Z_{ab} : Mutual impedance between conductor a and b

This can be applied to reduce contact wire and messenger wire, or rail conductors

B. *Mutual impedance between conductors*

On part A, self-impedance can be obtained. Then, the mutual impedance should be considered for two cases, conductor group – conductor and conductor group – conductor group.

Figure 7 illustrates parameters for two conductors on group 1 and conductor c. The mutual impedance Z_{1c} should be found.

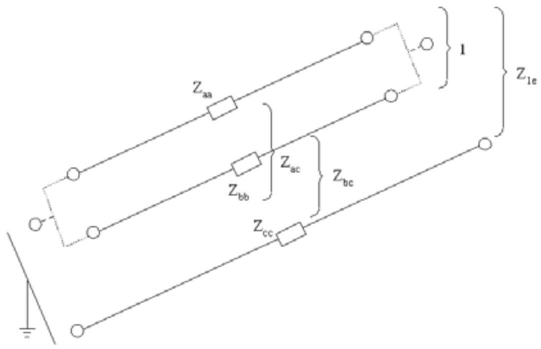

Fig 7. Mutual impedance between conductors group and conductor

$$Z_{1c} = \frac{Z_{ac}(Z_{bb} - Z_{ab}) + Z_{bc}(Z_{aa} - Z_{ab})}{Z_{aa} + Z_{bb} - 2Z_{ab}} \qquad (3)$$

Here, Z_{ac} : Mutual impedance between conductor a and c

Z_{bc} : Mutual impedance between conductor b and c

Also, the mutual impedance (Z_{12}) between two conductor groups should be defined as seen figure 8. Finding mutual impedance between rail conductors group and contact wires group, equation 4 can be used.

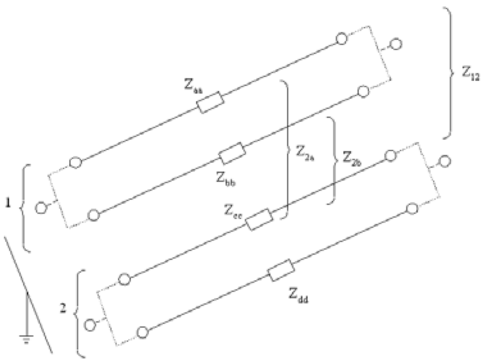

Fig 8. Mutual impedance between tow conductors groups

$$Z_{12} = \frac{Z_{2a}(Z_{bb} - Z_{ab}) + Z_{2b}(Z_{aa} - Z_{ab})}{Z_{aa} + Z_{bb} - 2Z_{ab}} \qquad (4)$$

Here, Z_{2a} : Mutual impedance between a and group 2

Z_{2b} : Mutual impedance between b and group 2

C. Boost wires and impedance bonds

Boost wires are electric connections which absorb the recurred current on rail to protect wire. On Korean railway system, they are installed per 1.2km. Impedance bonds that connect protect wires and earth wires are installed with boost wires.

IV. EMTDC Railway Systems

To simulate the novel fault location scheme, it is one of the most important to construct the railway systems on any digital simulation tool. In this paper, EMTDC (Electro-Magnetic Transient Design and Control) is chosen and the railway system is constructed as seen on figure 9. This system is modeled for two sectioning post for 43.2km. That is, it includes one railway substation at the center of it and two parallel posts between section post and substation.

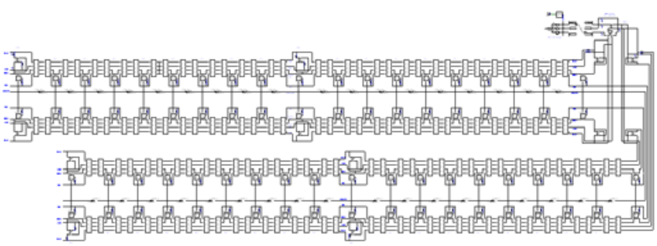

Fig 9. Railway systems on EMTDC

The system can be divided for four parts and each part has eight boost wires. The current sensors on boost wires are installed as seen on figure 10. Railway system on figure 9 has 64 current sensors.

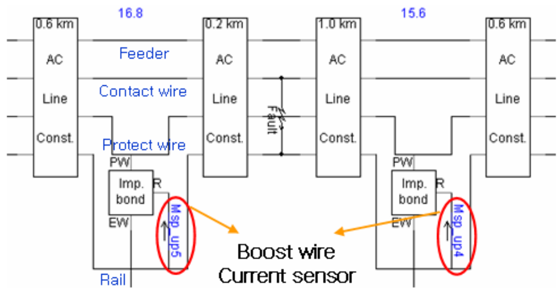

Fig 10. Boost wires and current sensors

On figure 10, there are 'AC Line Constant' modules. This module includes catenary system which is reduced and reconstructed as mentioned on part III. Each module receives the length as an input to determine fault location.

V. Case Studies

The novel fault location scheme finds faults by calculating the current ratio on two boost wire which has maximum current values. That is, the main point of this algorithm is to find two specific boost wires and maximum values of theirs and to calculate current ratio. The first operation is to find rough location of fault and the second operation is to determine accurate location in the section obtained by the fist operation. Part V performs various fault cases by fault types and several conditions.

A. Fault location for contact wire to ground fault

The faults between contact wire and ground are the most frequent faults in the railway system, because contacts wires physically contact with railway vehicle by pantograph. Actually, since the electric vehicles moves fast, contact wires are subjected to wear. In this part A, the fault on 16.6km is assumed as seen on figure 10.

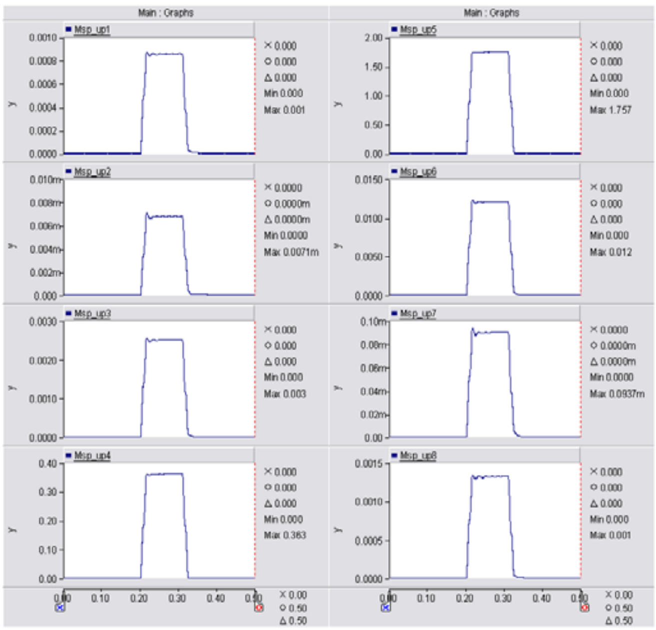

Fig 11. Current on boost wires (kA)

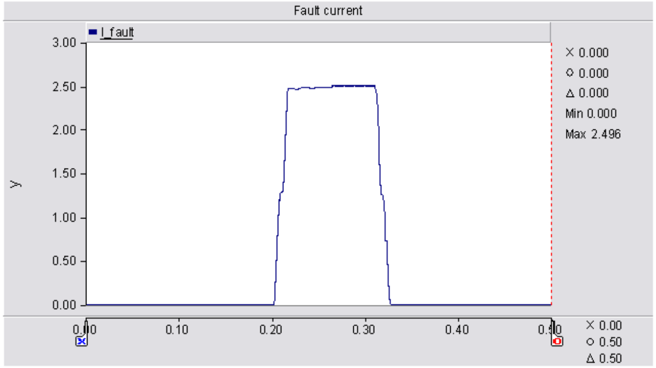

Fig 12. Fault current

Figure 11 illustrates the current magnitude on boost wires and figure 12 display fault current. On figure 11, the fourth and the fifth boost wires have maximum values. (Other 56 current sensors have much lower value) That is, we can find that the fault location is between 15.6km and 16.8km.

The fourth sensor value is 0.363[kA] and the fifth value is 1.757[kA]. By the current division rule, we can determine the accurate distance from the fourth boost wire as equation 5. Finally, the accurate fault location can be determined as equation 6.

$$1.2 \times \frac{1.757}{1.757+0.363} = 0.9945 \text{ [km]} \tag{5}$$

$$15.6 + 0.9945 = 16.5945 \text{ [km]} \tag{6}$$

B. Fault location for feeder to ground fault

When the faults between feeder and ground are occurred, current values and fault current value are on table 2. For the values on table 2, applying equation 5 and 6, the fault location can be calculated to 16.5946km.

Table 2. Simulation results for feeder to ground fault on 16.6km

	Current(kA)		Current(kA)
BW #1	0.000615	BW #2	0.0000135
BW #3	0.003	BW #4	0.395
BW #5	1.913	BW #6	0.013
BW #7	0.00011	BW #8	0.001
Fault current		2.718 kA	

C. Fault location for various fault impedances

Fault impedance on part A and B is assumed to 0.01 [Ohm]. On part C, fault location scheme for various fault impedances is analyzed.

The fault is still on 16.6km and fault type is contact wire to ground fault. Regarding that the base case is on part A, case 1 is with 0.1 [Ohm] fault impedance and case 2 is with 0.5 [Ohm]. In a practical manner, although it is announced that the fault impedance just effect the magnitude of fault current, the various cases are simulated to verify whether it has an effect on the novel fault location scheme. The results are on table 3.

Table 3. Simulation results for various fault impedances

	Cases	Current		Cases	Current
BW #1	Basecase	0.000871	BW #2	Basecase	0.000007
	Case 1	0.000870		Case 1	0.000007
	Case 2	0.000863		Case 2	0.000007
BW #3	Basecase	0.003	BW #4	Basecase	0.363
	Case 1	0.003		Case 1	0.363
	Case 2	0.003		Case 2	0.361
BW #5	Basecase	1.757	BW #6	Basecase	0.012
	Case 1	1.756		Case 1	0.012
	Case 2	1.747		Case 2	0.012
BW #7	Basecase	0.000094	BW #8	Basecase	0.001
	Case 1	0.000093		Case 1	0.001
	Case 2	0.000092		Case 2	0.001
Fault current		Basecase		2.496 [kA]	
		Case 1		2.495 [kA]	
		Case 2		2.483 [kA]	

From table 3, determined fault locations are 16.5945, 16.5935, and 16.5945km. It is concluded that the fault impedance does not severely influence fault location of the novel one.

D. Fault location with electric vehicle

It is needed to verify whether the electric vehicle has an effect on the novel fault location scheme. For the same fault on part A, two cases are suggested. Case 1 is with electric vehicle that is far from the fault and case 2 is with electric vehicle that is same place with fault. Table 4 summarizes the simulation results.

Table 4. Simulation results for various location of electric vehicle

	Cases	Current		Cases	Current
BW #1	Basecase	0.000871	BW #2	Basecase	0.000007
	Case 1	0.002		Case 1	0.272
	Case 2	0.000878		Case 2	0.000008
BW #3	Basecase	0.003	BW #4	Basecase	0.363
	Case 1	0.272		Case 1	0.368
	Case 2	0.003		Case 2	0.372
BW #5	Basecase	1.757	BW #6	Basecase	0.012
	Case 1	1.779		Case 1	0.012
	Case 2	1.798		Case 2	0.013
BW #7	Basecase	0.000094	BW #8	Basecase	0.001
	Case 1	0.000094		Case 1	0.001
	Case 2	0.000095		Case 2	0.001
Fault current		Basecase		2.496 [kA]	
		Case 1		2.531 [kA]	
		Case 2		2.558 [kA]	

From table 4, determined fault locations are 16.5945, 16.5943, and 16.5943km. It is concluded that the existence does not severely influence the novel fault location scheme.

VI. Conclusions

This paper suggests the novel fault location scheme to overcome location error of existing scheme. The most problem of existing one is that it generates 200[m] fault location error due to 10 km distance between current sensors. Therefore, the novel one suggests installing current sensors on boost wires which is located per 1.2km.

To construct the railway system that includes boost wires and impedance bonds, the existing 5-conductors catenary system model is needed to be modified to 9-conductors model. Actual 14 conductors are reduced to 9 conductor groups by the methodology that is explained part III, catenary systems. With this 9-conductors model, the railway system is constructed by adding the modules on part II.

Through part V, case studies, the superiority oh the novel fault location is verified. It can calculate accurate fault location for any fault type. Also, through the simulations with various fault impedances, the fault location error does not extend by the changes of fault impedance. Finally, existence and location of electric vehicle do not interrupt its fault location operations.

By applying the novel fault location scheme, it is expected that maintenance with stable railway operations and higher efficiency can be realized.

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VIII. Biographies

Hansang Lee was born in Korea in 1980. He received B.S. and M.S. degree in electric engineering from Korea University, Korea. He is currently pursuing Ph.D. degree at Korea University graduate school. His research interests include railway system, power quality, renewable generation, and energy storage system.

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