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전기철도 시스템의 사고 해석

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Fault Analysis for Electric Railway System

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Abstract - This paper presents the modeling of grounding system on Korean electric railway system. The system model is composed of the catenary system, the grounding-system, the sub-sectioning post, the fault point, the sectioning post, the autotransformer in the substation, and the electric vehicle. The increment of rail-ground voltage may be thought as an amplifier of danger on human body of equipment insulation. The rail-ground voltage on steady state and on fault condition should be under standard limit voltage. To analyze grounding system for steady state and fault condition on Korean railway, modeling for each railway system is performed by 10-port network model. Modeling and analysis of present grounding-system are important to protect human and electronic equipments. The examinations for systematic grounding-system are investigated.

1. Introduction

The 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. Nonetheless, it still has matters of unexpected fault occurrence threatening the safety of passengers or electrical and signal equipments [1].

On electric equipments of the railway, electric faults are inevitable and fatal. Especially, if a line-to-ground fault occurs, because fault current flows into the ground, the electric potential difference is occurred inside and outside of electric equipments and it is danger to human safety or the insulation of equipments. Moreover, in according to steep increment of power consumption by increment of output power of electric railway vehicles, the short circuit capacity increases and the electric potential difference by fault current rises significantly. Consequently, the increment of rail-ground voltage may be thoughtas an amplifier of danger on human body or the insulation of equipments. To prepare these problems, grounding-system is applied to the electric railway system in Korea. However, in case of an electric railway system in Korea, it is a disadvantage that an earth resistivity for the heart of a city and mountain area is high. Therefore, through the design for the grounding-system coincident with upper conditions, it is needed to establish countermeasures to suppress a rise of the rail-ground voltage and to control the magnitude of the fault current.

To analyze the grounding system for steady state and fault condition, modeling for each railway system is performed by 10-port network model. The modeling is performed for the catenary system, the grounding-system, the sub-sectioning post, the fault point, the sectioning post, the autotransformer in the substation, and the electric vehicle. Also, for each part, several cases are considered.

Korean railway system is composed by the common grounding system, which means rails on up/down track, protection wires on up/down track and grounding conductors are connected commonly. The overall conductors should be reduced equivalent 5 conductors electrically. The railway system is expressed by port network model. Korean railway systemwas represented by 8-port network model for harmonic analysis in the past papers[2, 3]. In this paper, Korean railway system should be modeled by 10-port representation for the analysis of steady state and fault condition.

10-port representation means that the system has 5 input ports, 5 output ports and a basic port. Namely, there are input/output ports of feeders on up/down track, input/output ports of contact wire groups on up/down track, input/output port of rail group and input/output port of the ground. The entire system can be easily modeled by the combination of 10-port representation of each component in parallel and/or series. The grounding systems are defined as three cases in the paper. Case 1 is for the system that has the ground-wire on only one side, case 2 is for the system that has two ground-wires, and case 3 is for the system that has one ground-wire and one GV80㎟ wire. The earth resistivity in Korea is about under 1,000 $\Omega \cdot m$. The earth resistivity is varied by temperature and humidity. The earth resistivities in this paper are defined as three cases of 200 $\Omega \cdot m$, 500 $\Omega \cdot m$, and 1,000 $\Omega \cdot m$, because the simulations regarding the rest of three cases can be simply performed on each condition. The AC electric railway systems in Korea are based on single-phase 55kV/27.5kV. AC feeding circuits supply electric trains with the electric power through 3-phase to 2-phase Scott-transformers, feeders, contact wires and rails. Autotransformers are installed approximately every ten kilometers with circuit breakers, which connect adjacent up and down tracks at the substation, the parallel post, and the sectioning post. If the distance of the Integral cross connection (ICC) is very short, there is no quietly cost-effectiveness. If it is very long, the rail-ground voltage may not be under standard limit voltage.

Finally, Fault current weakens reliability of equipment and occurs malfunction on relay or other electronics. Therefore, to analyze grounding system for steady state and fault condition on Korean railway, modeling for each railway system is performed by 10-port network model. Most of all, modeling and analysis of present grounding-system are important to protect human and electronics. The examinations for systematic grounding-system are investigated. On the general condition of the earth resistivity and the distance of ICC in Korean railway, we verify whether case 1, 2 and 3 are suitable in Korean railway or not. The rail-ground voltage is investigated.

2. System modeling

The AC electric railway system in Korea is based on single-phase 55 kV / 27.5 kV. AC feeding circuits supply electric trains with the electric power through 3-phase to 2-phase scott-transformers, feeders, contact wires and rails. Autotransformers are installed approximately every ten kilometers with circuit breakers which connect adjacent up and down tracks at the parallel post (PP). Substations (SS) are located about every fifty kilometers away, and a sectioning post (SP) is 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 [4, 5].

A. Catenary system and grounding-system

Modeling for the electric railway system is based on 10-port network model. The system has 5 input ports and 5 output ports. And voltage and current of components on 10 ports are noticed. The catenary system has several conductors with a complex geometry. The system consistsof contact wires (4, 6), messenger wires (3, 5), feeders (1, 2), rails (7, 8, 9, 10), protection wires (11, 12), and ground wires (13, 14). Droppers connect two conductors such as the contact wire and the messenger wire. Those conductors are electrically regarded as one conductor. This simplification is made possible by the auto aforementioned continuous parallel connection of some conductors. Finally, we can reduce the overall conductors to equivalent 5 conductors electrically [6]. The catenary system is denoted as follows:

C1: contact wire group on up track
F1: feeder on up track
R : rail group
C2: contact wire group on down track
F2: feeder on down track

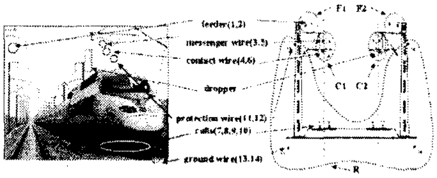

Fig. 1. Configuration of catenary system

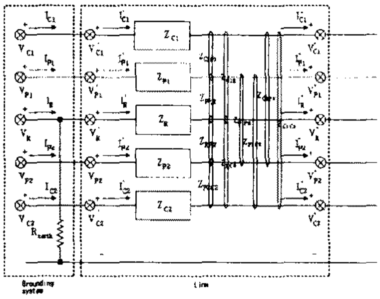

Fig. 2. A model for catenary system and grounding-system

Modeling on Fig. 2 consists of the catenary system and the grounding-system. Equation for these systems can be expressed as below. Eq. (1) is for the catenary system and Eq. (2) is for the grounding-system.

$$\begin{bmatrix} V'_{C1} \\ V'_{F1} \\ V'_{P} \\ V'_{C2} \\ V'_{F2} \\ I'_{C1} \\ I'_{F1} \\ I'_{P} \\ I'_{C2} \\ I'_{F2} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & Z_{C1C1} & Z_{C1F1} & Z_{C1P} & Z_{C1C2} & Z_{C1F2} \\ 0 & 1 & 0 & 0 & 0 & Z_{F1C1} & Z_{F1F1} & Z_{F1P} & Z_{F1C2} & Z_{F1F2} \\ 0 & 0 & 1 & 0 & 0 & Z_{PC1} & Z_{PF1} & Z_{PP} & Z_{PC2} & Z_{PF2} \\ 0 & 0 & 0 & 1 & 0 & Z_{C2C1} & Z_{C2F1} & Z_{C2P} & Z_{C2C2} & Z_{C2F2} \\ 0 & 0 & 0 & 0 & 1 & Z_{F2C1} & Z_{F2F1} & Z_{F2P} & Z_{F2C2} & Z_{F2F2} \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} V'_{C1} \\ V'_{F1} \\ V'_{P} \\ V'_{C2} \\ V'_{F2} \\ I'_{C1} \\ I'_{F1} \\ I'_{P} \\ I'_{C2} \\ I'_{F2} \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} V_{C1} \\ V_{F1} \\ V_{P} \\ V_{C2} \\ V_{F2} \\ I_{C1} \\ I_{F1} \\ I_{P} \\ I_{C2} \\ I_{F2} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{R_{earth}} & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} V'_{C1} \\ V'_{F1} \\ V'_{P} \\ V'_{C2} \\ V'_{F2} \\ I'_{C1} \\ I'_{F1} \\ I'_{P} \\ I'_{C2} \\ I'_{F2} \end{bmatrix} \qquad (2)$$

B. Sub-sectioning post

For sub-sectioning post, the model is shown in Fig. 3.

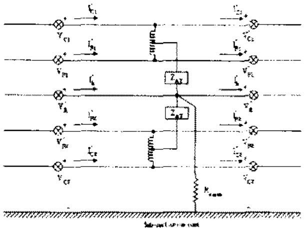

Fig. 3. A model for sub-sectioning post

The relations between voltage and current on 10-ports can be expressed as Eq. (3).

$$\begin{bmatrix} V'_{C1} \\ V'_{F1} \\ V'_{P} \\ V'_{C2} \\ V'_{F2} \\ I'_{C1} \\ I'_{F1} \\ I'_{P} \\ I'_{C2} \\ I'_{F2} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{4Z_{AT}} & \frac{1}{4Z_{AT}} & -\frac{1}{2Z_{AT}} & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ \frac{1}{4Z_{AT}} & \frac{1}{4Z_{AT}} & -\frac{1}{2Z_{AT}} & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -\frac{1}{2Z_{AT}} & -\frac{1}{2Z_{AT}} & \frac{2}{Z_{AT}}+\frac{1}{R_{earth}} & \frac{1}{2Z_{AT}} & -\frac{1}{2Z_{AT}} & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{1}{2Z_{AT}} & \frac{1}{4Z_{AT}} & \frac{1}{4Z_{AT}} & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{2Z_{AT}} & \frac{1}{4Z_{AT}} & \frac{1}{4Z_{AT}} & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} V''_{C1} \\ V''_{F1} \\ V''_{P} \\ V''_{C2} \\ V''_{F2} \\ I''_{C1} \\ I''_{F1} \\ I''_{P} \\ I''_{C2} \\ I''_{F2} \end{bmatrix} \qquad \text{..............................}(3)$$

C. Fault point

For faults, models are illustrated in Fig. 4.

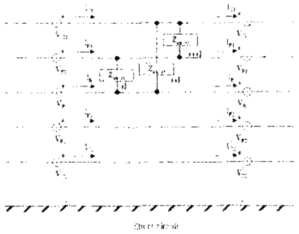

Fig. 4. A model for faults

Three combinations for three faults are considered. Each relation between voltage and current on 10-ports can be expressed as Eqs. (4) ~ (6).

1) Short between feeder line and rail

$$\left[\begin{array}{c} V_{C1} \\ V_{F1} \\ V_{P} \\ V_{C2} \\ V_{F2} \\ \hline I_{C1} \\ I_{F1} \\ I_{P} \\ I_{C2} \\ I_{F2} \end{array}\right] = \left[\begin{array}{ccccc|ccccc} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{Z_{short}} & -\frac{1}{Z_{short}} & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -\frac{1}{Z_{short}} & \frac{1}{Z_{short}} & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}\right] \left[\begin{array}{c} V'_{C1} \\ V'_{F1} \\ V'_{P} \\ V'_{C2} \\ V'_{F2} \\ \hline I'_{C1} \\ I'_{F1} \\ I'_{P} \\ I'_{C2} \\ I'_{F2} \end{array}\right] \qquad (4)$$

2) Short between contact wire and rail

$$\left[\begin{array}{c} V_{C1} \\ V_{F1} \\ V_{P} \\ V_{C2} \\ V_{F2} \\ \hline I_{C1} \\ I_{F1} \\ I_{P} \\ I_{C2} \\ I_{F2} \end{array}\right] = \left[\begin{array}{ccccc|ccccc} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \hline \frac{1}{Z_{short}} & 0 & -\frac{1}{Z_{short}} & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -\frac{1}{Z_{short}} & 0 & \frac{1}{Z_{short}} & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}\right] \left[\begin{array}{c} V'_{C1} \\ V'_{F1} \\ V'_{P} \\ V'_{C2} \\ V'_{F2} \\ \hline I'_{C1} \\ I'_{F1} \\ I'_{P} \\ I'_{C2} \\ I'_{F2} \end{array}\right] \qquad (5)$$

3) Short between feeder and contact wire

$$\left[\begin{array}{c} V_{C1} \\ V_{F1} \\ V_{P} \\ V_{C2} \\ V_{F2} \\ \hline I_{C1} \\ I_{F1} \\ I_{P} \\ I_{C2} \\ I_{F2} \end{array}\right] = \left[\begin{array}{ccccc|ccccc} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \hline \frac{1}{Z_{short}} & -\frac{1}{Z_{short}} & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{1}{Z_{short}} & \frac{1}{Z_{short}} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}\right] \left[\begin{array}{c} V'_{C1} \\ V'_{F1} \\ V'_{P} \\ V'_{C2} \\ V'_{F2} \\ \hline I'_{C1} \\ I'_{F1} \\ I'_{P} \\ I'_{C2} \\ I'_{F2} \end{array}\right] \qquad (6)$$

D. Sectioning post

For sectioning post, the model is expressed in Fig. 5.

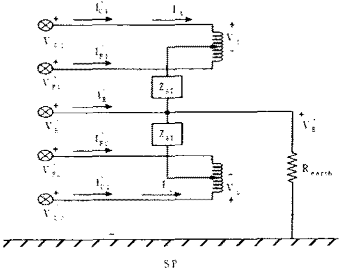

Fig. 5. A model for sectioning post

Eq. (7) expresses voltage and current relations for modeling sectioning post.

$$\begin{bmatrix} V'_{C1} \\ V'_{F1} \\ V'_{R} \\ V'_{C2} \\ V'_{F2} \\ \hline I'_{C1} \\ I'_{F1} \\ I'_{R} \\ I'_{C2} \\ I'_{F2} \end{bmatrix} = \left[\begin{array}{ccc|cc} 1 & 0 & 1 & 2Z_{AT} & 0 \\ -1 & 0 & 1 & 2Z_{AT} & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 2Z_{AT} \\ 0 & -1 & 1 & 0 & 2Z_{AT} \\ \hline 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{1}{R_{earth}} & -2 & -2 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{array}\right] \begin{bmatrix} V_1 \\ V_2 \\ V'_R \\ \hline I_1 \\ I_2 \end{bmatrix} \tag{7}$$

E. Autotransformer in substation

Like the sub-sectioning post and the sectioning post, the autotransformer in the railway substation is installed. A model for the autotransformer in the railway substation is shown in Fig. 6.

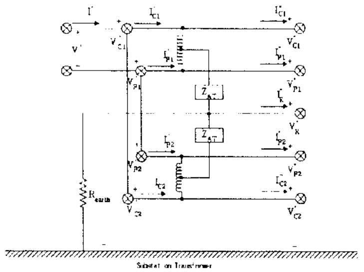

Fig. 6. A model for autotransformer in substation

Eq. (8) is expressed for the autotransformer in the substation.

$$\begin{bmatrix} E_M \\ E_M \\ E_M \\ E_M \\ E_M \end{bmatrix} = \left[\begin{array}{ccccc|ccccc} 1 & -1 & 0 & 0 & 0 & \frac{Z_M}{2} & -\frac{Z_M}{2} & 0 & \frac{Z_M}{2} & -\frac{Z_M}{2} \\ 0 & 0 & 0 & 1 & -1 & \frac{Z_M}{2} & -\frac{Z_M}{2} & 0 & \frac{Z_M}{2} & -\frac{Z_M}{2} \\ 1 & 0 & 0 & 0 & -1 & \frac{Z_M}{2} & -\frac{Z_M}{2} & 0 & \frac{Z_M}{2} & -\frac{Z_M}{2} \\ 2 & 0 & -2-\frac{Z_{AT}}{R_{earth}} & 0 & 0 & \frac{Z_M}{2} & -\frac{Z_M}{2} & -Z_{AT} & \frac{Z_M}{2} & -\frac{Z_M}{2} \\ 0 & 0 & -\frac{Z_{AT}}{R_{earth}} & 2 & 0 & 2R_{earth}+\frac{Z_M}{2} & 2R_{earth}-\frac{Z_M}{2} & 2R_{earth}-Z_{AT} & 2R_{earth}+\frac{Z_M}{2} & 2R_{earth}-\frac{Z_M}{2} \end{array}\right] \begin{bmatrix} V''_{C1} \\ V''_{F1} \\ V''_{R} \\ V''_{C2} \\ V''_{F2} \\ \hline I''_{C1} \\ I''_{F1} \\ I''_{R} \\ I''_{C2} \\ I''_{F2} \end{bmatrix} \tag{8}$$

F. Railway vehicle

For the railway vehicle, the model is expressed as a current source. Fig. 7 shows the modeling scheme.

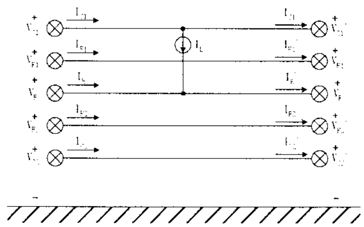

Fig. 7. A model for railway electric vehicle

To analyze railway system numerically, Eq. (9) is expressed for the model of the railway vehicle.

$$\begin{bmatrix} I''_{C1} \\ I''_{F1} \\ I''_{R} \\ I''_{C2} \\ I''_{F2} \\ \hline I'_{C1} \\ I'_{F1} \\ I'_{R} \\ I'_{C2} \\ I'_{F2} \end{bmatrix} = \left[\begin{array}{ccccc|ccccc} 1 &&&&&&&&& \\ & 1 &&&&&&&& \\ && 1 &&&&&&& \\ &&& 1 &&&&&& \\ &&&& 1 &&&&& \\ \hline &&&&& 1 &&&& \\ &&&&&& 1 &&& \\ &&&&&&& 1 && \\ &&&&&&&& 1 & \\ &&&&&&&&& 1 \end{array}\right] \begin{bmatrix} I''_{C1} \\ I''_{F1} \\ I''_{R} \\ I''_{C2} \\ I''_{F2} \\ \hline I''_{C1} \\ I''_{F1} \\ I''_{R} \\ I''_{C2} \\ I''_{F2} \end{bmatrix} + \begin{bmatrix} \\ \\ \\ \\ \\ \hline I_L \\ \\ -I_L \\ \\ \\ \end{bmatrix} \tag{9}$$

3. Analysis for voltage rising of rail–ground

To analyze voltage rising of the rail-ground, simulations for several cases are performed. There are categorized by the number of ground-wire, the kind of ground-wire, the specific ground resistance and the distance of ICC. Case 1 is for the system that has ground-wire on only one side, case 2 is for the system that has two ground-wires, and case 3 is for the system that has one ground-wire and one GV80 ㎟ wire. Case 3 is more economical than case 2, because case 3 doesn't need to dig the ground to establish the ground wire. The illustrations of case 1, case 2 and case 3 are shown in Fig. 8 respectively.

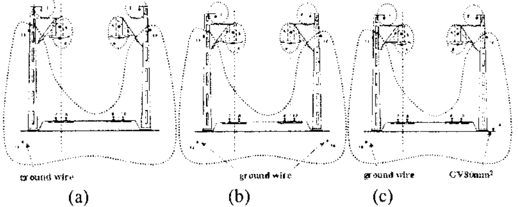

Fig. 8. Model of (a) case 1, (b) case 2, and (c) case 3

A. Simulation conditions

The transformer impedance on phase M, the autotransformer impedance, and the grounding resistance are applied for these simulations as following.

Table 1. Simulation conditions

Symbols	Meanings	Values
Z_m	Transformer impedance on phase M	0.264+j8.218
Z_{at}	Autotransformer impedance	j0.35
R_{earth}	Grounding resistance	

The value of grounding resistance is calculated by Eq. (10).

$$R=\frac{\rho}{2\pi l}\left(\ln\frac{2l}{r}-1+\ln\frac{l+\sqrt{l^2+4t^2}}{2t}+\frac{2t}{l}-\frac{\sqrt{l^2+4t^2}}{l}\right)[\Omega] \tag{10}$$

On Eq. (10), symbol r is radius of the ground-wire, symbol t is depth of the ground-wire, symbol l is length of the ground-wire, and symbol ρ is specific earth resistivity.

Assuming that short impedance is 5 [Ω], R_{earth} is applied on simulation after being defined by varying the value of earth resistivity as 200, 500, and 1,000 Ω·m.

The characteristics of various conductors used in the impedance calculations are listed in Table 2. The conductor coordinates for Korean railway system are listed in Table 3.

Table 2. Conductor characteristics

	Area [㎟]	Resistance [Ω/km]	Equivalent Diameter [cm]
Rail	76.35	0.0126	4.93
Contact wire	1.7	0.104	1.549
Messenger wire	0.8	0.276	1.15
Feeder	1.5	0.118	1.6
Protective wire	0.75	0.239	1.11
GV80	0.8	0.229	1.08
Ground wire	0.38	0.5579	1.11

Table 3. Conductor Coordinates for Korean railway system

Conductor	X Coordinate [m]	Y Coordinate [m]
Rail	-3.22	0.6
Rail	-1.78	0.6
Contact wire	-2.15	5.8
Messenger wire	-2.15	6.76
Feeder	-3.75	8.062
Protective wire	-5.15	6.1
Ground wire	-6.15	-0.75
Rail	1.78	0.6
Rail	3.22	0.6
Contact wire	2.15	5.8
Messenger wire	2.15	6.76
Feeder	3.75	8.062
Protective wire	5.15	6.1
GV80 ㎟	6.15	0

For the case 200 Ω·m, short current by fault is shown in Fig 9.

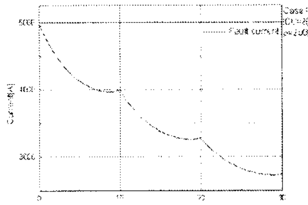

Fig. 9. Short current by fault

B. Analysis of rail-ground voltage on steady state

To simulate base cases, simulations are performed for two cases. On steady state, one is for one vehicle that is 0.5 km away from the railway substation and the other is for two vehicles that are 0.5 km and 15 km away from substation.

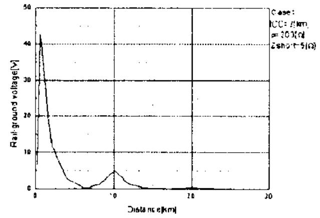

Fig. 10. Rail-ground voltage in case of one electric vehicle

Fig. 10 is the simulation result when one vehicle is 0.5 km away from railwaysubstation. In this case, load current is 400 A which means the Korea Train express (KTX) runs. The active power of the KTX is almost 15 MW. The peak voltage points appear the location of vehicle and the autotransformer. The maximum voltage is about 45 V.

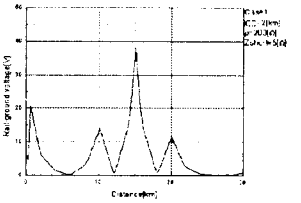

Fig. 11. Rail-ground voltage in case of two electric vehicles

Fig.11 shows the simulation result when two vehicles are 0.5 km and 15 km away from the railwaysubstation. Load current is 800 A. The peak voltage points appear at the location of vehicles and the autotransformer. The maximum voltage is about 38 V. On these steady state simulations, the rail-ground voltage of second case is under 60 V. EN50122-1 standard recommends that rail-ground voltage should be under 60 V although loads increase.

C. Rail-ground voltage on fault occurrence

Distances of the ICC are defined as 2.0km, 2.5km and 3.0km.

Simulations on three ρ values are performed for three cases and distances of the ICC. As mentioned before, case 1 is for the system that has ground-wire on only one side, case 2 is for the system that has two ground-wires, and case 3 is for the system that has one ground-wire and GV80 mm^2 wire. The values of earth resistivity are 200, 500, and 1,000 $\Omega \cdot m$. Simulations are performed for 27 cases combined three kinds of distance of ICC, three kinds of ρ values and cases 1~3. Objects of these simulations are to decide whether rail-ground voltage exceeds, 430 V, the limitation by Korean Railway Facility Regulation for any case and to find which method is superior for any ρ value and which grounding-system has better operation.

1) 200 $\Omega \cdot m$ of ρ value

When the distance of ICC is 2.0 km, the simulation results are shown in Fig. 12.

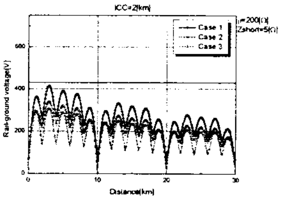

Fig. 12. Simulation result for 200 $\Omega \cdot m$ and 2.0 km of ICC

When the distance of ICC is 2.5 km, the simulation results are shown in Fig. 13.

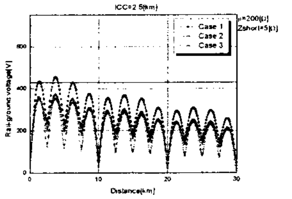

Fig. 13. Simulation result for 200 $\Omega \cdot m$ and 2.5 km of ICC

When the distance of ICC is 3.0 km, the simulation results are shown in Fig. 14.

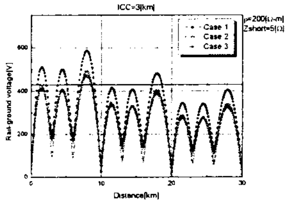

Fig. 14. Simulation result for 200 $\Omega \cdot m$ and 3.0 km of ICC

2) 500 $\Omega \cdot m$ of ρ value

When the distance of ICC is 2.0 km, the simulation results are shown in Fig. 15.

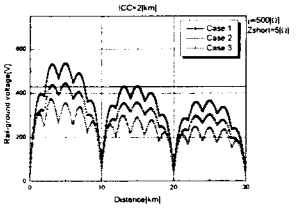

Fig. 15. Simulation result for 500 $\Omega \cdot m$ and 2.0 km of ICC

When the distance of ICC is 2.5 km, the simulation results are shown in Fig. 16.

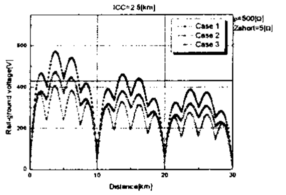

Fig 16. Simulation result for 500 $\Omega \cdot m$ and 2.5 km of ICC

When the distance of ICC is 3.0 km, the simulation results are shown in Fig. 17.

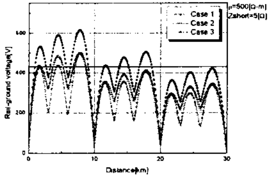

Fig. 17. Simulation result for 500 $\Omega \cdot m$ and 3.0 km of ICC

3) 1,000 $\Omega \cdot m$ of ρ value

When the distance of ICC is 2.0 km, the simulation results are shown in Fig. 18.

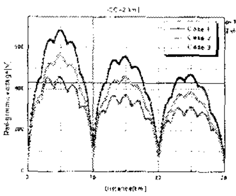

Fig 18. Simulation result for 1,000 Ω·m and 2.0 km of ICC

When the distance of ICC is 2.5 km, the simulation results are shown in Fig. 19.

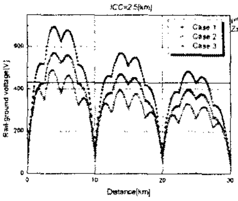

Fig. 19. Simulation result for 1,000 Ω·m and 2.5 km of ICC

When the distance of ICC is 3.0 km, the simulation results are shown in Fig. 20.

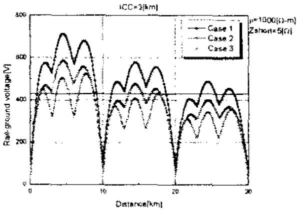

Fig. 20. Simulation result for 1,000 Ω·m and 3.0 km of ICC

For ICC length, the shorter ICC interval is installed, the higher constructing cost is. This means on these simulation that case 1 is more economic than case 3 and case 3 is more economic that case 2. However, case 2 and case 3 make the rail-ground voltage maintain under 430V.

By cost-effectiveness, In case of 200Ω·m, case 1 of 2.0km is optimal in this simulation. In case of 500Ω·m, case 2 of 2.5km is optimal in this simulation. In case of 1,000Ω·m, the rail-ground violatge of all cases are higher than limit voltage lever. other solutions should be suggested.

Table 4. Maximum voltage of rail-ground

			Distance of ICC		
			2.0 km	2.5 km	3.0 km
ρ	200 Ω·m	Case1	415 V	450 V	590 V
		Case2	305 V	350 V	495 V
		Case3	340 V	375 V	500 V
	500 Ω·m	Case1	540 V	570 V	610 V
		Case2	370 V	405 V	500 V
		Case3	440 V	470 V	500 V
	1,000 Ω·m	Case1	680 V	695 V	710 V
		Case2	455 V	490 V	520 V
		Case3	560 V	570 V	590 V

Through all over the simulation results it is known that the location of the maximum voltage of rail-ground is between substation and the location where the first autotransformer is installed. Also, the farther the location is from substation, the lower the peak voltage is. Based on these phenomena, it is suggested that the distance of ICCs between substation and the first autotransformer should reduce and the distance of other ICCs are remained. We set the distance of ICC from the substation to the first autotransformer to 1.5km. simulations are performed. Simulation results are on table 5.

Table 5. Maximum voltage of rail-ground (the distance of ICC from the substation to the first autotransformer : 1.5km)

			Distance of ICC		
			2.0 km	2.5 km	3.0 km
ρ	200 Ω·m	Case1	333 V	370 V	487 V
		Case2	248 V	294 V	406 V
		Case3	273 V	302 V	393 V
	500 Ω·m	Case1	433 V	462 V	505 V
		Case2	300 V	329 V	412 V
		Case3	358 V	380 V	409 V
	1,000 Ω·m	Case1	556 V	570 V	578 V
		Case2	368 V	394 V	428 V
		Case3	459 V	469 V	475 V

Resulty, by cost-effectiveness, in case of 200Ω·m, case 3 of 3.0km is optimal in this simulation. In case of 500Ω·m, case 3 of 3.0km is optimal in this simulation. In case of 1,000Ω·m, case 2 of 3.0km is optimal in this simulation.

Although the way to reduce the distance of ICC only from substation to the first autotransformer is suggested on this paper, the ICCs distance can be installed differently by the location from substation, when ground systems are constructed on field.

4. Conclusion

In this paper, the grounding systems are defined as three cases. Case 1 is for the system that has the ground-wire on only one side, case 2 is for the system that has two ground-wires, and case 3 is for the system that has one ground-wire and one GV80■ wire. The earth resistivity in Korea is about 100Ω·m ~ 1,500 Ω·m. The earth resistivity is varied by temperature and humidity. The earth resistivities in this paper are defined as three values of 200 Ω·m, 500 Ω·m, and 1,000 Ω·m, because the simulations regarding the rest of three cases can be simply performed on each condition. Distances of the ICC are defined as 2.0km, 2.5km and 3.0km.

Korean railway system is composed by the common grounding system, which means rails on up/down track, protection wires on up/down track and grounding conductors are connected commonly. The overall conductors should be reduced equivalent 5 conductors electrically. The railway system is expressed by port network model. Korean railway systemwas represented by 8-port network model for harmonic analysis in the past papers [2, 3]. In this paper, Korean railway system should be modeled by 10-port representation for the analysis of steady state and fault condition.

The examinations for systematic grounding-system are investigated. For the cases applying one ground-wire, two ground-wires, or one ground-wire and GV80■ wire, simulations by varying ρ values and distances of ICC are performed. In according to simulation results, if the distance of ICC is shorter and the ρ value is lower, the rail-ground voltage gets lower

The most economic optimal ground system is determined according to the values of earth resistivity, the distance of ICC, and the combination of case 1, 2, and 3. Because the maximum value of rail-ground voltage is presented between substation and the first autotransformer, the way to reduce the distance of ICC only from substation to the first autotransformer is suggested in this paper. However, the ICCs distance can be installed differently by the location from substation, when ground systems are constructed on field. In conclusion, this paper suggest the way to determine ground system by earth resistivity, the interval of ICC, the number of grounding wire, and the kind of grounding wire on 10-port network.

5. References

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