Harmonic Analysis Model based on PSCAD/EMTDC

Han-Min Lee†**, Chang-Mu Lee*, Gil-Soo Jang** and Sae-Hyuk Kwon****

Abstract - This paper presents the model for an AC electric railway system using the PSCAD/EMTDC program. It is composed of a scott-transformer, an auto-transformer, catenary and electric trains, etc. After obtaining the models of the fundamental elements describing the AC electric railway system and its behavior, we have analyzed and tested an actual AC electric railway system focused on the amplification of harmonic current to verify the proposed model. The simulation results from the proposed approach and the measurement data from the test are described.

Keywords: amplification of harmonic current, resonance frequency, PSCAD/EMTDC

1. Introduction

The modern AC electric train has thyristor or PWM (Pulse Width Modulation)-controlled converters, which give rise to higher harmonics. The harmonic current injected from the AC electric train is propagated through a power feeding circuit. As the feeding circuit is a distributed constant circuit composed of RLC, the capacitance and the inductance of the feeding circuit on the side of the power system cause a parallel resonance and amplification of harmonic current at a specific frequency.

The amplified harmonic current usually brings about various problems. That is, the harmonic current causes interference in the adjacent lines of communications and the railway signaling system. Furthermore, in case it flows on the side of the power system, not only overheating and vibration at the power capacitors but also erroneous operation at the protective devices can occur.

Therefore, an exact assessment of the harmonic current flow must be undertaken during the designing and planning stage for the AC electric railway systems. From this point of view, this study presents an approach to model and to analyze a traction power feeding system focused on the amplification of the harmonic current.

The system model is made using the PSCAD/EMTDC [1] program. Representation for each component of this system has many advantages:

1) Overhead catenary lines, which have impedances and shunt admittances, can be easily represented by the PSCAD/EMTDC.
2) Distributed circuit parameters for the line model can be effortlessly defined.
3) The entire system can be easily modeled by the combination of each component in parallel and/or series.
4) Harmonic calculation can be performed straightforwardly.

The proposed model is applied to a real AT (Auto-transformer)-fed system in which the electric train with thyristor-controlled converters is running. In order to verify the proposed model, we modeled the actual AC electric railway system using the PSCAD/EMTDC. We have analyzed and tested this system, which is focused on the amplification of the harmonic current. The simulation results from the proposed model and the measurement data from the test are described.

2. AC Electric Railway System

The AC electric railway systems are based on single-phase 55kV/27.5kV. They are connected to a three-phase power system to be supplied with a large single-phase load. AC feeding circuits supply vehicles with necessary power by a 3 to 2 phase Scott transformer through the feeder, contact wire and rail. Auto-transformers are installed at approximately every ten kilometers with circuit breakers, which connect adjacent up and down tracks at the parallel post (PP). Substations (SS) are located at about every fifty kilometers and there is a sectioning post (SP) midway 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 [2].

Fig. 1 shows an AC electric railway system.

In order to achieve an overall model to provide reliable results for the system in Fig. 1, particular attention must be given to the modeling of each subsystem. Fig. 2 illustrates

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the integrated model of each subsystem made by the PSCAD/EMTDC method.

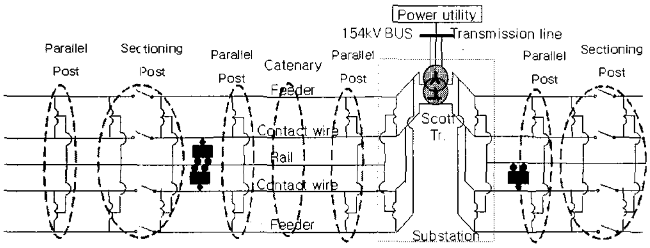

Fig. 1 AC electric railway system

2.1 Power supply

The power utility supplies 154kV to the AC electric railway system through underground transmission lines. The scott transformer in the substation is stepped down from 154kV to 55kV. Two pair of single-phase power is obtained from a scott connecting transformer. The turn ratios of T-phase and M-phase are $\frac{\sqrt{3}}{2}N_1 : N_2$ and $N_1 : N_2$ respectively.

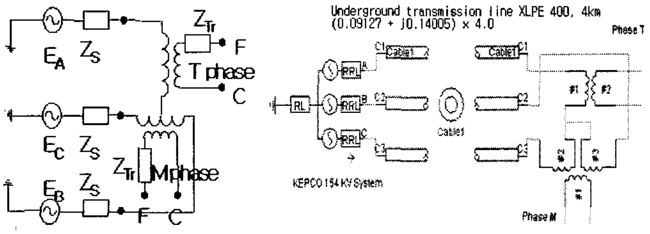

Fig. 3 Power utility, Transmission line, Main transformer

The scott transformer's characteristic is expressed as follows. The connection diagram of windings in the scott transformer appears in Fig. 4. The current and voltage relationships of the primary and secondary of the scott transformer are

$$I_L^a = \frac{-2}{\sqrt{3}}\frac{N_2}{N_1}I_{L1} \tag{1}$$

$$I_L^b = -\frac{i_L^a}{2} - \frac{N_2}{N_1}i_{L2} = \frac{N_2}{N_1}\left(\frac{1}{\sqrt{3}}i_{L1} - i_{L2}\right) \tag{2}$$

$$I_L^c = -\frac{i_L^a}{2} + \frac{N_2}{N_1}i_{L2} = \frac{N_2}{N_1}\left(\frac{1}{\sqrt{3}}i_{L1} + i_{L2}\right) \tag{3}$$

$$V_{L1} = -\frac{N_2}{N_1}V_{pcc}^{ab}\angle -30^o, \quad V_{L2} = j\frac{N_2}{N_1}V_{pcc}^{ab}\angle -30^o \tag{4}$$

and

$$V_{pcc}^a = \frac{V_{pcc}^{ab}\angle -30^o}{\sqrt{3}} \tag{5}$$

$$V_{pcc}^b = \frac{V_{pcc}^{ab}\angle -30^o}{\sqrt{3}}a^2 \tag{6}$$

$$V_{pcc}^c = \frac{V_{pcc}^{ab}\angle -30^o}{\sqrt{3}}a \tag{7}$$

$$V_{L1} = -\sqrt{3}\frac{N_2}{N_1}V_{pcc}^a, \quad V_{L2} = j\sqrt{3}\frac{N_2}{N_1}V_{pcc}^a \tag{8}$$

$$I_{L1}^* = \frac{S_{L1}}{V_{L1}} = \frac{-S_{L1}}{\sqrt{3}\frac{N_2}{N_1}V_{pcc}^a}, \quad I_{L2}^* = \frac{S_{L2}}{V_{L2}} = \frac{-jS_{L2}}{\sqrt{3}\frac{N_2}{N_1}V_{pcc}^a} \tag{9}$$

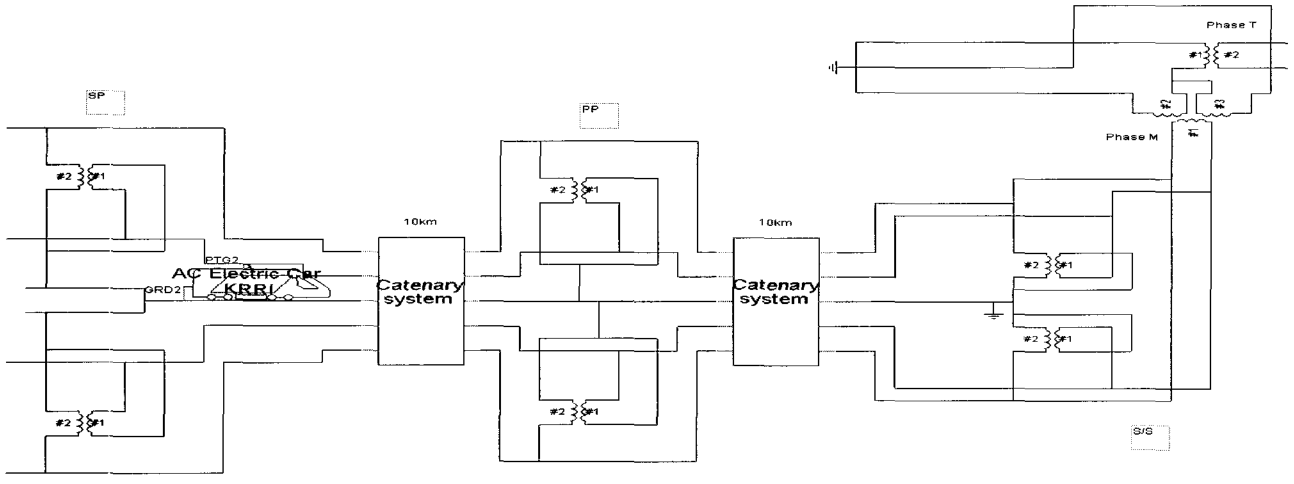

Fig. 2 Model of AC electric railway system

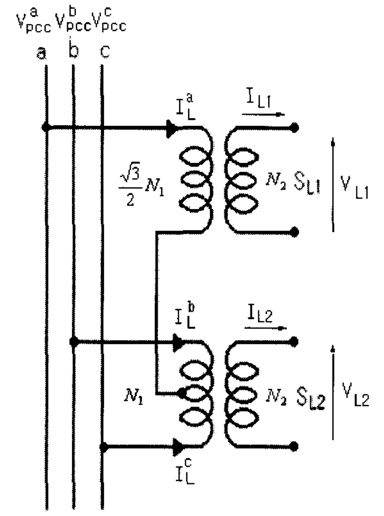

Fig. 4 Scott transformer

2.2 Auto-transformer

The auto-transformer is connected between the catenary and an adjacent feeder with the rails connected to the center point on the winding. The AC electric railway system supplies 55kV between the contact wire and the feeder with the auto-transformer of ratio 1:1 (feeder-rail : rail-contact wire) to obtain a 27.5 kV. The auto-transformer of the AC electric railway system steps down the high voltage (55kV) to 27.5kV

Auto-transformers are installed approximately every 10km along the railroad. The equivalent circuit of the auto-transformer is presented in Fig. 5.

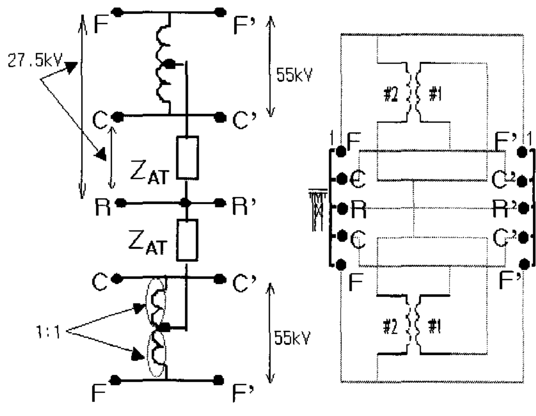

Fig. 5 Auto-transformer

2.3 Catenary system

The overhead catenary system has several conductors with a complex geometry. This system could consist of contact wires (4, 6), messenger wires (3, 5), feeders (1, 2), rails (7, 8, 9, 10), protection wires (11, 12) and buried earth wires (13, 14). Droppers every few meters connect two conductors such as contact wire and 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 overall conductors to the equivalent of 5 conductors [3, 4].

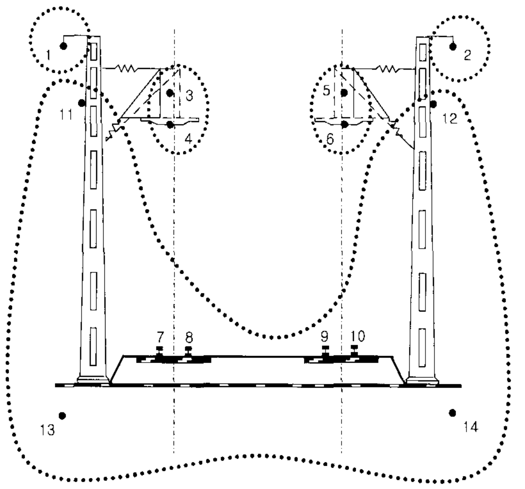

Fig. 6 Configuration of the contact lines

All values for impedances are evaluated using the carson equations. The equivalent 5 conductors are calculated by the reduction method. The reduced catenary system is composed by PSCAD/EMTDC. The equivalent model for the reduced catenary system is illustrated in Fig. 7.

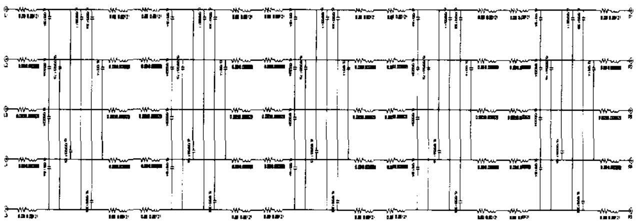

Fig. 7 Detailed model of the Catenary system

2.4 Harmonic Current source

A harmonic current source in the AC electrified railway system is, mainly, the electric train car. It can be considered as a harmonic current source injected from rail to contact line as shown in Fig. 8.

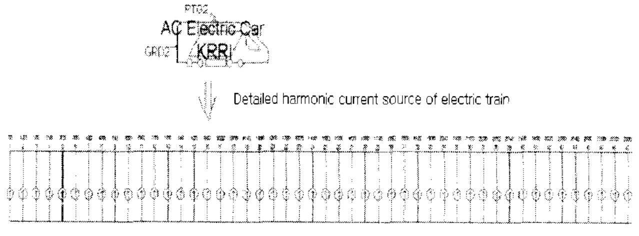

Fig. 8 Harmonic current source

3. Resonance Frequency and Amplification of Harmonic Current

The resonance frequency does not depend on the location of the electric train. Amplification of the harmonic is a function of the position of a train. The farther the train is from the substation, the higher the amplification of the harmonic current is. The longer the catenary length is, the lower the resonance frequency is. Thus, results are shown in this paragraph by the following equations [5].

3.1 Resonance frequency

From Fig. 9, we can write the following formula.

$$I_T = I_1 + I_2 \tag{10}$$

$$I_1 = I_T \cdot \frac{Z_2}{Z_1 + Z_2 + \frac{Z_1 \cdot Z_2}{Z_T}} \tag{11}$$

$$I_2 = I_T \cdot \frac{Z_1}{Z_1 + Z_2 + \frac{Z_1 \cdot Z_2}{Z_T}} \tag{12}$$

where

I_T : current of the electric train

I_1 : contact line current towards the substation

I_2 : contact line current towards the end of the line

Z_1 : contact line input impedance towards the substation and seen from the electric train

Z_2 : contact line input impedance towards the end of the supply section and seen from the electric train

Z_T : internal impedance of the electric train

$$Z_1 = Z_0 \cdot \frac{Z_{SS} \cosh \gamma L_1 + Z_0 \sinh \gamma L_1}{Z_{SS} \sinh \gamma L_1 + Z_0 \cosh \gamma L_1} (\Omega) \tag{13}$$

$$Z_2 = Z_0 \cdot \frac{\cosh \gamma L_2}{\sinh \gamma L_2} (\Omega) \tag{14}$$

where

L_1 : distance between the electric train and the substation

L_2 : distance between the electric train and the end of the feeder section

Z_{SS} : resultant impedance of the feeder substation

Z_0 : characteristic impedance of the contact line

γ : unit length propagation constant of the contact line

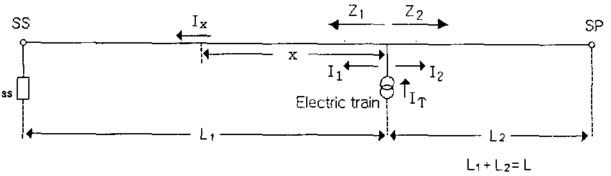

Fig. 9 Diagram of contact line

Z_1 and Z_2 are composed as the parallel circuit by the electric train. The parallel impedance, Z_P, is expressed by the following formula:

$$Z_P = \frac{Z_1 \cdot Z_2}{Z_1 + Z_2} = \frac{Z_0 \cosh\gamma(L - L_1) \cdot (Z_{SS} \cosh\gamma L_1 + Z_0 \sinh\gamma L_1)}{Z_{SS} \sinh\gamma L + Z_0 \cosh\gamma L} (\Omega) \tag{15}$$

When the denominator is zero from equation 15, the circuit becomes the condition of resonance. The harmonic current is amplified. And the resonance frequency is independent of the location of the electric train.

3.2 Amplification of harmonic current

From Fig 9, I_T is the current of the electric train. I_1 is the contact line current towards the substation. I_2 is the contact line current towards the end of the line. Assuming that the electric train may be replaced by an ideal current generator, Z_P must be considered as infinite.

$$I_1 = I_T \cdot \frac{Z_2}{Z_1 + Z_2} = I_T \cdot \frac{(Z_{SS} \sinh\gamma L_1 + Z_0 \cosh\gamma L_1)\cosh\gamma L_2}{Z_{SS} \sinh\gamma L + Z_0 \cosh\gamma L} (A) \tag{16}$$

The contact line current at point X is expressed as follows:

$$I_X = I_1 \cdot \frac{\cosh\gamma L_2 [Z_{SS} \sinh\gamma(L_1 - X) + Z_0 \cosh\gamma(L_1 - X)]}{Z_{SS} \sinh\gamma L + Z_0 \cosh\gamma L} (A) \tag{17}$$

I_X / I_1 can be defined as the amplification of harmonic current. The Amp (I_X / I_1) is expressed by the following equation.

$$Amp = \frac{\cosh\gamma L_2 [Z_{SS} \sinh\gamma(L_1 - X) + Z_0 \cosh\gamma(L_1 - X)]}{Z_{SS} \sinh\gamma L + Z_0 \cosh\gamma L} (pu) \tag{18}$$

When the location of the electric train is at the end of line ($L_2 = 0$), the harmonic current (I_X) is maximum.

From equation 17, the resonance condition of the system is expressed by the following equations.

$$Z_{SS} \sinh \gamma L + Z_0 \cosh \gamma L = 0 \tag{19}$$

$$\gamma L = \tanh^{-1}\left(-\frac{Z_0}{Z_{SS}}\right) \approx -\theta_\gamma \tag{20}$$

When the electric train is located at the end of line (SP), the condition is as follows.

$$L_2 = 0,\ I_1 = I_{SP},\ I_X = I_{SS} \text{ and } X = L \tag{21}$$

Finally, the amplification of harmonic current is expressed by the following equation.

$$K = \frac{I_{SS}}{I_{SP}} = \frac{Z_0}{Z_{SS}\sinh\gamma L + Z_0\cosh\gamma L}(pu) \tag{22}$$

Therefore, the farther the electric train is from the substation, the higher the amplification of harmonic current will be.

4. Case Studies

In order to verify the proposed model, we have analyzed and tested a real traction power feeding system focused on amplification of the harmonic current.

Fig 10 illustrates the harmonic current vs. vehicle location. We change the location of the electric train from the substation (0km) to 30km. All the resonance frequency is source at the 24th order, even if the location of the electric train is changed. The resonance frequency does not depend on the location of the vehicle as shown in Fig. 10. The amplification of the harmonic is, however, a function of the position of a train. The farther the electric train is from the substation, the higher the amplification of the harmonic current is. These results are similar to those of reference .

Fig. 11 illustrates the correlation between catenary length and harmonic resonance. From the result, the longer the catenary length is, the lower the resonance frequency is.

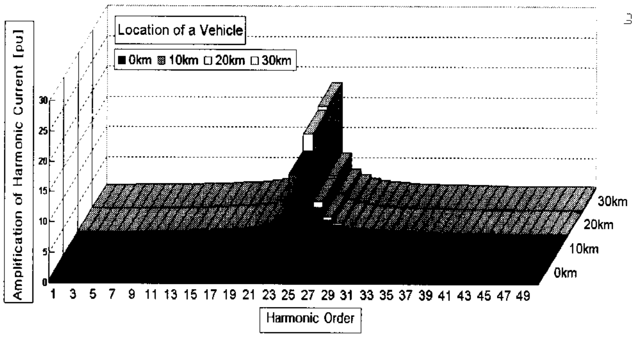

Fig. 10 Amplification of current harmonic as a function of the position of a train

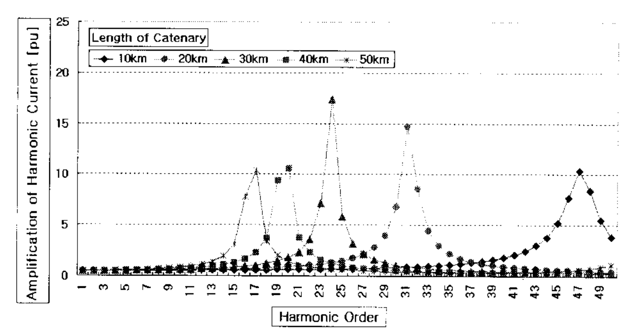

Fig. 11 Correlation between catenary length and harmonic resonance

Finally, we obtained the amplification of harmonic current on the real AC electric railway system by applying reduced line constants.

We simulated and measured the amplification of harmonic current regarding the sections, which are Shinchungju-Yongjung and Pyongtaek-Maha. The distance of those sections is as follows:

- Shinchungju-Yongjung: 28.59km
- Pyongtaek-Maha: 21.32km

The harmonic resonance was simulated and measured for the actual AC electric railway system. The results are presented in Table 1 and Figs. 12 ~ 15.

Table 1 Results of simulation and measurement of harmonic resonance according to catenary length

Distance	Classification	Resonance Harmonic Order
21.32km	Simulation	30th order
	Measurement	30th order
28.59km	Simulation	25th order
	Measurement	24th order

The amplification of harmonic current was simulated and measured on the actual AC electric railway system. The simulation result and the measurement data are almost identical. As such, we conclude that the proposed model is well in accordance with the real AC electric railway system.

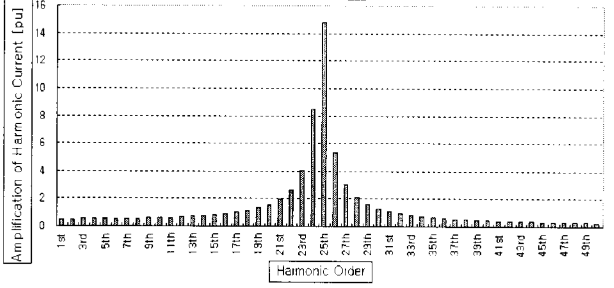

Fig. 12 Amplification of harmonic current (Simulation) - (Shinchungju-Yongjung) 28.59km

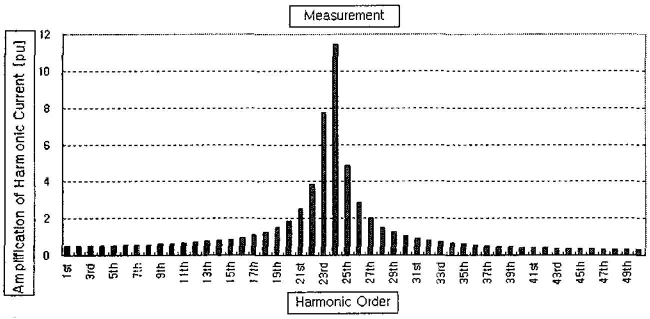

Fig 13 Amplification of harmonic current (Measurement) - (Shinchungju-Yongjung) 28.59km

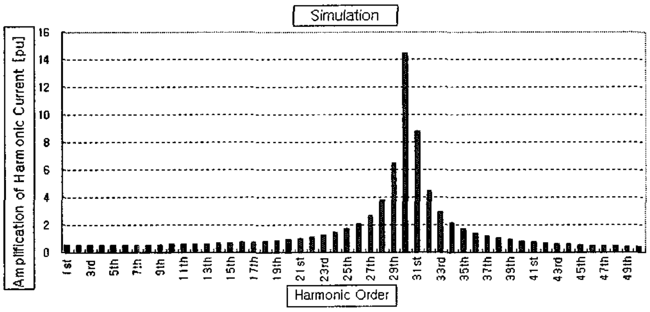

Fig. 14 Amplification of harmonic current (Simulation) - (Pyongtaek-Maha) 21.32km

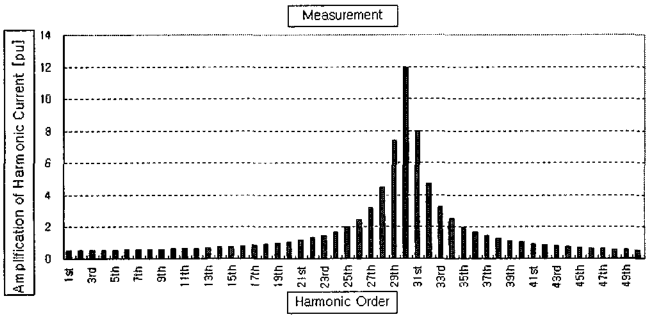

Fig. 15 Amplification of harmonic current (Measurement) - (Pyongtaek-Maha) 21.32km

Comparing simulation results with measurement data proves the proposed model. The proposed model would be a powerful tool for the harmonic studies on the real AC railway system.

5. Conclusion

This study presents an approach to model and to analyze a traction power feeding system focused on amplification of the harmonic current. Through the work the following conclusions can be made:

- The system model for the harmonic studies

1) Aggregating subsystems compose the overall system.
2) The proposed model is well in accordance with the actual railway system.

- Advantages of a model made by PSCAD/EMTDC

1) It is easy, flexible, and efficient to use.
2) It accurately models all components.
3) It is used for repeated simulations.
4) It can easily represent impedances and shunt admittances for the catenary system.

- Harmonic Analysis

1) The resonance frequency does not depend on the location of the vehicle. The amplification of the harmonic is a function of the position of an electric train.
2) The longer the catenary length is, the lower the resonance frequency is.

The simulation results of the proposed model and the measurement data from the test are compared. The results are almost identical. Therefore, the proposed model is in good agreement with the actual railway system.

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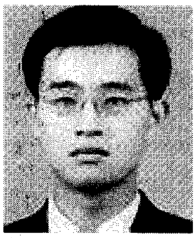

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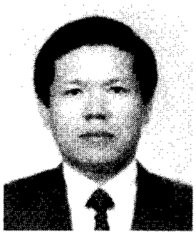

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