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A Study on a Catenary Impedance Estimation Technique using Boosting Current Compensation Based on Current Division Characteristics of an AT Feeding System

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Abstract – Generally, an autotransformer(AT) feeding system consists of double tracks, up and down, with the trolley wire and feeder wire of the up and down tracks connected in the sectioning post(SP). Consequently, load current or fault current flows on two tracks based on catenary impedance characteristics, making it difficult to estimate catenary impedance accurately. This paper presents a technique for the estimation of catenary impedance using boosting current compensation based on the current division characteristics of an AT feeding system to improve the operation performance of impedance relay. To verify the technique, we model an AT feeding system through a power analysis program (PSCAD/EMTDC) and simulate various operation and fault conditions. Through the simulation, we confirmed that the proposed technique has estimated catenary impedance with a similar degree of accuracy to the actual catenary impedance.

Keywords: AT feeding system, Boosting current compensation, Current division characteristics, Catenary impedance estimation

1. Introduction

In Korea, AC railway systems generally have a feeding system using an autotransformer (AT). The AT is installed at substation (SS), sectioning post (SP) and sub-sectioning post (SSP) to reduce the voltage drop of the catenary system and electromagnetic interference in the communication line. Impedance relay is the main protective relay of the AT feeding system, and is installed at a 55kV terminal at the substation to calculate the fault impedance using fault voltage and current. The impedance relay can set the protection range of zone 1 and zone 2, and separately set the operation time for each protection range of the up and down tracks. Generally, zone 1 is set to 90% distance from substation and time is 0.05 sec, while zone 2 is set as 120% distance and time is 0.2 sec for backup protection. Thus, an accurate estimation of catenary impedance depending on distance is important for accurate setting of an impedance relay [1~3]. But the estimated catenary impedance from the substation is not in proportion to the distance because of the AT installed in SS, SSP and SP. In addition, it is much more difficult to estimate catenary impedance due to the boosting current on AT and the current flow of the other track current, because the double track comprising an up and down track is a tie connection between the up and down track on SP and rail bonding [4, 5].

The Carson-Pollaczek equation is usually used in estimating catenary impedance. But this approach has a theoretical limitation in terms of its application to estimations of catenary impedance, taking into account the current boosting on double track. An artificial ground fault test is carried out using a measurement device in the operation line for actual measurement, but it is impossible to set the protection zone to the fault location because of the artificial fault test limitation in the operation line [6~8].

Thus, in this paper we present a catenary impedance estimation technique that uses boosting current compensation based on the current division characteristics of the AT feeding system. For this technique, 55kV catenary impedance on the up and down track acquired by impedance relay is compared with the conventional technique. The difference of impedance magnitude due to boosting current is expressed in the form of an equation. In this way, a new impedance calculation method using boosting current compensation is presented using existing impedance relay.

Finally, the performance of the impedance calculation method using boosting current compensation that is proposed in this paper is evaluated through simulation data depending on various operation and fault conditions of the AT feeding system modeled using a power analysis program.

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2. Catenary Impedance Estimation Technique using Boosting Current Compensation

2.1 Calculation of catenary impedance between SS and SSP using current division characteristics

To reduce the voltage drop in the AT feeding system on double track, a tie connection between feeder wire and trolley wire on the up and down track at SP is used. This causes load current to flow partially on the down track, in addition to the up track, when the train is in operation on the up track.

The current flow pattern has been evaluated through previous studies, and the overall current flow on the double track is as shown in Fig. 1 [8].

4 closed loops are arranged and voltage equation is presented in order to calculate the catenary short circuit impedance in Eq. (1).

$$Z_{55kV} = \frac{2V_{trolly-feeder}}{I_{fault}}$$
$$= -\frac{m^2}{D}\left\{Z_t\left(3k+1\right)+4Z_r\right\}+4m\left(Z_t+Z_r\right)+4Z_{fault} \quad (1)$$

where,

Z_{55kV} : Catenary impedance on 55 kV terminal [Ω]
I_{fault} : Fault current ($=2I_1+2I_2$) [A]
Z_t : Trolley wire impedance per unit length [Ω/km]
Z_r : Rail impedance per unit length [Ω/km]
Z_f : Feeder wire impedance per unit length [Ω/km]
D : Distance between SS and SSP [km]
m : Distance from SS to fault location [km]

k : Boosting current ratio constant $= \dfrac{Z_t}{Z_t+Z_f}$

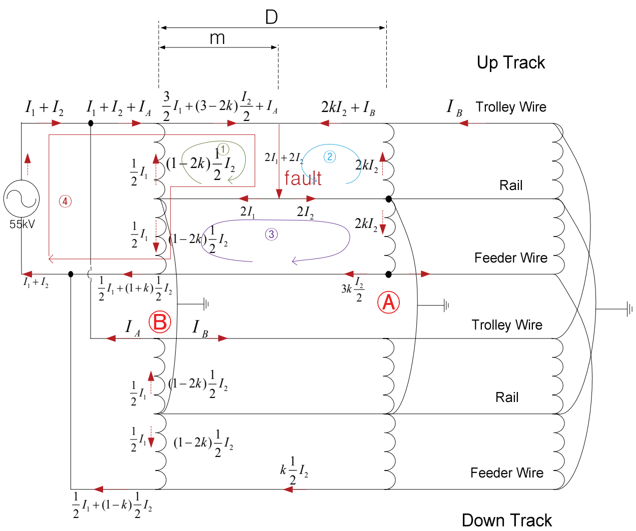

Fig. 1. Current flow of between substation and sub-sectioning post

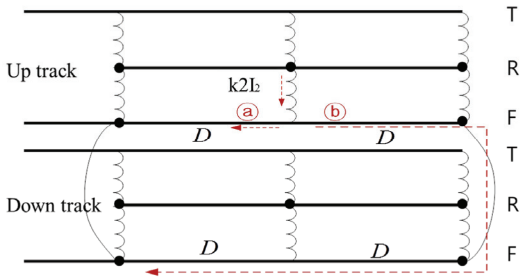

Fig. 2. Characteristics of Current division ratio at Ⓐ point

$$I_A = \left(I_1+I_2\right)\left(\frac{1}{2}-\frac{m}{2D}\right)-\frac{1}{2}kI_2,$$
$$I_B = \frac{1}{2}\left\{\frac{m}{D}\left(I_1+I_2\right)-kI_2\right\}$$

Current division ratio at Ⓐ in Fig. 1 is as shown in Eq. (2) according to the characteristics of the AT feeding system in Fig. 2[7].

$$ⓐ\ : I_{ff}up = \frac{3D}{D+3D}\cdot k\cdot 2I_2 = 3k\frac{I_2}{2}$$
$$ⓑ\ : I_{ff}dn = \frac{D}{D+3D}\cdot k\cdot 2I_2 = k\frac{I_2}{2} \quad (2)$$

Current I_A and I_B depending on current division at point Ⓑ in Fig 1. are as shown in Eqs. (3) and (4) according to the characteristics of the AT feeding system shown in Fig. 3.

$$I_{SS-AT} = \frac{1}{2}I_1+\frac{I_{SS}}{4} = \frac{1}{2}I_1+\left(\frac{Z_f-Z_t}{Z_f+Z_t}\right)\frac{1}{2}I_2$$
$$= \frac{1}{2}I_1+\left(1-2k\right)\frac{1}{2}I_2 = I_A+I_B$$
$$I_f = I_{SSP-AT} = \frac{Z_t}{Z_f+Z_t}\cdot 2I_2 = 2kI_2$$

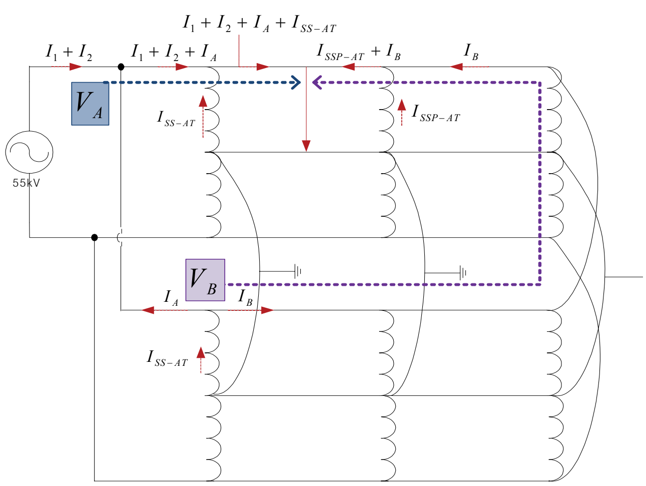

Fig. 3. Characteristics of Current division ratio at Ⓑ point

$$V_A = \left(I_1 + I_2 + I_A + I_{SS-AT}\right) m Z_t$$
$$V_B = 3DZ_t I_B + \left(D-m\right) Z_t \left(2kI_2 + I_B\right)$$

Because $V_A = V_B$, so,

$$I_B = \frac{\left(2I_1 + 2I_2\right)m - 2kI_2 D}{4D} \tag{3}$$
$$I_A = I_{SS-AT} - I_B$$
$$I_A = \frac{1}{2}\left(I_1 + I_2\right) - kI_2 - \frac{\left(I_1 + I_2\right)m}{2D} + \frac{1}{2}kI_2$$
$$I_A = \left(I_1 + I_2\right)\left(\frac{1}{2} - \frac{m}{2D}\right) - \frac{1}{2}kI_2 \tag{4}$$

2.2 Calculation of catenary impedance between SSP and SP using current division characteristics

Fig. 4 shows the fault current division on the catenary of the up and down track when short circuit fault occurs between SSP and SP on the up track. Catenary impedance (Z_{55kV}) is calculated as shown in Eq. (5) by the voltage equation based on current division characteristics.

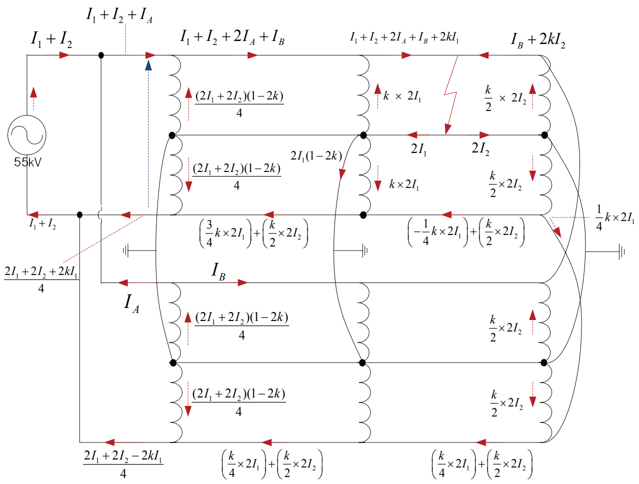

Fig. 4. Current flow between sub-sectioning post and sectioning post

$$Z_{55kV} = \frac{2V_{trolly-feeder}}{I_{fault}} = -\frac{m^2}{D}\left\{Z_t\left(1+3k\right) + 4Z_r\right\}$$
$$+m\left\{2Z_t\left(1+k\right) + 4Z_r\right\} + \left(3-3k\right)DZ_t \tag{5}$$

2.3 Catenary impedance calculated by impedance relay

Fig. 5 shows the voltage and current measuring point of the impedance relay, which is the main protection of the AT feeding system. It calculates the catenary impedance by acquiring the current of trolley wire and feeder wire and voltage between trolley wire and feeder wire. In the event of a short circuit, catenary impedance at 27.5 kV is 1/4 that at 55kV. When a short circuit fault occurs in the double track system, boosting current is generated and catenary impedance from 55kV as shown in Eq. (6) equals the parallel sum of the up and down track impedances. Therefore, catenary impedance calculated on the up track relay is greater than total catenary impedance at 55kV.

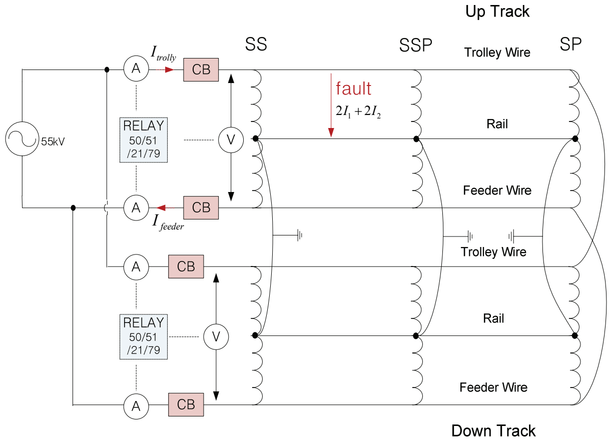

Fig. 5. Voltage and current measuring point of impedance relay

$$Z_{55kV} = Z_{55kV(up)} // Z_{55kV(down)} = \frac{Z_{55kV(up)} \cdot Z_{55kV(down)}}{Z_{55kV(up)} + Z_{55kV(down)}} \tag{6}$$

$$Z_{55kV} = \frac{2V_{trolly-feeder}}{I_{fault}} = \frac{2V_{trolly-feeder}}{2I_1 + 2I_2} \tag{7}$$

2.4 Calculation of catenary impedance considering boosting current of other tracks

In the existing impedance relay technique, catenary impedance is calculated after acquiring the current of trolley wire and feeder wire and voltage between trolley wire and feeder wire on the up and down track, respectively. Impedance calculated at impedance relay (up track at 55kV) considering the current of trolley wire and feeder wire in Fig. 1 is as described in Eq. (8). Because the denominator is calculated after subtracting the boosting current (I_{boost}) from the fault current (I_{fault}), it is calculated as being greater than the actual catenary impedance (Z_{55kV}).

$$Z_{55kV(up)} = \frac{V_{trolly-feeder(up)}}{\frac{1}{2}\left(I_{trolly(up)} + I_{feeder(up)}\right)}$$
$$= \frac{2V_{trolly-feeder(up)}}{\left\{I_1 + I_2 + I_A\right\} + \left\{\frac{1}{2}I_1 + \frac{1}{2}I_2 + \frac{1}{2}kI_2\right\}}$$
$$= \frac{2V_{trolly-feeder(up)}}{\left\{2I_1 + 2I_2\right\} - \left\{\frac{1}{2}I_1 + \frac{1}{2}I_2 - \frac{1}{2}kI_2 - I_A\right\}} = \frac{2V_{trolly-feeder}}{I_{fault} - I_{boost}} \tag{8}$$

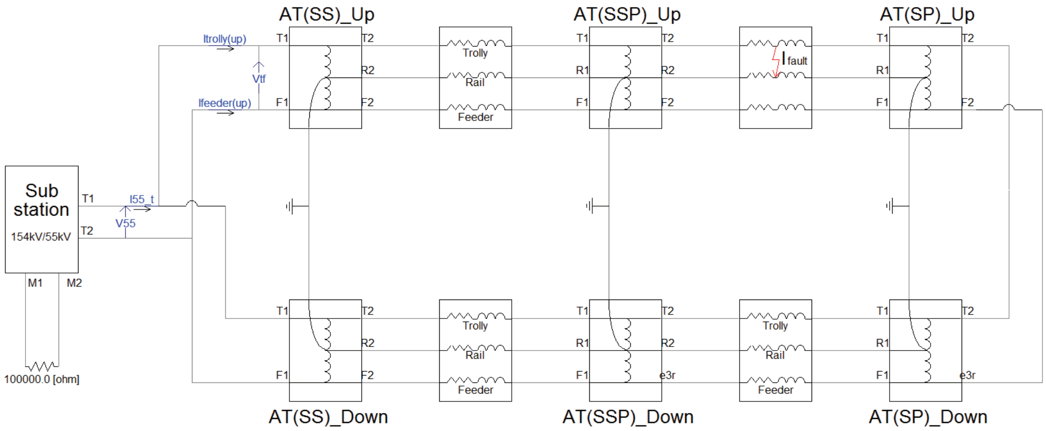

Fig. 6. Model system

When the impedance relay is set based on a calculation method that uses conventional relay, overreach may occur, and fault location estimation errors using the impedance method may increase. Thus, for a more accurate catenary impedance calculation and setting of the operation zone, it is necessary to correct the impedance calculation technique, taking into account the boosting of current magnitude. To that end, Eq. (9) can be obtained by applying boosting current (I_{boost})$=(I_1+I_2)\frac{m}{2D}$ and arranging I_{fault} in Eq. (8). It is also confirmed that catenary impedance on the up track (Eq. (9)) is inversely proportional to the magnitude of $\left(1-\frac{m}{4D}\right)$ with total catenary impedance (Eqs. (1) and (5)).

$$Z_{55kV(up)} = \frac{2V_{trolly-feeder}}{(2I_1+2I_2)-(2I_1+2I_2)\frac{m}{4D}} = \frac{2V_{trolly-feeder}}{I_{fault}\left(1-\frac{m}{4D}\right)}$$

$$= Z_{55kV}\left\{\frac{2V_{trolly-feeder}}{1-\frac{m}{4D}}\right\} \tag{9}$$

Eq. (10)($Z_{55kV(up)-comp}$) is total catenary impedance obtained as compensating boosting current(I_{boost}) from Eq. (8) to make an equal impedance value($Z_{55kV(up)}$) calculated by impedance relay with total catenary impedance (Z_{55kV}).

$$Z_{55kV(up)-comp} = Z_{55kV(up)}\cdot\left(1-\frac{m}{4D}\right) = Z_{55kV} \tag{10}$$

3. AT Feeding System Simulation and Performance Eluation

3.1 System modeling

To verify the performance of the catenary impedance technique considering boosting current compensation, we model an AT feeding system using a power analysis program(PSCAD / EMTDC) in Fig. 6. For AT feeding system, we model a 3-phase 154kV module supplied from a power company, a railway substation module which converts to two single-phase 55kV, an AT module and a catenary module. The distance between SS, SSP and SP is set as 10km, and the up track and down track are tie-connected at SP. Parameters of each component are provided in Table 1 [9~11].

Table 1. Model system parameters

System	Value
AT	10MVA, j0.4 Ω
Trolley wire	0.1076 + j0.2614 Ω/km
Rail	0.1052 + j0.4736 Ω/km
Feeder wire	0.1180 + j0.4519 Ω/km
Fault resistance	0.01 Ω

3.2 Verification of current division characteristics

To verify the current division in the AT feeding system the output is compared using the estimated value from Eq. (2) and the simulation output. Fig. 7 shows the current magnitude divided on point Ⓐ from the simulation, which is almost the same as expected in the estimated value.

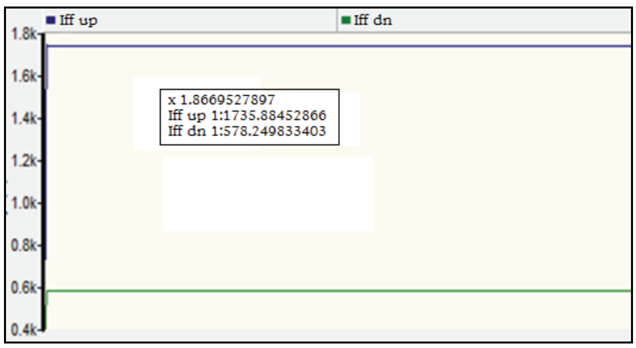

Fig. 7. Simulation output of Current division on Ⓐ point

Fig. 8. Simulation output of Current division on Ⓑ point

[Estimated value from Eq. (2)]

ⓐ : $I_{ff}up = 3k\frac{l_2}{2} = 3\times 0.377\times\frac{6,125}{4} = 1,732[A]$,

ⓑ : $I_{ff}dn = k\frac{l_2}{2} = 0.377\times\frac{6,125}{4} = 577[A]$

To verify the current division characteristics on point Ⓑ, we compare the value estimated using Eq. (3) with the value obtained through the simulation output. Fig. 8 shows the current magnitude divided on Ⓑ, which is almost the same as the estimated value.

[Estimated value from Eq. (3)]

$$I_B = \frac{(I_1 + I_2 + 2I_{SS-AT})m - (D-m)I_{SSP-AT}}{4D}$$
$$= \frac{(3,062+3,062+1,506)\cdot 0.5-(10-5)\cdot 2,309}{4\cdot 10}$$
$$= 954[A]$$

3.3 Evaluation of impedance estimation performance using simulation

Short-circuit conditions are simulated with the AT feeding system model tie-connected up and down track. Eq. (8), which calculates impedance from protective relay, Eq. (10) and the simulation value are compared. To estimate the track impedance only, short circuit resistance between trolley wire and rail is set as 0.001Ω and a simulation of a short circuit between trolley wire and rail is carried out at 100m intervals starting from the substation.

Fig. 9 and Table 2 show total catenary impedance (Z_{55kV}), impedance ($Z_{55kV(up)}$) calculated by impedance relay in up track and impedance ($Z_{55kV(up)-comp}$) calculated by boosting current compensation by distance on the double track of the AT feeding system

As shown in Fig. 9, impedance magnitude from substation is a typical non-linear system. Total catenary impedance magnitude, which is calcuted by parallel sum of catenary impedance on both the up and down track, is less than the impedance measured on the up track. However, catenary impedance magnitude using boosting current compensation is equal to total catenary impedance.

As shown in the simulation output, there is a significant difference between existing impedance estimated by impedance relay and real total catenary impedance. In particular, between SSP and SP the maximum error is doubled because of the increased boosting current. Consequently the farther the distance from the substation, the greater the estimation error.

On the other hand, when an impedance estimation technique that compensates boosting current is applied, maximum error is about 2%, which is considered to be almost the same as catenary impedance. Thus, an estimation technique that considers boosting current between up and down track can more accurately estimate catenary impedance, which would improve the performance of an impedance-based fault locator.

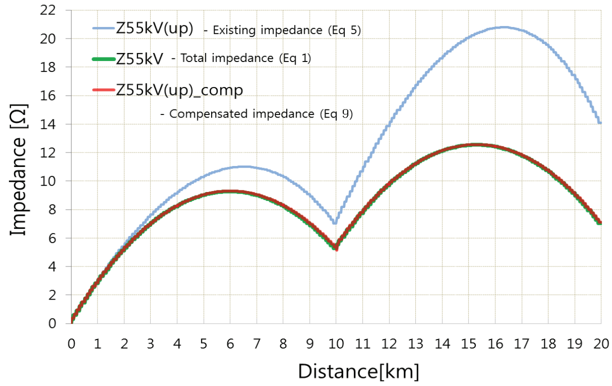

Fig. 9. Comparison of simulation output

Table 2. Comparison of simulation output

Distance [km]	Catenary impedance [Ω]			Error ratio [%]	
	Z_{55kV} (A)	$Z_{55kV(up)}$ (B)	$Z_{55kV(up)-comp}$ (C)	$\left(\frac{(A)-(B)}{(A)}\right)\times 100$	$\left(\frac{(A)-(C)}{(A)}\right)\times 100$
0	0	0	0		
1	2.874	2.889	2.817	0.52	1.98
2	5.168	5.395	5.125	4.39	0.83
3	6.958	7.672	7.077	10.26	1.71
4	8.244	9.129	8.216	10.74	0.34
5	9.027	10.285	8.999	13.94	0.31
6	9.305	10.941	9.272	17.58	0.35
7	9.080	10.926	8.987	20.33	1.02
8	8.351	10.369	8.295	24.16	0.67
9	7.120	9.088	7.043	27.64	1.08
10	5.386	7.044	5.283	30.78	1.91
11	7.823	10.687	7.748	36.61	0.96
12	9.757	13.863	9.704	42.08	0.54
13	11.189	16.756	11.268	49.75	0.71
14	12.116	18.601	12.091	53.52	0.21
15	12.540	20.033	12.521	59.75	0.15
16	12.460	20.765	12.407	66.65	0.43
17	11.877	20.558	11.769	73.09	0.91
18	10.790	19.565	10.761	81.33	0.27
19	9.200	17.441	9.157	89.58	0.47
20	7.108	14.088	7.044	98.20	0.90

4. Conclusion

This paper presents a catenary impedance estimation technique, which is needed to set a protective relay for protecting the catenary of an AT feeding system. As a conventional impedance relay does not consider the boosting current of another track, there might be differences between actual impedance and estimated impedance magnitude. Such an error could cause a malfunction of the protective relay, and reduce the accuracy of the fault locator. Therefore, this paper presents a technique of compensating boosting current based on current division characteristics depending on impedance distribution of the AT feeding system to minimize errors in the estimation of magnitude by protective relay compared to actual value.

To verify the performance of the technique proposed in this paper, we carry out modeling of an AT feeding system through a power analysis program (PSCAD/EMTDC) and by simulating various operation and fault conditions. As a result, it is found that there is no difference between the magnitudes estimated using the proposed technique and the actual impedance magnitude. When we compare impedance estimated with the conventional technique and the proposed technique, the estimation of magnitude using the conventional technique can have an error of up to 98%, while the error using the proposed technique is within 2%.

After verifying the performance using the operation data obtained from an actual AT feeding system, the technique could potentially be applied to a protection system for protecting catenary.

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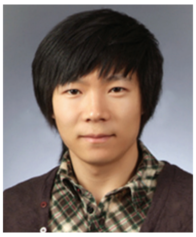

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