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


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[1,2]. 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 [3, 4].

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 [5, 6].

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.
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 [6].

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

\[
Z_{55kV} = \frac{2V_{\text{trolley-feeder}}}{I_{\text{fault}}}
\]

\[
= -\frac{m}{D} \left\{ Z (3k + 1) + 4Z_f \right\} + 4m(Z + Z) + 4Z_{\text{fault}}
\]

(1)

where,

- \( Z_{55kV} \): Catenary impedance on 55 kV terminal [Ω]
- \( I_{\text{fault}} \): Fault current (= 2\( I_t + 2I_f \)) [A]
- \( Z \): Trolley wire impedance per unit length [Ω/km]
- \( Z_f \): 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 = \( \frac{Z}{Z_f + Z} \)

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

\[
A : I_{\text{rup}} = \frac{3D}{D + 3D} \cdot k \cdot 2I_f = \frac{3k}{2} I_f
\]

\[
B : I_{\text{dn}} = \frac{D}{D + 3D} \cdot k \cdot 2I_f = \frac{k}{2} I_f
\]

(2)

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

\[
I_{\text{rup}} = \frac{1}{2} I_f + \frac{1}{4} I_s = \frac{1}{2} I_f + \left( \frac{Z_f - Z}{Z_f + Z} \right) \frac{1}{2} I_f
\]

\[
= \frac{1}{2} I_f + (1 - 2k) \frac{1}{2} I_f = I_A + I_B
\]

\[
I_f = I_{\text{SSP-AT}} = \frac{Z_f}{Z_f + Z} \cdot 2I_f = 2kI_f
\]
VA = \left( h + I_z + I_A + \Delta S - AT \right) mZd \\
Vb = 3DZIb + (D - m)Z \left( 2kI_d + Ib \right)

Because \( V_A = V_b \), so,

\[
I_b = \frac{(2h + 2I_z)m - 2kI_dD}{4D} \tag{3}
\]

\[
I_A = \Delta S - AT - Ib \\
I_A = \frac{1}{2}(h + I_z) - kI_d - \frac{(h + I_z)m}{2D} + \frac{1}{2}kI_d \\
I_A = (h + I_z) \left( \frac{1}{2} \cdot \frac{m}{2D} \right) - \frac{1}{2}kI_d \tag{4}
\]

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.

\[
Z_{55kV} = \frac{2V_{\text{trolley--feeder}}}{I_{\text{fault}}} = -m \frac{Z_A(1 + 3k) + 4Z_V}{D} \nonumber + m \left( 2Z_A(1 + k) + 4Z_V \right) + \left( 3 - 3k \right)DZ_A \tag{5}
\]

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 55 kV. When a short circuit fault occurs in the double track system, boosting current is generated and catenary impedance from 55 kV 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 55 kV.

\[
Z_{55kV} = Z_{55kV}^{(\text{up})} // Z_{55kV}^{(\text{down})} \nonumber = \frac{Z_{55kV}^{(\text{up})} \cdot Z_{55kV}^{(\text{down})}}{Z_{55kV}^{(\text{up})} + Z_{55kV}^{(\text{down})}} \tag{6}
\]

\[
Z_{55kV} = \frac{2V_{\text{trolley--feeder}}}{I_{\text{fault}}} = \frac{2V_{\text{trolley--feeder}}}{2h + 2I_z} \tag{7}
\]

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 55 kV) 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 (\( I_{\text{fault}} \)) from the fault current (\( I_{\text{fault}} \)), it is calculated as being greater than the actual catenary impedance (\( Z_{55kV} \)).

\[
Z_{55kV}^{(\text{up})} = \frac{V_{\text{trolley--feeder}}^{(\text{up})}}{\frac{1}{2}(I_{\text{trolley}}^{(\text{up})} + I_{\text{feeder}}^{(\text{up})}) - \frac{1}{2}(h + I_z + I_A)} \nonumber = \frac{2V_{\text{trolley--feeder}}^{(\text{up})}}{\frac{1}{2}(h + I_z + I_A) + \left[ \frac{1}{2}h + \frac{1}{2}I_z + \frac{1}{2}kI_d \right]} \nonumber = \frac{2V_{\text{trolley--feeder}}^{(\text{up})}}{\left( 2h + 2I_z \right) - \left( \frac{1}{2}h + \frac{1}{2}I_z - \frac{1}{2}kI_d - I_A \right)} \tag{8}
\]
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 \( I_{\text{boost}} = \frac{m}{2D} \) and arranging \( I_{\text{fault}} \) in Eq. (8).

It is also confirmed that catenary impedance on the up track (Eq. (9)) is inversely proportional to the magnitude with total catenary impedance (Eqs. (1) and (5)).

\[
Z_{55kV}^{(\text{up})} = \frac{2V_{\text{trolley\,-\,feeder}}}{1 - \frac{m}{4D}} = \frac{2V_{\text{trolley\,-\,feeder}}}{I_{\text{fault}}} \left( 1 - \frac{m}{4D} \right) = Z_{55kV} \left( \frac{2V_{\text{trolley\,-\,feeder}}}{1 - \frac{m}{4D}} \right) \tag{9}
\]

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

\[
Z_{55kV}^{(\text{up})-\text{comp}} = Z_{55kV}^{(\text{up})} \left( 1 - \frac{m}{4D} \right) = Z_{55kV} \tag{10}
\]
To verify the current division characteristics on point B, we compare the value estimated using Eq. (3) with the value obtained through the simulation output. Fig. 8 shows the current magnitude divided on B, which is almost the same as the estimated value.

\[
I_B = \frac{(I + I_2 + 2i_{SS-AT})m - (D - m)i_{SSP-AT}}{4D} \\
= \frac{(3.062 + 3.062 + 1.506) \times 0.5 - (10 - 5) \times 2.309}{4 \times 10} \\
= 954[A]
\]

### 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 \(Z_{55kV}(up)\text{-comp}\) calculated by boosting current compensation by distance on the double track of the AT feeding system.
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.

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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References


Hosung Jung
He graduated from Sungkyunkwan University in 1995. He received his MSc. and Ph.D. degree in Electrical and Computer Engineering from Sungkyunkwan University, Korea in 1998 and 2002, respectively. He is currently a Principal Researcher and Head of the R&D Strategy Division of Korea Railroad Research Institute. His research interests include protection of electric railway power systems and energy efficient power and railway system technology.

Hyungchul Kim
He received his BS and MS degree in Electrical Engineering from Korea University, Seoul, Korea in February 1991 and in February 1993 respectively. He then worked for LG electronics Inc. for 6 years. He received a Ph.D. degree from Texas A&M University in August 2003. Currently, He is working for Korea Railroad Research Institute. His research area is traction power system and power system reliability.
Sang-Hoon Chang He received his Ph.D degree in department of electrical engineering from Hongik University in Korea. He has been working for Korea Railroad Research Institute(KRRI) in Korea since 1994. His special fields of interest include power supply system design and analysis for electric railway system.

Joorak Kim He received his B.S, M.S., Ph.D. degree in electrical engineering from Hongik university in 1997, 1999, and 2010, respectively. He is currently senior researcher in Korea Railroad Research Institute. His research interests are design and analysis of traction power supply system.

Myung-Hwan Min He received his B.Sc. degree in electrical engineering from Soongsil University, Korea in 2010 and his M.Sc. degree from Sungkyunkwan University, Korea, in 2012. He is currently working for ENTEC Electric & Electronic, Ltd. His research interests include the protection of electric generators, power distribution and electric railway power systems.

Tae-Pung An He received his B.Sc. degree in electronic engineering from Sungkyunkwan University, Korea in 1992. He is currently working for ENTEC Electric & Electronic, Ltd. as a managing director of the technical research center. His research interests include power system protection as well as communication systems.

Sung-II Kwon He received his B.Sc. degree in electrical engineering from Choong-ju National University, Korea, in 1996 and his M.Sc. degree from Chungbuk University, Korea, in 2012. He is currently working for Korea Railroad Corp. as a director in the rail systems development research center. His research interests include railway power systems.