A Study on the Application Analysis of the Railway System of Tap-Changing Transformer

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Abstract: In this paper, a new type of automatic transmitter (AT) is proposed to properly adjust the voltage of the train without installing additional equipment. The proposed tap-changing AT is expected to raise the voltage between catenary and rail by regulating the turn-ratio between primary and secondary winding according to catenary voltage and verified its effects through the multi ports network analysis technique modeling of it. Through the simulation and analysis of the electric railway systems, it is shown that it can secure the load capacity and solve the large voltage drop problem by raising the voltage across railway vehicles back to the normal voltage level.

Key words: Railway, voltage drop, tap-changing AT, power compensation.

1. Introduction

Most sections have been electrified due to the increase in demand for railways in South Korea, with the recent ratio of electrification at 69.1%, and about 85% in the future. Electricity supply methods for electric railways include DC and AC. Worldwide, AC feeding systems account for about 61%. The AC feeding system has a direct power supply method, a BT (booster transformer) power supply method, and an AT (autotransformer) power supply method. In Korea, 25 kV×2 AT power supply is mainly used for intercity mainline railways and high-speed railways [1-6].

The AT power supply method, which uses AT for railway power supply systems, is more effective than other power supply methods as a means of widening the gap between substations due to location selection and construction cost problems in the AC feeding system. The voltage drop is reduced and the distance between substations is extended. It also uses the AT power supply method around the world as it greatly improves the problem of induced disturbance of communication lines. This AT rapid electricity method inserts AT in parallel between feeder and catenary. The AT connects two windings wound around the same iron core in series and pulls the terminals out of the neutral point so that they act in the first and second order, connecting to the catenary-rail and rail-feeder. This means that the supply voltage of the substation is divided evenly at 1:1 to maintain the same voltage between the catenary-rail and rail-feeder.

In recent years, train operations have continued to increase due to the expansion of the Seoul metropolitan area and the resulting expansion of passenger and cargo transport. As the number of trains increases, the train load on the supply lines increases, thereby lowering the current collection voltage and the terminal voltage of the supply lines. If a voltage drop occurs in the power supply system, train operation outside the normal range will be impossible. Therefore, under any circumstance, the current collection voltage of the train must be maintained above the minimum operational voltage at all time. The method of increasing the supply capacity by improving the current collection voltage of the train in the supply system and offsetting the reactive voltage
drop by adjusting the impedance of the track can be considered. Methods such as ESS (Energy Storage System) and Static Synchronous Compensator (STATCOM) are being studied as ways to increase supply capacity, but substantial costs are required for practical use. In addition, methods to offset the reactive voltage drop have been studied to use the SVC (Static VAr Compensator) by eliminating induced reactance of the supply line with capacitive reactance, but require a separate footprint and high cost. Therefore, this paper proposes to increase the supply voltage of the load side by changing the winding ratio of the AT used in the AT supply method by improving the voltage of the vehicle without installing additional facilities. It was shown that a tap-changing AT that changes the winding ratio of the primary and secondary sides of the AT according to the voltage of the catenary can be proposed and the voltage can be increased through analysis of the power supply system.

2. Modeling of Alternating Current Railways Using Tap-Changing AT

The AT proposed in this paper is a tap-changing AT to adjust the voltage at the secondary side of the AT within the appropriate voltage range by changing the winding ratio of the AT. A tap-changing AT modeling technique is proposed to predict the effectiveness of the application of such a tap-changing AT to the AC railway power supply system currently in operation.

2.1 AC Electrical Railway System

The domestic alternating current railway system receives 3-phase 154 kV AC power from the power system and converts it into 2-phase (M-phase/T-phase) 55 kV through a Scott transformer to supply power to the supply lines. The power supply lines supply electric vehicles with power of 55 kV via AT and catenary, feeder, and rail with a winding ratio of 1:1. The AT is normally installed at intervals of 10 km, with one side of the windings connected to the catenary, the other to the supply wire, and the neutral point to the rail. The AT installation site installed in the middle of the track is divided into SSP (Subsection Post) and PP (Parallel Post) depending on the connection method of the track. The distance between the substation and the substation is determined by power capacity, train load, and nearby railway substation systems, usually based on 50 km. A sectioning post (SP) is installed at the midpoint between substations to electrically separate both substations during normal power supply. The AC Electric Railway System is shown in Figure 1.

2.2 Tap-Changing AT Modeling

The AT used in the catenary system has twice the number of turns on the primary side, and the series winding and shunt winding have a winding ratio of 1:1.

The voltage at the primary side is 55 kV, the voltage at the secondary side is 27.5 kV, and the rail is connected at the point where the two windings are connected.

The AT is assumed to be the ideal transformer that ignores the interwinding leakage impedance as shown in Fig. 2. Between T-R and R-F, voltage $V_{TR}$, $V_{RF}$ with a relation of $\frac{n_1+n_2}{n_2} = \frac{V_{RF}}{V_{TR}} = \frac{V_{TR}}{V_{RF}}$ are abandoned in proportion to $(n_1+n_2)$.

When an electric vehicle load of $I_2$ is connected between T-R, current $I_1$ satisfying $I_1(n_1+n_2)=I_2n_2$ ampere turn is introduced from the power source. Thus, ignoring has a relationship where the current is $\frac{n_1}{n_1+n_2} = \frac{I_1}{I_2}$, but the transformer windings in the T-R section have a difference $(I_1-I_2)$ between the power side and the load side current.

The AT used in the existing AT power supply method shall have the same voltage between T-R and R-F. In other words, the AT is used to make the winding ratio $n_1/n_2=1$ to be $V_{TR}=V_{RF}$. 


The AT used in the AC power supply method is for substation, sectioning post, and subsection post, which are modeled as follows:

2.2.1 Tab-Changing AT for Substation

The AT installed in the railway substation (SS; Substation) is supplied with 55 kV power supply on the primary side (left side). The secondary side (right) is distributed at the catenary-rail, rail-feeder terminals according to the ratio of the AT windings. Based on the number of winding turns between rail and feeder, the circuit model of the tab-changing AT on the substation side is established as shown in Fig. 3 below.
To make this a model equation, expressing the current-voltage relationship of the tab-changing AT as a formula can induce the relationship as shown in Eq. (1) below.

\[
\begin{align*}
V_1' &= V_1'' + V_2'' + nV \\
I_1' &= \frac{n+1}{n+1} I_1'' - \frac{1}{n+1} I_2'' \\
I_1 &= \frac{n}{n+1} V_1 + \frac{Z_{at}}{n+1} I_1'' + \frac{Z_{at}}{n+1} I_2'' \\
I_2 &= \frac{V_2'' - V}{Z}
\end{align*}
\] 

where \( Z_{at} = (n+1)Z \)

2.2.2 Tab-Changing AT for Subsection Post

The tab-changing AT in the subsection post (SSP) is connected in parallel in the middle of the catenary system, and the circuit model is shown in Fig. 4.

In Fig. 4, the voltages between the catenary-rail and the rail-feeder of the AT for the subsection post shown in the substation post are the same as those seen in the sectioning post respectively. The current relationship can be represented as shown in Fig. 4.

\[
\begin{align*}
V_1' &= V_1'' + V_2'' + nV \\
I_1' &= \frac{n+1}{n+1} I_1'' - \frac{1}{n+1} I_2'' \\
I_1 &= \frac{n}{n+1} V_1 + \frac{Z_{at}}{n+1} I_1'' + \frac{Z_{at}}{n+1} I_2'' \\
I_2 &= \frac{V_2'' - V}{Z}
\end{align*}
\]

2.2.3 Tab-Changing AT for Sectioning Post

The tab-changing AT installed in the sectioning post (SP) is located at the end of the catenary system, so no right circuit exists as shown in Fig. 5 below. Therefore, the current flowing through the catenary is equal to the current flowing between the catenary-rail of the AT. Also, the current flowing through the feeder is equal to the current flowing between the rail-feeder of the AT. As shown in Fig. 5, the current flowing through the catenary is \( I' \), and the current flowing through the catenary-rail of the AT is \( I_{1p} = I'_1 \).

The current flowing between the rail-feeder is \( nI'_1 \) according to the tab-changing AT characteristic, or \( n : 1 \)’s current ratio, which results in \( I'_2 = nI'_1 = nI_{1p} \).
The relationship between the winding voltage $V$ between the AT rail-feeder and the voltage $V_{sp}$ between the catenary-rail is $V_{sp} = \frac{1}{n} V - n I_{sp} Z$, which becomes when summarized for $V$. If you replace it with the formula above and organize it, the following Eq. (5) shall be shown.

$$
\begin{align*}
V' &= V_{sp} \\
V'' &= V - n I_{sp} Z \\
I'_1 &= I_{sp} \\
I'_2 &= n I_{sp}
\end{align*}
$$

3. Case study

3.1 Voltage Improvement by Tap-Changing AT

Electric railway power supply systems have limitations in supplying electric vehicles located in the catenary system. This limitation is due to the voltage drop caused by the internal impedance of the Scott transformer and the impedance of the catenary system. For the typical AC, AT power supply section and the maximum load power can be supplied when the existing AT is used. The improvement of load power supply when the tap-changing AT is applied. When an electric vehicle located in the catenary system travels from a railway substation to a sectioning post, the voltage of the electric vehicle under the load of the electric vehicle appears as shown in Fig. 6.

![Fig. 6 Voltage drop with increasing load and distance (existing AT).](image)
As the load on the electric railway increases from 10 MW to about 50 MW, the voltage at the load point gradually decreases as the distance from the substation increases. Depending on the characteristics of the AT, the minimum voltage is generated between the AT. In the above figure, the load voltage becomes the lowest when the distance from the substation is 25.9 km, and the voltage drop increases rapidly as the load increases and the supply limit of the feed line approaches.

Fig. 7 shows the following when calculating the change in current collection voltage due to the increase in vehicle load for the point at which the voltage drop is the greatest (25.9 km). As shown in Fig. 7, an increase in the load power of a railway vehicle results in a lower voltage and an increase in the loss on the track.

As the load power of the electric vehicle increases and approaches the supplyable threshold of the catenary system, the voltage slows rapidly. Track losses will also increase exponentially, making it impossible to supply the power required for railway vehicle loads.

When the voltage of the vehicle decreases due to the increase in railway vehicle load, adjusting the winding ratio of the AT increases the voltage on the vehicle side. The increase in voltage reduces track losses compared to the existing AT, enabling additional load power supply.

If the voltage of the railway vehicle is below 24 kV, the railway vehicle will operate in load limiting mode, so the primary adjustment voltage to adjust the winding ratio is set to 24 kV and the secondary adjustment voltage is set to 23 kV. The results of this brief review are shown in Table 1 and Fig. 8.

As shown in Fig. 8, the increasing load of the railway vehicle causes the voltage of the railway vehicle to fall. When the voltage reaches the primary adjustment voltage (24 kV), the winding ratio is adjusted to increase the voltage between the catenary-rail of the AT, increasing the voltage of the railway vehicle. When the load of the railway vehicle continues to increase and the secondary adjustment voltage (23 kV) is achieved, the voltage between the catenary-rail of the AT is raised, allowing the railway vehicle to load more.

In summary, as shown in Table 1, the maximum load that can be supplied can be powered by the use of the tap-changing AT from 49.84 MW to 53.56 MW,
an increase of 3.72 MW. The voltage of railway vehicles also increased by 4.4 kV from 17.6 kV to 22 kV, and the loss of power to railway vehicles also decreased by 1.55 MVA from 17.77 MVA to 16.22 MVA.

4. Conclusion

This paper suggests a tap-changing AT that can increase the voltage of a railway vehicle and increase the load power by adjusting the winding ratio of the AT without installing additional compensation facilities such as SVC to compensate for the voltage drop in the AC system.

Including the proposed analytical model, the proposed model formula was useful by performing a circuit analysis of the AC railway supply system. Using the proposed AT model, the voltage and load capacity of electric vehicles were calculated for the 30 km section, which is a typical power supply section of the alternating current railway AT method. As a result, the maximum available load was 3.72 MW, 7.5% more load than the maximum load when using the existing 1:1 AT. The lowest voltage could be increased by 4.4 kV, which showed that the voltage could be increased by 25% compared to using the existing AT.

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A Study on the Application Analysis of the Railway System of Tap-Changing Transformer

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