Simulation Analysis of Distribution Characteristics of Urban Rail Transit Stray Current in Power System

Li XIAO*, Guo-xing WU, Fan ZHANG, Long CHEN, Zhen-yu LAI, Wen-wei SONG and Wei-zhao HUANG
Shenzhen Power Supply Bureau Co., Ltd, Shenzhen 518001, China
*Corresponding author

Keywords: Rail transit, Stray current, Ground potential, DC magnetic bias, Capacitor blocking device.

Abstract. The stray current generated by urban rail transit could cause DC magnetic bias problems in transformers round the subway, threatening the safe and stable operation of transformers and AC grid systems. In order to solve such problem, the static distribution model of subway stray current, the multi-layer block soil model of Shenzhen and the simulation model of Shenzhen AC power system were established. The variation of the ground potential of the AC power grid substation and the distribution characteristics of the neutral point DC current of the transformer caused by the stray current were calculated and analyzed. The results show that the change of ground potential and DC current through transformer neutral point is related to the operating conditions of the subway. For the autotransformer, it is pointed out that the installation of the capacitive blocking device only at the DC over-standard site cannot eliminate such DC magnetic bias problems, and it is necessary to properly arrange the blocking device from the perspective of the entire regional power grid.

Introduction

With the large-scale construction of urban rail transit in China, a series of problems caused by stray currents are becoming increasingly serious and can no longer be ignored. On the one hand, stray currents can cause severe electrochemical corrosion on buried metal components around the track, shorten the service life of metal pipes, and reduce the strength and durability of the main structure of subway reinforced concrete [1-2]. On the other hand, for the AC power system, the stray current will enter the grounding grid and the neutral point of the main transformer in the substation along the subway, which will aggravate the electrochemical corrosion of the grounding grid and cause DC bias, resulting in abnormal increase of temperature, noise, vibration and other indicators of the transformer, which increases the harmonic component in the AC system, increases the closing current of the transformer, and threatens the safe and stable operation of the transformer and the AC grid system. In Shenzhen, such adverse effects have been very significant [3].

At present, there are many research results in the DC bias problem of transformers, mainly related to the mechanism, influence, simulation model and suppression measures [4-6]. However, these research results are mainly concerned with the DC bias problem caused by UHVDC transmission project. And for the DC bias problem caused by urban rail transit, only the impact on the transformer in single substation along the subway and the suppression measures are analyzed [7-8]. There is no research on the distribution characteristics of stray currents and suppression measures from the perspective of the entire regional AC power system.

The distribution model of subway stray current, the multi-layer block soil model and the simulation model of AC power system were built, based on the relevant parameters of the subway, the geological characteristics of Shenzhen area and the parameters of AC power grid. The ground potential change of the substation and the distribution characteristics of the neutral point DC current of the transformer caused by the stray current were calculated and analyzed. The main influencing factors were pointed
out, and the specialty in the treatment of the DC bias problem caused by the stray current in the
autotransformer was described.

Static Distribution Model of Stray Current

Urban rail transit stray current mainly refers to the current leakage from the subway train using DC
power supply to the track bed and its surrounding soil during operation. Combined with the bilateral
power supply mode of Shenzhen subway, the static distribution model of stray current was
constructed by the structure of "rail-drainage network-buried metal-earth resistance". The equivalent
circuit diagram of the static distribution model of the subway stray current during the operation of a
single train is shown in Fig.1.

![Figure 1. Equivalent circuit diagram of static distribution model of stray current.](image)

Figure 2. Subway train operation current curve.

In the static model, the longitudinal resistance of the rail, the drainage net, the buried metal and the
soil, and the equivalent transition conductance between the rail and the drainage net, between the
drainage net and the buried metal, and between the buried metal and the earth are all set to constant.
Therefore the static distribution model of stray currents could be described as in Eq.1, where \( y(x) \) is
the vector consisting of the current and the potential difference between the layers, \( D \) is the matrix
consisting of longitudinal resistance and equivalent transition conductance and \( f \) is the excitation
term with traction current.

\[
\frac{dy(x)}{dx} = D \cdot y(x) + f
\]  

(1)

The traction current of Shenzhen subway train can reach up to 4000A during the start, and the
energy feedback system is used for braking. In the simulation, the current trend of the traction current
of the subway train is set as shown in Fig.2, where the train running time is set to 10s, including
traction acceleration, constant speed operation and braking inbound and the traction current is set as
positive when the train takes the flow from the grid.
The Soil Model of Shenzhen Area

With reference to the geological model of the earth's soil, the conventional horizontal soil model and the vertical soil model are not suitable for the actual situation in Shenzhen. Therefore, the multi-layer block soil model is used to model the soil in Shenzhen.

With reference to the direction of the geological fault zone in Shenzhen and ignoring the insignificant details of soil structure in each region, the Shenzhen area can be divided into five sections, including: marine area, reclamation area, continental areas, Futian area and Dameisha area, each of which is modeled by different soil stratification according to its soil characteristics.

Referring to the spatial distribution of the various layers, and according to the geological exploration data during the construction of each site, the soil model uses the granite layer as the bottom layer of the model. The top layer of the granite layer has a depth of 45 m and an average thickness of 20 m. Shenzhen is located on the southeast coast of China. The ocean is a medium with a much larger area than the land and a resistivity much smaller than the soil resistivity. Therefore, the influence of the ocean on the distribution of stray current in the subway in Shenzhen should be considered in the modeling. At the same time, because the groundwater in Shenzhen is rich in electrolytes and the groundwater level is high, the soil resistivity in the same soil in Shenzhen may be slightly lower than in other regions.

Under the premise of ensuring the accuracy of the simulation, in order to simplify the soil model, the stratification of soil resistivity outside the metro operation area is neglected. Considering the high-resistance nature of the soil in Guangdong, the soil resistivity of all areas outside the area was set to 300 Ω•m in the simulation.

Simulation Results and Analysis

In the Shenzhen power grid, only the neutral point of the main transformers in the 500kV and 220kV substations is grounded, while that in the 110kV substation is generally not grounded. Therefore, the rail traffic stray current can only enter the AC power system through the 500kV and 220kV substation main transformer neutral point. As a result, only the 500kV and 220kV substations are considered in the simulation.

Analysis of Ground Potential Distribution Simulation Results

The simulation calculation is carried out by using the MALZ module in the CDEGS software. Since the influence of the subway tunnel space, station structure and buried metal on the ground potential distribution in the study area is not obvious, only the influence of the stray current of the subway rail, the location of the subway track and the soil medium is considered in the simulation. Six different operation conditions of the subway were selected, and the ground potential distribution change caused by stray current was simulated. Six representative substations were selected for analysis. Among them, 220kV Daitian Station and 220kV Xiuli Station are located in areas with dense subway lines, and the latter is closer to the subway line. The 220kV Pingshan Station and the 500kV Kunpeng Station are far from the urban area, and there is currently no subway line nearby. The 220kV Wutong Station is located in the coastal area with no subway line running nearby. There is only one subway line running near the 500kV Shenzhen Station. The simulation results are shown in Table 1.

| Substation                  | Condition 1 (V) | Condition 2 (V) | Condition 3 (V) | Condition 4 (V) | Condition 5 (V) | Condition 6 (V) |
|----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 220kV Daitian Substation   | -51.3           | -34.6           | -17.2           | -5.5            | 37.3            | -31.5           |
| 220kV Xiuli Substation     | 56.8            | -64.8           | -57.4           | 22.2            | -36.6           | 66.0            |
| 220kV Pingshan Substation  | 24.8            | 20.5            | 8.3             | 3.1             | 7.7             | -5.5            |
| 220kV Wutong Substation    | 33.3            | 41.2            | 27.0            | 1.5             | 15.5            | -28.8           |
| 500kV Shenzhen Substation  | 35.9            | 35.7            | 21.3            | 7.3             | 19.6            | -22.1           |
| 500kV Kunpeng Substation   | 17.8            | 12.2            | 5.5             | 3.0             | 5.8             | -2.0            |
According to the simulation results, the amplitude of the substation ground potential rise caused by stray current can be as high as 66V, which may threaten the safe and stable operation of the power grid. The ground potential distribution has the following characteristics: In the dense area of subway lines, the closer the substation is to the subway line, the greater the change in ground potential. The ground potential distribution of the substation away from the subway line is also affected by the stray current. The farther the distance is, the smaller the ground potential change amplitude is. The rising potential of the substation ground potential is greatly affected by the distance to subway lines, and is less affected by the stray current intensity. The ground potential distribution in different voltage level substations is affected by basically the same degree. The ground potential distribution of the substation in the coastal area is affected more than the inland area. Due to the randomness of the subway operation conditions, stray current amplitude and direction are both in strong uncertainty. As a result, the ground potential distribution of each substation is in a random state.

Analysis of Simulation Result of DC Current through the AC Power System

The PSCAD/EMTDC simulation software was used to build the simulation model for the Shenzhen power system. In the calculation, the external grid static equivalent method was simplified for the power grid outside Shenzhen, and the equivalent results are added to the AC system simulation model to ensure the accuracy of the simulation calculation.

For a three-winding transformer commonly used in 220kV substations, the DC current through the neutral point is equal to that through the winding. For the autotransformer commonly used in 500kV substations, the situation is more complicated due to the electrical connection between the high and medium voltage side windings.

The DC Current Distribution of Transformer Neutral Point. Under the six operation conditions of the subway, the DC current distribution of the transformer neutral point of each substation was simulated and seven representative substations were selected for analysis. The simulation results are shown in Table 2.

| Substation          | Total DC current through the neutral point of the transformer |
|---------------------|-------------------------------------------------------------|
|                     | Condition 1 | Condition 2 | Condition 3 | Condition 4 | Condition 5 | Condition 6 |
| 220kV Daitian Substation | -46.7       | -16.6       | -28.4       | -26.7       | 56.1        | -32.2       |
| 220kV Xiuli Substation      | 51.1        | -60.6       | -35.8       | 11.9        | -43.1       | 52.4        |
| 220kV Pingshan Substation    | -9.2        | -7.2        | -2.6        | -1.8        | 3.3         | 2.4         |
| 220kV Wutong Substation      | 22.0        | 15.8        | 17.1        | -4.1        | 8.0         | -15.7       |
| 500kV Shenzhen Substation     | 33.3        | 25.7        | 12.9        | -2.6        | 5.2         | -21.5       |
| 500kV Kunpeng Substation      | -8.1        | -5.3        | -1.8        | -2.1        | -3.4        | 1.2         |
| 500kV Zhenzhou Substation     | -9.6        | 1.5         | -1.9        | -3.8        | -2.6        | -6.4        |

In the simulation results, the variation range of DC current through the transformer neutral point of each station is almost the same as the actual test result. According to the simulation results, the distribution of the DC current through the transformer neutral point exhibits the following characteristics: The change trend of the DC current through the neutral point of each transformer is basically consistent with the trend of ground potential change, showing random oscillation. The DC current level through the neutral point of the transformer in the substation located in the dense area of subway lines is significantly higher than that away from the dense area of subway lines, with more intense oscillation. The DC current level through the neutral point of the transformer in the substation in coastal areas is more affected by urban rail transit stray current than that in inland areas. In some substations operated with separated bus bars, DC current may flow through the neutral point of one transformer into the ground and then through the neutral point of the other transformer to the other bus bar. Typically, such substations are located away from subway lines. In some substations outside Shenzhen area, such as the 500kV Zhenzhou station, the
DC current amplitude through the transformer neutral point could be high in some cases, owing to
their electrical connection with substations in the dense area of subway lines, and the large ground
potential difference due to geographical factors.

The DC Current Distribution of Autotransformer Winding. For the autotransformer, the
direction of the DC current flowing into the winding of the transformer may be the same or opposite.
DC current through the neutral point of the transformer cannot truly reflect the DC current in the
transformer winding, or measure the severity of the DC bias caused by the stray current.

When the DC current flowing into winding of different sides is in the opposite direction, the DC
current through the winding of each side might be much higher than that through the neutral point of
the transformer. For example, according to the simulation results, the DC current through the
transformer neutral point of the 500kV Zijing station at a certain time is 0.5A, which is lower than the
transformer's bias magnetic tolerance. However, the DC current through the high-voltage winding of
the transformer is -35.6A, the medium-voltage winding is 36.1A. At this time, the DC current in the
winding also causes severe distortion of the excitation current. Although the DC current through the
neutral point of the main transformer does not exceed the limit of relative regulations, the transformer
will still suffer severe DC bias, which threatens its safe and stable operation.

Therefore, when using the regular capacitive type blocking device at the neutral point to deal with
the DC bias problem caused by stray current, single point configuration at the DC over-standard site
could only block the DC current through the neutral point, leaving a DC loop formed by the neutral
point of the transformer in other substation, the winding and transmission lines. The DC current in the
winding could still threaten the safe operation of the transformer. The capacitive type DC blocking
device only installed at the neutral point of the transformer could not solve the DC bias problem.

As a result, in order to effectively solve the DC bias problem of the autotransformer caused by stray
current, it is necessary to plan from the perspective of the entire regional power grid, and
comprehensively consider the optimal configuration of the DC blocking device, blocking the DC
current path and preventing it from forming a closed loop, leaving the DC current no access to the
winding, so as to avoid DC bias problems from the source.

Summary
(1) The change of ground potential distribution caused by stray current of urban rail transit is in a
random state. The distance between the dense area of the subway line and whether located in the
coastal area is the main factor affecting the distribution of the ground potential. The closer to the
dense area of the subway line, the greater the variation of the ground potential, and the change of the
ground potential in the coastal area is more obvious than that in the inland area.

(2) The distribution characteristics of DC current through the neutral point of the transformer are
basically consistent with the trend of the ground potential distribution, which is relatively random.
The amplitude of the DC current through the neutral point of the transformer is affected by the
distance between the dense area of the subway line and whether located in the coastal area. And the
DC current can spread to the distance through the neutral point of the transformer and the
transmission line, causing the DC current level of the transformer in other areas to exceed the
standard.

(3) For autotransformers, the DC current through the neutral point cannot truly reflect the severity
of DC bias caused by stray current. When using the capacitive type blocking device at the neutral
point to deal with the DC bias problem caused by stray current, it is necessary to properly arrange the
blocking device within the entire regional power grid.

Acknowledgement
This research was financially supported by the Science and Technology Project of CSG
(090000KK52180006).
References

[1] Y. Liu, J. Wang, L. Zhao, Mathematical model of stray current distribution in subway, Chinese Journal Of Engineering Mathematics. 26 (2009) 571-576.

[2] Y. Zhao, X. Zhou, Numerical analysis of stray current distribution in subway, Urban Mass Transit. 12 (2009) 42-47.

[3] B. Zhang, W. Huang, X. Chen, Probe into impacts of DC magnetic bias on main transformer in Shenzhen power grid and its countermeasures, Shaanxi Electric Power. 42 (2014) 67-72, 85.

[4] X. Wen, T. Guo, Z. He, Review of the related problems of DC magnetic bias, High Voltage Apparatus. 52 (2016) 1-8.

[5] Q. Chen, H. Ma, J. He, Field monitoring and analysis on vibration and noise of 500 kV electrical transformer under DC current biasing, High Voltage Apparatus. 45 (2009) 93-96.

[6] H. Li, X. Cui, T. Lu, Electric circuit and magnetic circuit combined model of DC biased power transformer, Proceedings of the CSEE. 29 (2009) 119-125.

[7] C. Liu, C. Huang, M. Pan, Optimal configuration of capacitor blocking devices for suppressing DC bias in transformers, High Voltage Engineering, 42 (2016) 2308-2314.

[8] P. Peng, W. Zhou, Y. Xie, Analysis and research on DC bias of transformer caused by metro stray current, Transformer, 54 (2017) 26-30.