Simulation Study of the Influence of Stray Current on DC Bias of Power Transformer

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Abstract. The running of subway rail transit can generate stray currents. This is a current that causes severe corrosion of the buried metal near the subway, and also generates DC bias, which affects nearby power transformers. There are few studies related to the influence of DC bias created by stray current on power transformers. This makes it difficult to determine the impact of subway rail transit on the DC bias of nearby power transformers. To explain the effect of stray current on the DC bias of the power transformer, the characteristics, master sheets of stray current and the principle of DC bias of stray current are analyzed, and a power transformer model of stray current generating exciting current is established. The harmonic components in the stray current are simulated and analyzed. The simulation results show that the track insulation aging caused by subway operation will generate stray current, which will flow into the grounding grid and cause DC bias of the neutral grounding transformer, and then make the transformer core saturated. The amplitude of harmonic component and excitation current will increase with the increase of stray current.

Keywords: Stray currents; Power transformer; Harmonic component; DC bias.

1. Introduction
With the rapid development of the economy, the traffic congestion in large and medium-sized cities has become more and more serious in China, thus subway has gradually become the best public transportation tool. The direct current of metro train is supplied by the positive pole of traction substation through the third track. The direct current flows from the grounding brush to the steel wheel and flows back to the negative pole of the traction substation. Since the rail resistance is not actually zero and the train's operating current is around several thousand amperes, the voltage drop across the rail can cause a certain voltage difference between the rail and ground. If the insulation between the rail and the ground is not ideal, a transit resistance will be formed between the two, causing a part of the current to flow to the ground through the rail, that is, stray current [1,8]. The flow direction of the stray current is not a fixed orientation and has the characteristic of preferentially flowing through the low impedance conductor. Therefore, metal pipelines near the subway rails, building reinforcements, and substation grounding grids provide the main flow path for stray currents. If the nearby metal pipelines or building reinforcements are not connected to the negative end of the traction substation, the stray current may electrochemically corrode the metal pipelines and structures during the process of returning to the negative pole of the traction substation, accelerating corrosion and causing safety hazards [2]. If stray current flows into the grounding grid of a nearby power substation, the current will then flow into power transformer through its grounded neutral point and cause DC biasing of the transformer [9,10].
transformer generates a large number of harmonics under DC bias, which drops the power quality. The core hysteresis causes the winding vibration to generate great noise, heat and CT malfunction[11,12]. In 2013, Shenzhen Power Grid discovered that the transformers near the Shenzhen Metro Line 3 showed DC bias phenomenon, which was initially identified as stray current. However, due to the lack of relevant research, the principle, coupling path and influencing factors of DC bias caused by stray current could not be determined. Therefore, research on the influence of stray current on DC bias of transformers and suppression measures are urgently needed and very necessary.

Nowadays the research on stray current at home and abroad takes the corrosion problem as the research goal, mainly focusing on the research on the mechanism and distribution characteristics of stray current. YU JG et al. used the transmission line method to derive the orbital characteristic equations by analyzing the electrical characteristics of the track, and studied the factors affecting the orbital characteristics based on this equation [13]. Jinfuqun analogs the distribution characteristics of stray current whether the drainage is conducted or not, by using the mathematical model of Metro DC traction power supply system, and analyzed the influence of each parameter on the stray current distribution [14]. Liu Yan used the micro-element method to establish the mathematical model of stray current distribution. The distribution characteristics of stray current were analyzed from the perspective of soil resistivity and transition resistivity. The increase of track resistance, the reduction of soil resistivity and transition resistance were found to be the main cause of stray current [15]. In the establishment of the stray current distribution model, the magnitude of the stray current can only be estimated by a simplified empirical formula. The calculation is only for the theoretical understanding of the stray current, and aiming at finding ways to control stray currents through the variables in the formulas. According to the current research, the equations for the orbit-soil system have been deduced in detail, but the research on the distribution of stray current in the AC grid is still in a blank stage.

When power transformers are affected by DC bias caused by subway stray current, the iron core enters into high saturation section, causing severe distortion of the excitation current waveform, sharp increase of peak value, rapid increase of harmonic components, and widening the harmonic distribution. When the harmonic components of the excitation current increase, the reactive power consumption of the transformer will increase, the voltage waveform of the secondary side of the transformer will be distorted, and the harmonic content of the transformer load will also increase, which will degrade the power quality. At present, the research on DC bias magnetism is mainly focusing on GIC (Geomagnetically Induced Currents) and DC electrodes in HVDC transmission projects. Therefore, it is urgent to explore the principle of DC bias magnetism caused by stray currents in practice and to alleviate the negative effects of subway stray current on transformers.

This paper revealed that the stray current generated in the operation of subway rail transit will cause DC bias phenomenon in nearby transformers. The principle and characteristics of stray current generation are analyzed. The possible propagation paths of stray current are studied. The transformer simulation model is established to simulate the influence of stray current on the harmonic components of the excitation current, which provides a guiding direction for the research of this problem.

### 2. Analysis of the Generation Mechanism and Characteristics of Stray Current

#### 2.1. The Generation Mechanism of Stray Current

The subway rail transit in China uses 750V or 1500V DC traction power supply system. The traction substation delivers current to the train via the positive rail (i.e. the third rail). The collector shoe collects current into the train and flows to the wheel via the grounding brush. At the end, the current returns to the negative pole of the rectifier of the traction substation. The rail resistance in actual operation is not zero, and the traction current of several thousand amps will cause a voltage drop on the rail, so that there is a certain potential difference between the rail and the earth. Therefore, part of the current will flow from the rail to the earth and return from the earth to the negative pole of the traction substation. This part of the current flowing from the rail to the earth is called stray current. Stray currents do not have a fixed flow path, their flow depends on the impedance characteristics of the object. Generally, stray currents flow along low-impedance paths, i.e., building reinforcements, metal pipes, substation ground networks,
and so on. Stray current not only accelerates the corrosion of metal pipes and buildings along the line, but also affects the neutral grounded transformer in the nearby substation, which is harmful to the operation of the transformer. Figure 1 shows a typical stray current collection system [16].

![Figure 1. Capacitor bank switching equivalent circuit](image)

After the stray current flows out of the rail, a portion of it runs back to the negative pole of the traction substation by the drainage network and pipeline. However, due to the limited conductivity of the draining net, a part of the stray current still flows in. The other conductors in the soil flow out of the other conductors and eventually flow back to the negative pole of the traction substation rectifier. When the return diode is on, the summation of stray current flowing through the return diode is called collector current, and the collected current, together with the negative return current through the rail, constitutes the negative return current of the entire system. Among them, R1, R2, and R3 are resistors for measuring negative return current, collecting current, and uncollected stray current, respectively.

The main purpose of stray current distribution simulation is to model the equivalent circuit of Figure 1 structure, and use resistance to represent all the resistive components in the figure to form ladder equivalent circuit [16]. Because the metro locomotive is in motion, and has a fixed route and schedule, if the stray current measurement point is to fixed, the motion characteristics of the metro locomotive need to be modelled. By combining the two models, the characteristics of stray current distribution in a certain period of time can be obtained.

### 2.2. The Characteristic Analysis of Stray Current

The distribution model of stray current is simplified by Japan Railway Technology Research Institute, and the estimation formula of the total stray current between two adjacent traction substations is given in (1).

\[ I_{sc} = \frac{I \cdot R \cdot L^2}{12r} \]  

Where \( I \) represents the load current of the locomotive (A), \( R \) represents the resistance of running rail per kilometre (Ω), \( L \) represents the distance between two adjacent traction substations (km) and \( r \) represents the resistance of the running rail to the ground per kilometre (Ω). Equation (1) shows that the value of the stray current is proportional to the load current of the locomotive, the resistance of running rail, and the square of the distance between two adjacent traction substations, but inversely proportional to the resistance of the running rail to the ground. However, the actual stray current calculation model is much more complex than the relationship represented by equation (1). First of all, the train is running continuously, and the number and time interval of the trains passing through the calculation area are not the same. The distribution of stray current is instantaneously changed. Secondly, the factors affecting the stray current are not quantified, and there are still many unstable factors. These unstable factors cause the generation and distribution of stray current to be difficult to predict. Taiwan
scholars conduct real-time monitoring of stray current in a running station in the Taipei MRT Blue Line (750V DC power supply). The test time is from 6:00 am to 24:00 pm. The test results show that the highest value of the collected stray current appears at 7:15 am, and the value is up to 665A. And the stray current value during the morning peak (6:00 am-9:00 am) is much larger than other times, most of which are distributed between 50A and 200A, mainly concentrated near 100A. The stray current value in other times is small, basically less than 50A [16]. According to calculations, the stray current collected by the stray current collecting device of the subway station accounts for 40% of the total stray current, that is, 60% of the stray current still flows into other conductors, which poses a threat to the surrounding facilities.

In summary, the stray current is greatly affected by the load current of the locomotive, the resistance of running rail, the distance between two adjacent traction substations, the resistance of the running rail to the ground, locomotive running time and density, and it has time-varying characteristics, so it is necessary to synthesize various influencing factors to obtain accurate analysis results.

3. Influence of Stray Current on DC Bias of Transformer

3.1. The Propagation Path of Stray Current

The propagation path of the stray current through the AC grounding grid into the neutral grounded transformer is shown in Figure 2.

![Figure 2. Schematic diagram of subway stray current intruding AC transmission system](image)

In the figure, the stray current flowing into the soil that is not collected by the subway drainage device during the operation of the subway is divided into two parts, one is $I_{sc1}$, which represents the stray current flowing into the AC ground network, and the other is $I_{sc2}$, which represents the stray current not flowing into the AC network. After $I_{sc1}$ enters into the AC ground network, part of it diffuses through the ground network, and part of it enters into the neutral grounded transformer, which is called $I_{AB}$. $I_{AB}$ enters the transmission line from transformer A to transformer B, and then enters the earth by the ground network of transformer B, and finally returns to the negative pole of the subway traction substation. From the above analysis, it can be seen that the transformer-transmission line-transformer system constitutes a stray current circulation circuit, so that the AC system with transformer neutral directly grounded is highly likely to exhibit DC bias.

3.2. Simulation Model and Results

In order to verify the effect of stray current on the DC bias of the transformer, a single-phase analog transformer is simulated in MATLAB. The transformer used in the simulation is a 500kV single-phase autotransformer with a rated capacity of 250MVA and a rated voltage of 525kV. The winding turns on the high voltage side of the transformer are 845. The characteristics of $M_s = 1.6 \times 10^6$ the core are described by the Jiles-Atherton model [17,18]. The equivalent sectional area of the core is 0.9246 m², the equivalent length of the magnetic circuit is 75.2439m, and the JA model parameters are: $a = 3 \times 10^{-3}$, $a = 15.1$, $K = 7$ and $c = 0.65$. The simulation schematic is shown in Figure 3.
The simulation system is mainly composed of a transformer, an AC voltage source and a DC voltage source. In the case of no DC bias, the excitation current and harmonic content of the excitation current of the transformer are shown in Figure 4 and Figure 5 respectively.

The simulation results show that the excitation current mainly contains odd harmonic content and almost no even harmonics. According to the analysis in Section The Characteristic Analysis of Stray Current, the stray current entering the transformer is not constant DC, but varies with time. As the subway passes through, the stray current at a fixed point on the subway rail increases first and then decreases. The stray current entering the transformer flows through the soil and the substation ground network, and the waveform should be gently changed. Assume that the subway has an average speed of 80km/h, and the length of each car is about 20m. The total length of the subway locomotive for the six cars is 120m. The time for the subway to pass through the fixed point on the rail is 5.4s. The DC voltage source at the neutral point of the transformer is a like semi-periodic sine wave that rises and falls gently within 0s to 5.4s. The maximum amplitude is 40V, and the DC voltage value after 5.4s is zero, as shown in Figure 6.
Figure 6. DC voltage source waveform of transformer neutral point
The DC current waveform of the transformer neutral point is shown in Figure 7. The waveform is similar to the DC voltage waveform. The maximum amplitude is about 1.2A. Because the inductance in the transformer circuit is large, when the DC voltage is reduced to zero, the DC current does not decrease to zero, and there is a certain hysteresis.

Figure 7. The waveform of stray current at the neutral point of the transformer
In the case of DC bias caused by stray current as shown in Figure 7, the excitation current and harmonic content of the excitation current of the transformer are shown in Figure 8 and Figure 9 respectively. From the Figure 8 and Figure 9, it can be seen that when the stray current has DC bias effect on transformer, the amplitude of the excitation current increases and even harmonics appear.

Figure 8. Excitation current with DC bias
In conclusion, the simulation results show that the harmonic content of the excitation current are mainly odd harmonics when there is no DC bias. When the stray current enters the neutral grounded transformer, the harmonic content of the excitation current increases, especially the even harmonic content.

4. Summary

Based on the generation mechanism of stray current and the distribution law of DC in AC power grid, this paper puts forward a problem that the stray current generated in the operation of the subway will cause DC bias of nearby transformers. The characteristics and propagation modes of stray current are analysed, and the transformer model is simulated to analyse the influence of stray current on the DC bias of the transformer. The simulation results show that the stray current has DC bias effect on the adjacent neutral grounded transformer, which will increase the harmonic content of the excitation current of the transformer, especially the even harmonic content. The research in this paper provides a preliminary research basis for the problem of the influence of subway stray current on the transformer, which has a certain guiding significance.

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