Analysis of current characteristics of transformer bias caused by subway stray current based on measured data

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Abstract. The metro stray current, as the driving source which causes the magnetic bias of the urban network transformer, has the characteristics of rapid change, complex propagation path, and many influencing factors. It’s unknown where the stray current leaks from, and its specific value cannot be obtained through measurement methods. Therefore, this paper studies the characteristics of transformer neutral magnetic current bias based on the measured data and fault recording data in the process of measurement, and analyzes the influence of stray current on transformer in urban network.

1. Introduction

The transformer bias of the geomagnetic storm on March 13, 1989 induced a blackout in the Quebec power grid[1]. Through this accident, for the first time people realized that the geomagnetic storm may cause serious damage to the transformer bias. China is the largest UHV power transmission country in the world. During the development of UHV, it was found that DC grounding electrode unipolar operation would cause magnetic bias of transformer and bring certain influence[2]. Subsequently, China took the lead in researching the influence of DC grounding electrode unipolar operation on transformer magnetic bias, and now it basically eliminates the risk of magnetism bias accidents caused by grounding electrodes[3].

In 1990, F. J. Lowes discovered the stray current leaking from the subway traction network and the electromagnetic field generated by it[4]. Later, other scholars found that stray current accelerated the electrochemical corrosion of buried metal components and pipes[5]. With the development of the city, in order to alleviate the pressure on ground transportation and meet the travel needs of citizens, the scale of subway has been further expanded, and the degree of coupling between the metro and urban power grid has been further deepened. In 2011, the phenomenon of transformer bias caused by stray current was first discovered in Shenzhen[6]. Later, transformer magnetic bias caused by stray current...
was also found in Fuzhou, Guangzhou and Changsha[7]-[9], and relevant observation and research was carried out for a transformer, and obtained data such as measured current and noise at the neutral point of the transformer. However, the number of stations monitored is small, so the obtained data and the level of magnitude are relatively insufficient which is not enough to study the characteristics of magnetic current bias caused by stray current in urban network.

Based on the research of the magnitude level and variation law of the neutral point bias current data of multiple transformers in a city of China, the results show that the magnitude of the bias current and its variation characteristics are very different, in other words, it is difficult to find the characteristic law only through the measured data of the biased magnetic current in a single substation. Therefore, this paper analyzes the measured data of neutral magnetic current of many transformers by statistical method, and studies the magnitude characteristics and risks of transformer magnetic current bias.

2. Observation experiment and measurement site conditions
In order to explore the effects of various influencing factors on the transformer caused by metro stray current, 7 stations of 220kV and 1 station of 500kV were selected for observation experiments. In September 2020 and January 2021, a total of 13 220kV transformers and 2 500kV transformers have completed the measurement experiments of magnetic bias current at neutral points.

2.1. Observation experiments
The experiment include an open Hall element (100A/2mA), an open zero-sequence current transformer (100A/5A) and a portable DC bias monitoring device to measure the bias current. When measuring, put the neutral ground wire of the transformer into the opening of the Hall element and zero-sequence current transformer, and the measured value is read and displayed by the DC bias monitoring device in time. The stray current flowing back to earth from the transformer neutral point is positive, and vice versa is negative.

2.2. Measurement sites
1) Site 1: Two 220kV three-winding transformers connected with YNyn0d11 were measured at the measuring station 1, and the two transformers operated separately. The measurement station 1 is located in the downtown area of the city. The straight-line distance between the two subways is 1500m and 350m respectively, and 370m away from the nearest subway station. There is no turning or transfer of subway line within 1000m of the measurement site.

2) Sites 2: Three 220kV auto-transformers were measured at measuring station 2, located in the intersection area of four subway lines. The linear distance between the measurement station and the four subway lines are 160m, 670m, 700m and 960m, respectively. All the outgoing substations A, B, C and D of measuring station 2 are close to the subway line, so the possibility of metro stray current flows between substation A, B, C and D and measuring station 2 cannot be ruled out.

3) Sites 3: Two 220kV auto-transformers were measured at measuring station 3. The measuring station 3 is close to the subway transfer station, and the straight-line distance from the three subway lines is less than 300m. The operation schedules of the three subway lines are inconsistent, and the measurement station 3 is affected by three subway lines at the same time. The influencing factors that need to be considered in the study are too complicated, which is not convenient to study the influence of stray current on transformer magnetic bias under a single condition. It is more suitable for studying the characteristics of the influence of multiple lines.

4) Sites 4: Measurement site 4 is equipped with two 220kV transformers, one of which is a three-winding transformer and the other is a double-winding transformer. The linear distances between the measurement site 4 and the subway are: 950m, 700m, and 500m (the two lines overlap each other).
5) Sites 5: The measurement site 4 is located at the edge of the city, with two 220kV three-winding transformers, and only one of the transformers was measured for the neutral bias current. Compared with other test stations, station 4 is farther away from the subway line. The distance from the end point of one of the lines is 3000m, and the straight-line distance from the nearest subway line is 4000m.

6) Sites 6: Site 6 is equipped with three 220kV transformers, located in the suburbs of the city, and there is only one subway line around. The distance between site 6 and the end of the subway line is 1300m.

7) Sites 7: Measurement site 7 is a 220kV station with two transformers, and only one of the transformers was measured for the neutral bias current. There is only one subway line around site 7, with a straight-line distance of 300m and a distance of almost 460m from the nearest subway station. In the vicinity of the measurement site 7, the turning of the subway line has a certain impact on the distribution of the geoelectric field around the site 7.

8) Sites 8: Measuring station 8 is an underground 500kV station with two 500kV single-phase autotransformers, located in the downtown area and surrounded by many subway lines. During substation debugging in 2010, the noise of the main transformer did not exceed the limit. In 2015, subway line A and subway line B were put into use successively. Noise and vibration of transformers at station 8 were intensified, with obvious DC magnetic bias.

3. Analysis of measured bias current data

The magnitude of the obtained measurement data and its variation characteristics are vary greatly. The following studies the risk of subway transformer biasing through the analysis of influencing factors and the magnitude of the bias current.

3.1. Multi-line influence characteristics in urban areas

Measurement sites 1-4 are located in urban areas and are affected by multiple subway lines. The measured curve of the neutral bias current presents the characteristics of rapid change in positive and negative directions and large amplitude fluctuations, as shown in Fig. 1.
The magnitude of the bias current is affected by operating factors such as the train start, acceleration, constant speed, and deceleration. In addition, although the subway train has set a operation sequence, some unpredictable changes usually occur in the actual operation process. Therefore, the subway stray current and the interference current that may cause the transformer biasing have the characteristics of pulsating change, randomness, and unpredictability.

3.2. Influence on the location of the outlet substation

Although there are two subway lines around the measurement site 4, but the linear distance from one of them is far away, it can be approximated as being affected by only one subway line. Fig. 2 shows the measured curves of neutral magnetic bias current at measuring stations 6 and 5. It is found that the level and fluctuation of the magnetoelectric flux at the neutral point at the measurement site 5 are much higher than that at the site 6.

![Fig.2 The measured curve of the transformer neutral point bias current at measurement site 5 and 6](image)

The the Earth electrical structure and the number of surrounding subway are similar between the two. The biggest difference is that the opposite transformers of measuring station 5 are all located in the central urban area, while only a few transformers of station 6 are located near the subway. The stray current is transmitted to the neutral point of the transformer at the measuring station 5 through the transformers at the opposite end of the wire. Therefore, although the measurement site 5 is farther from the end of the subway line than the site 6, the neutral bias current level is higher than that of the measurement site 6. It shows that when studying the influence of metro stray current on urban network transformers, in addition to the relative position of the substation and the subway line, the relative position of the substation and the subway line should also be considered.

3.3. Influence of subway operating conditions

The speed of the subway train and the number of the train that running on the line are adjusted with the size of the passenger flow. There are more trains running on the line during the peak period is large, the train departure and operation interval is short, and the value of stray current fluctuates greatl,while it is relatively small in off-peak period.

In order to study the changes of transformer neutral current during peak and off-peak times transformer No.2 at site 8 with dense subway lines around was selected to measure the neutral bias current at 7 different times. Select the representative measurement data at 3 moments for analysis, the curve of the current as shown in Fig. 3.
From Fig. 3, it can be found that the bias current at the neutral point during the peak period is almost negative. Compared with the off-peak period, the magnitude level changes more dramatically and faster. And after the train is out of service, the neutral point bias current of site 8 is almost zero. Therefore, it can be determined that the operation of the subway is the cause of the transformer bias at site 8.

The waveform analysis of the disturbance record data of site 8 on the day of the measurement is shown in Fig. 4 and 5. It can be clearly seen that the analysis results are consistent with the existing harmonic analysis conclusions of transformer DC bias. There are obvious differences between the harmonic characteristics of the transformer high-voltage side current during the peak period and that after the subway is out of service: the 2nd, 4th, 8th and 10th harmonic of the transformer high-voltage side current are prominent during subway operation, and the 2nd harmonic content of even harmonic is the highest. However, after the subway shutdown, it is mainly the 5th, 7th, 11th and 13th harmonics, and even harmonics caused by DC magnetic bias is almost eliminated. It proves again that the stray current of subway is the cause of DC magnetic bias of transformer in urban network.
4. Conclusion
Through the observations at 8 selected stations, the measured data of the neutral point current of multiple transformers were obtained, and the influence of the stray current on the 220kV and 500kV transformers of the urban power grid was studied. The conclusions are as follows:

1) The current generated by metro stray current at the neutral point of transformer in urban network generally has the characteristics of change randomly, and the situation is very complicated due to many influencing factors, so it is difficult to carry out accurate theoretical calculation;

2) The position of the transformer at the opposite end of the substation is also one of the influencing factors that affect the level of the bias current at the neutral point of the transformer;

3) Metro stray current is the main reason for the transformer DC bias in urban power grid. With the change of subway operating conditions, the influence degree of DC magnetic bias of transformers in urban network is different: the peak period has the deepest impact, the second in flat peak period. And there is basically no impact after the subway shutdown.

Acknowledgments
Project supported by State Grid Science & Technology Project(520940200013).

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