Analysis and Evaluation of the DC Magnetic Bias for 1000kV Ultra-High Voltage Transformer Caused by Changsha Rail Transit

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Abstract: In this paper, the stray current distribution network model of Changsha rail transit system is constructed from the perspective of the stray current induced by rail transit in the adjacent substation. We evaluated the degree of influence of the stray current of urban rail transit lines after the completion of the Changsha 1000 kV UHV substation, which provided a reference for the UHV transformer DC bias prevention experience.

1. Introduction
The 1000kV UHV substation site is located in Huangqiao Village, Ansha Town, Changsha County, Hunan Province. The site is about 20km away from Changsha City and only 11.23km away from Guangsheng Metro Station of Changsha Rail Transit Line 3. A large amount of operating data and experience show that the daily operation of the rail transit system may cause DC bias in the transformer.

It is different from the DC transmission earth return current intrusion AC system. Early warning of stray currents in rail transit systems requires consideration of track-to-ground insulation and train operating characteristics[1]. For example, the transition resistance of rail transit systems characterizes the track-to-ground insulation. In the big data modeling of stray current warning, we need to apply a coating to the model. Except for the above-ground part, the subway track is generally buried 15m~20m underground in the city. The coupling mechanism of rail transit and power grid is very complicated, which belongs to the coupling of line-point form. There are multiple trains running simultaneously in the rail transit system, and the system's operating characteristics are highly complex and time varying.

Stray current is affected by two factors: the rail-to-ground potential and the rail-to-ground transition resistance. The higher the potential of the running rail to ground, or the worse the insulation of the rail, the stray current will increase. Although the potential of the rail to ground is not fixed, it is related to the power supply distance, load current, rail resistance and the surrounding geological environment. When the insulation performance is poor, the transition resistance is small. As the train's operating state changes, the distribution of stray currents also changes[2,3].

The train in the traction power supply system can be regarded as a moving load. Because the distance between stations on the line is often within thousands of kilometers, the train accelerates and decelerates more frequently, and the traction current increases or decreases regularly as the train runs. The power changes drastically during the train starting and braking phases, which will inevitably affect the urban power grid. The traction current is related to the running speed of the train, the
condition of the track line, and the weight of the body. The train starts accelerating when it starts, and it takes direct current from the traction network to accelerate, and the motor power increases linearly. After the speed reaches the limit, the train begins to enter the idle zone, and the current decreases with increasing speed. The train will run with electricity, and after a few tens of seconds, the power will be cut off by inertia. When the train adopts braking measures to decelerate to stop, the energy generated by regenerative braking returns to the catenary to supply power to the train, and the current value is a negative number. When the distance between the power supply sections is small, the train running time is short, and it may not idle. There are only acceleration and deceleration phases\(^4,5\).

Since there is only a slight fluctuation in the network pressure during the train operation, when we calculate the rail traffic load, we can think that the network pressure remains unchanged, and the power is equal to the voltage times the current. Then the formula for calculating train traction is:

\[
P = \begin{cases} 
Fv_i & \text{(acceleration)} \\
Wv_i & \text{(coasting)} \\
(W + B)v_i & \text{(deceleration)} 
\end{cases}
\]

(1)

\[
P = U_i I_0
\]

(2)

In the actual operation process, we can directly obtain the train traction current-time curve through the actual measurement method. As can be seen from the traction current curve of the train (Figure 1 example), although the traction current varies greatly, it can simplify the histogram that changes with time. The purpose is to maintain the maximum traction current during the starting and braking phases, and the train current is close to zero during the coasting phase\(^6,7\). The train adopts speed closed-loop control to realize the three processes of traction acceleration, natural coasting and braking deceleration, so that there are three operating conditions during train operation, including traction, idle and braking.

![Train traction current curve](image)

**Fig. 1.** Train traction current curve

### 2. Model building method

The magnitude and direction of the resultant force on the train determine the train’s operating state. The train operating characteristic curve is shown in Figure 2.9. Train traction calculations are performed under three operating states: train start-up acceleration, idling, braking deceleration. When the acceleration is started, the maximum traction force is used to make the train speed within the target speed range. The intermediate process keeps the train speed between high and low speed limits. When the train runs to the target position, it goes into the reverse braking process.

During traction, electrical energy is converted into kinetic energy for train operation. When the train accelerates, the traction remains unchanged and the speed gradually increases. It can be seen from the traction power formula that the traction power increases and the train power remains unchanged after reaching the maximum limit, and the traction force is inversely proportional to the speed(Figure 2 example). When the train enters the idle zone, the traction force and traction power are zero. When braking, the electrical energy is returned to the traction network for use by other trains in the traction state or back to the power system.
The traction performance of the train is mainly reflected in the acceleration ability of the train below a certain speed. We regard the train as a single particle model, then the basic force equation of the train is as follows:

\[
C = \begin{cases} 
F - W & \text{(acceleration)} \\
-W & \text{(coasting)} \\
-W - B & \text{(deceleration)} 
\end{cases}
\]  

(3)

In the formula, C is the total force; W is the resistance; F is the starting traction; B is the braking force; M is the mass of the EMU and trailer, and the unit is t; V is the speed of the vehicle.

Based on the above operation strategy, in order to facilitate the further introduction of the train operation process based on the operation diagram, a corresponding traction calculation model is established in a section of operation. We assume that the train runs between the two substations and uses regenerative braking. The feedback energy is completely absorbed by the catenary. It can be seen from the traction current curve of rail transit trains that although the traction current varies greatly, it can be simplified to a rectangular graph that changes with time. We ignore the process of current rise and fall. The purpose is to maintain the maximum traction current during the starting phase and the maximum braking current during the braking phase. Combined with the train running trajectory, we divide the running route according to the power supply distance and the train length, and each section of rail corresponds to a different traction flow. When the power supply distance is large, the train runs in the order of starting acceleration, taxiing, and braking deceleration. If the power supply distance is small, the train may not have a coasting distance\[8\]. Figure 3 shows the corresponding relationship between train running speed, load current and position. We divide each power supply interval into multiple small segments. Each subsection corresponds to different speed and load current. The speed limit of the train is 80 km/h. After the train accelerates to the maximum speed limit, it turns into a coasting motion until it reaches the braking point and begins to decelerate. The acceleration and braking deceleration processes in the figure respectively account for 30% of the power supply interval.

In addition, the traction load of rail transit presents two characteristics of regularity and mobility. Trains must strictly follow the operation plan, and the departure intervals of different trains are fixed. Each train moves continuously along the line, and trains running in the same direction will not overlap.

We assume that the grounding grid is a network of thin cylindrical conductors connected in any position or direction. The radius is much smaller than its length, and there is a semi-infinite medium with a conductive resistivity of $\rho$. The dielectric constant is $\varepsilon = \varepsilon_r \cdot \varepsilon_0$. We regard air as a non-conductive medium, and there is coupling between the conductors of different grounding systems.

We simplified the rail transit line into a grounded equivalent circuit composed of r segments of conductors and n nodes. The longitudinal current flowing through each section of conductor is $i_h$, and the leakage current flowing evenly into the ground is $i_k$. DC current source is a single-frequency current injected into one or more nodes. It can energize the grounded network. In addition, in the
grounding system of rail transit, there is a potential difference between different nodes due to electromagnetic coupling and the flow of current between conductors. However, when the segments are very short, each segment can be considered as equipotential. The principle of segmentation must balance accuracy and efficiency. The denser the segmentation, the higher the calculation accuracy, but the calculation time is also longer. The voltage of each section of conductor is determined by the average voltage of the nodes at both ends.

\[ U_k = \frac{V_i + V_j}{2} \]  

where \( i, j \) are the nodes at both ends of conductor \( k \), which can be expressed as: \( U = KV \) \( (5) \)

In the formula, \( U \) is the rail conductor voltage column vector; \( V \) is the rail node voltage column vector; \( K \) is the correlation matrix between \( r \times n \) conductor nodes.

\[ K = \begin{cases} 
\frac{1}{2} & \text{(The node is connected to the conductor)} \\
0 & \text{(The node is disconnected from the conductor)} 
\end{cases} \]  

There is a longitudinal current in each segmented conductor. In addition, due to the conductivity of the surrounding medium, each section of the conductor branch has a stray current leaking into the ground. The current between each section of conductor flowing into the surrounding environment and the potential of each section of conductor has the following matrix relationship:

\[ I = R_o^{-1}U \]  

where \( R_o \) is the transition resistance vector, which is determined by the surrounding soil conditions and the insulation performance of the rail. We divide the stray current of each conductor into two parts, so the current flowing from the node is defined as:

\[ J_j = \sum_{k=1}^r c_{k,j} J_k \]  

If the node is connected to the conductor, \( c=1 \); otherwise, \( c=0 \). \( J = K^T I \) \( (9) \)

It can be known from the node voltage method:

\[ I_v - J = R_g^{-1}V \]  

where \( R_g \) is the column vector of the longitudinal resistance of the rail, and \( J \) is the column vector of the stray current considering the capacitance effect and the conduction effect. \( I_0 \) is the column vector of the current source, which is related to the magnitude of the load and the position of the traction substation at a distance. Equations (4) \(~(10)\) can be organized as:

\[ I_v = (K^T R_o^{-1} K + R_g^{-1}) V \]  

\( (11) \)
The column vector $I_0$ of the injected current is a known quantity, and the column vector $V$ of the node voltage can be obtained by Equation (5). Then, the conductor potential $U$ of each segment can be obtained accordingly, and then the column vector of the stray current can be obtained.

The resistance of the urban transmission network is relatively low, which has a certain attractive effect on the stray current, and makes part of the stray current flow into the urban power grid through the neutral point of the power transformer. The uneven distribution of the ground potential is the main cause of the DC bias of the transformer. The earth resistivity is the decisive factor of the ground potential. According to China's design requirements for urban subway rail transit, the government clearly stipulates that the ground resistance of the rail must be less than 0.5Ω, and the ground resistance of substations above 220kV in the AC grid is also less than 0.5Ω. When the distance between the driving line and the nearby substation is relatively short, the leakage of stray current can flow into the substation through the grounding grid, causing the problem of DC magnetic bias.

The path of stray current entering the ground and flowing into the transformer through the grounding grid is shown in Figure 5. Some of the stray current not collected by the drainage device flows into the grounding transformer of substation A through soil or metal conductors, and then enters the AC grid[9]. It flows into the transformer of another substation B via the transmission line with extremely low resistance, and it finally enters the ground through the grounded neutral point, and flows back to the negative pole of the traction substation.

![Fig. 5. Stray current flowing into the AC grid](image)

3. Model analysis and conclusion

This section mainly introduces the influence of the stray current of Changsha rail transit on the DC bias of Changsha UHV substation. Figure 6 shows the geographical distribution of the Changsha rail transit system and the nearby power grid system.

Changsha Rail Transit Line 3 is scheduled for trial operation in 2020. The influence of Line 3 on the DC bias of Changsha UHV substation is an important consideration. Considering that the project time is urgent, the project only carried out the research on the impact of the rail transit stray current of Guangsheng-Sifangping section of Line 3 on Changsha Station. According to the overview of the Changsha rail transit system, the Changsha rail transit system uses DC power supply with a power supply voltage of 1500 V. The operating load current of the train is related to several factors. We take typical values, as shown in Figure 3 for the two power supply intervals. The maximum value of the acceleration load current is 3 kA, and the minimum value of the braking load current is $-1.5 kA$. The section from Guangsheng Station to the Luositang section is closest to the UHV substation, so the DC magnetic bias current caused by the train running on this section will be studied first.

Under standard load conditions, the maximum DC bias current of the main transformer is 1.19 A. The current direction is reversed during braking, and the current drops to 0.59 A. The maximum value of DC bias current from Luositang to Wentizhongxin is 1.19A. When braking, the current drops to 0.59 A. In addition, the maximum DC bias current from Wentizhongxin to Songyahu is 1.17A, and the current drops to -0.58 A during braking. The maximum DC bias current from Songyahu to Xingsha is 1.16A, and the current drops to $-0.58A$ during braking. The maximum DC bias current from Xingsha to Xianglong is 1.14A, and the current value drops to $-0.57 A$ during braking. The maximum DC bias current from Xianglong to Changsha University is 1.11A, and the current value drops to $-0.56 A$
during braking. The maximum DC bias current from Changsha University to Yaquehu is 1.08 A, and the current value during braking drops to -0.54 A. The maximum value of DC bias current from Yaquehu to Sifangping is 1.05 A, and the current value drops to -0.53 A during braking[10].

Based on the above calculation results, we found that a single train running under standard conditions does not cause an excessive risk of DC bias. However, in the rail transit system, there are multiple trains running in the same direction on the same route. Therefore, we still have to consider the maximum DC bias risk caused by the transformer when multiple trains are running at the same time. The following is a specific analysis.

Fig.6. Changsha Rail Transit and Hunan Power Grid's Geographic Information

If the two trains depart at the same direction and enter the acceleration stage at the same time, the DC bias current of the UHV transformer is the superposition of the running currents of the two trains, so the maximum DC bias current at this time is 1.19A×2=2.38 A. It can be seen that the two trains running in the same direction at the same time may cause the risk of DC bias of the UHV transformer to exceed the standard, which needs to attract people's attention.

If the reverse operation of the two trains enter the acceleration phase in a certain section at the same time, the DC bias current of the UHV transformer is also the superposition of the running currents of the two trains. Therefore, the maximum DC bias current is still 1.19A×2=2.38 A. It can be seen that the reverse operation of the two trains in the same section may also cause the risk of DC bias of the UHV transformer to exceed the standard. However, if one train accelerates and one train decelerates, the DC bias current caused by the two will be cancelled.

The report is based on the research results of "Calculation of Electromagnetic Characteristics of UHV Transformer No-load DC Bias". The ODFPS-1000000/1000 UHV transformer withstands DC bias current of 2.0 A. The following is an introduction to DC bias current.

Regarding the above analysis, the urban rail transit in Changsha uses a more complicated train dispatch operation mode and the train load is random, so the analysis of the problem is more complicated. Overall, we consider that after multiple trains are running at the same time, the UHV transformer will always withstand a DC bias current higher than the limit value for a certain period of time. In addition, the daily operation time of the rail transit system is long, which will cause a certain degree of DC bias damage to the UHV transformer. This requires that Changsha UHV substation must adopt DC bias control measures. The purpose is to prevent the risk of DC bias caused by stray currents in rail transit[11]. Other stations affected by Changsha Rail Transit Line 3 in Hunan Power Grid is shown in Table I.
Table I Other stations affected by Changsha Rail Transit Line 3 in Hunan Power Grid

| Substation            | Dc magnetic bias current/A | Whether the risk exceeds the limit |
|-----------------------|----------------------------|------------------------------------|
|                       | Single train  | Multiple trains |                           |
| 500kV Ding Gong Substation | 2.17          | 17.39            | Yes, recommended governance |
| 500kV Sha Ping Substation | 0.68          | 5.47             | No, enhanced monitoring is recommended |
| 220kV Ke Da Substation  | 1.72          | 13.79            | Yes, recommended governance |
| 220kV Yang Gao Substation | 1.84          | 14.79            | Yes, recommended governance |
| 220kV Dong Shan Substation | 0.59          | 4.72             | No, enhanced monitoring is recommended |
| 220kV Shumu Ling Substation | 0.31          | 2.44             | No                             |
| 220kV Lang Li Substation   | 1.46          | 11.6             | Yes, recommended governance |
| 220kV Cao Jia Ping Substation | 3.09          | 24.68            | Yes, recommended governance |
| 500kV Xing Cheng Substation | 1.61          | 12.87            | Yes, recommended governance |
| 220kV Cheng Nan Substation | 0.44          | 3.52             | No                             |
| 220kV Shi Chong Substation | 0.49          | 3.89             | No                             |
| 220kV Long Wang Substation  | 0.58          | 4.64             | No, enhanced monitoring is recommended |
| 220kV Xue Shi Substation   | 0.51          | 4.09             | No                             |
| 220kV Tan Bei Substation   | 0.47          | 3.72             | No                             |

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