

Article

Mitigation Strategy of Neutral-Point DC for Transformer Caused by Metro Stray Currents

Aimin Wang ¹, Sheng Lin ^{2,*}, Guoxing Wu ³ and Xiaopeng Li ⁴¹ School of Electrical Engineering and Electronic Information, Xihua University, Chengdu 610039, China; 1220210049@mail.xhu.edu.cn² School of Electrical Engineering, Southwest Jiaotong University, Chengdu 611756, China³ Shenzhen Power Supply Bureau Co., Ltd., China Southern Power Grid, Shenzhen 518000, China; wuguoxing@sz.csg.cn⁴ State Grid Sichuan Electric Power Research Institute, Chengdu 610044, China; lixp6053@sc.sgcc.com.cn

* Correspondence: slin@swjtu.edu.cn

Abstract: Metro stray currents flowing into neutral-point-grounded transformers can cause serious direct current (DC) bias. Affected by both metro train and urban power grid operations, transformer neutral-point DC caused by metro stray current is complex, dynamic, and time-varying, which changes the DC bias risk level of transformers. Thus, just installing blocking devices (BDs) at transformer neutral points with high instantaneous DC may make it difficult to comprehensively mitigate DC bias and lead to increased BD installation. To solve this, through optimizing BD installation placements, a mitigation method for transformer DC bias is proposed. In the proposed method, the DC bias risk level and BD installation number are included in the constraint and objective functions. To evaluate the risk level of transformer DC bias, four indicators are proposed considering the distribution characteristics of neutral DC. To optimize the BD installation placements, the effects of both the metro train dynamic operation and the operation topology of the urban power grid on neutral DCs are considered. The Monte Carlo method is used to sample the train operation conditions and a relation matrix among transformers is established. Applying the method to a certain power system, the result of BD installation placements shows that the transformers supplying the metro system must have BDs installed at their neutral points.



Citation: Wang, A.; Lin, S.; Wu, G.; Li, X. Mitigation Strategy of Neutral-Point DC for Transformer Caused by Metro Stray Currents. *Electronics* **2024**, *13*, 2467. <https://doi.org/10.3390/electronics13132467>

Academic Editor: Christos Volos

Received: 20 May 2024

Revised: 9 June 2024

Accepted: 19 June 2024

Published: 24 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: metro stray current; transformer DC bias; mitigation strategy; blocking device; installation placement

1. Introduction

Since the direct current (DC) metro rail is not completely insulated from the soil, the DC current can leak from the rail and form metro stray currents [1–3]. The metro stray current can flow into the transformer's neutral points through the soil, ground wire and cable armoring, as shown in Figure 1, which can result in the transformer working in the DC bias state [4–6]. Because the metro network is widely distributed, stray currents may cause a large number of transformers to operate in the DC bias state [7]. DC bias not only damages the physical performance of transformers but also threatens the reliability of the urban power grid [8]. Therefore, to protect the transformer and system, it is urgent to comprehensively mitigate the transformer DC bias induced by DC metro stray currents.

To protect the transformer and urban power grid from transformer DC bias, one widely accepted existing method is to install a blocking device (BD) in series at the transformer neutral point [9–11]. Since the BD consists of capacitors, once installed, the BD truly and completely stops the flow of DC from the neutral point to the transformer windings [12]. Therefore, after the transformer neutral DC exceeds the threshold, the installation of BD can completely block neutral DC and mitigate the DC bias. However, when DCs simultaneously

flow into a large number of transformers, the blocked DC by BD can flow to other neutral-point-grounded transformers, because transformers are interconnected by transmission lines and cables [6,7,13]. Thus, just installing BDs in series at the neutral points of the transformers that have high neutral DCs cannot eliminate the transformer DC bias risk of the whole urban power system.

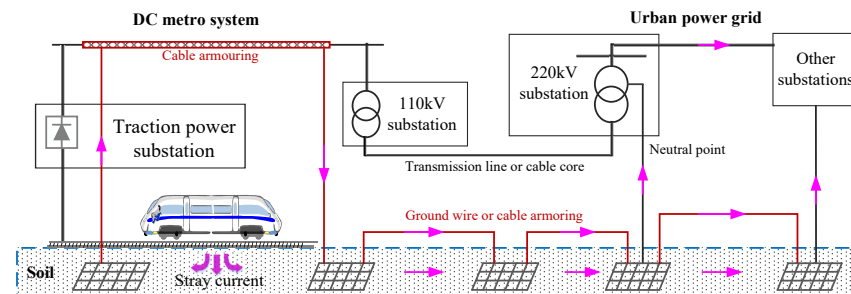


Figure 1. Paths of stray current flowing into transformer.

To comprehensively mitigate transformer DC bias, the BD installation placements have been optimized [11,14]. The neutral DC can be caused by geomagnetically induced current (GIC), grounding electrode direct current (GEDC) of high-voltage direct current systems, and metro stray current [4,15,16]. When the neutral DC is caused by GIC, the optimized methods of BD installation have considered equipment limits and operational constraints such as permissible voltages, power, and transformer heating [9,11]. The objective function is to minimize the cost function, which is affected by BD installation number [14]. When mitigating the transformer DC bias caused by GEDC, the fluctuation of neutral DCs is ignored and the maximum value is used to determine whether the transformer operates in the DC bias state [17,18]. The most significant constraint is that all neutral DC magnitudes are smaller than the threshold. And the objective function is to minimize the BD installation [10,12]. The research for mitigating neutral DCs caused by metro stray currents is light, and the maximum value is used to determine whether the transformer works in the DC bias state [13].

To this extent, when judging whether there is a DC bias risk, the magnitude of the neutral DC is the critical index. But, in the field, the transformer neutral DC caused by metro stray currents is dynamically affected by the traction and braking operations of metro trains [4]. For example, in a certain urban power grid, the neutral DC of a 220 kV transformer for 2 days is shown in Figure 2a. For 220 kV transformers, the neutral DC threshold is 5 A [17]. Thus, the transformer DC bias risk exists only during the peak periods (about 7:00–10:00 and 16:00–20:00) of train operations. If the number of times the neutral DC exceeds the threshold is very small, and the risk of DC bias is relatively very low, BD installation may be a waste. Moreover, the operation strategies of the urban power grid, such as loop-closed operation and isolated operation, also affect the neutral point DCs of transformers. For instance, the transformer neutral DCs of a certain 220 kV substation under different urban power grid operation strategies are shown in Figure 2b. The transformer DC bias risk exists only under loop-closed operation. Therefore, to mitigate transformer DC bias risk and minimize the installation of BDs, new evaluation indexes of DC bias risk should be proposed and the operations of the metro trains and urban power grid should be considered.

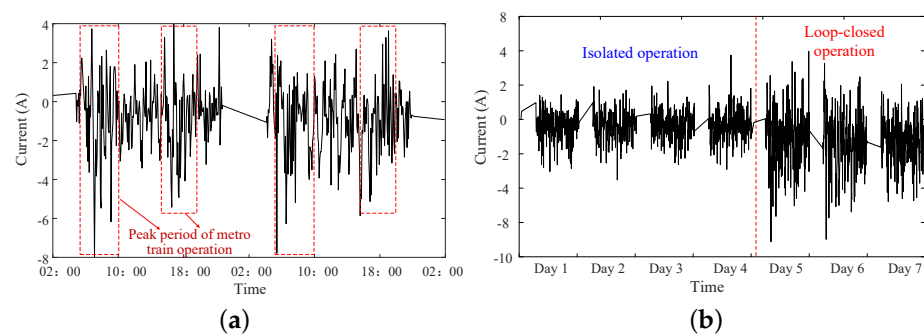


Figure 2. Transformer neutral DCs. (a) Effect by dynamic metro train operations. (b) Effect by urban power system operations.

To address the above issues, a mitigation method for transformer DC bias risk caused by metro stray currents is proposed. The novelties are as follows:

- (1) In the proposed method, considering the neutral DC magnitude and fluctuation characteristics, four indicators are proposed to evaluate the transformer DC bias risk. Then, the risk level of transformer DC bias is used as the mitigation constraint, and minimizing the number of BD installations is used as the optimizing objective.
- (2) In the optimizing process, the effect of metro train and urban power system operations on the BD installation placements are both considered. The Monte Carlo method is used to sample the metro train operations and a relation matrix is proposed to describe the connection structures and network topology of AC power systems. The mitigation strategy of transformer DC bias risk is obtained by collecting the BD installation placements under each sampling condition.

By comparing it with the existing method, the proposed method can decrease the BD installations and keep the DC bias risk of transformers under an allowed level. The BD installation results show that the transformers supplying the metro system must have BDs installed at their neutral points.

The remainder of this paper is organized as follows. The evaluation indicators are presented in Section 2. Section 3 presents the optimized method of BD installation placements considering the operations of metro trains and the urban power system. Section 4 applies the proposed method and compares it with the existing method based on a certain urban power system. Section 5 concludes the whole paper.

2. Evaluation Indicators of Transformer DC Bias Risk

Affected by the operations of the metro trains and the urban power grid, the neutral DC of the transformer caused by the stray current is alternately positive and negative and randomly fluctuates [4]. Considering the magnitude and fluctuation characteristics of transformer neutral DC, evaluation indicators are proposed to assess the transformer DC bias risk level.

2.1. Indicator P_i

The magnitude of the transformer neutral-point DC can reflect the severity of the transformer DC bias. The greater the neutral-point DC of the transformer, the higher the transformer DC bias risk level [7]. Thus, considering the amplitude of the transformer neutral-point DC, the first evaluation indicator is proposed. The evaluation indicator P_i is given as follows:

$$P_i = \begin{cases} \frac{|I_i| - I_{th}}{|I_i|} 100\%, & |I_i| > I_{th} \\ 0, & |I_i| \leq I_{th} \end{cases} \quad (1)$$

where I_i is the neutral DC value of the transformer; I_{th} is the magnitude threshold of the transformer neutral DC. The indicator is $0 \leq P_i < 1$. P_i is always less than 1. The greater

the indicator P_i is, the larger the magnitude of neutral point DC is, then the higher the DC bias risk is. Thus, the indicator can be used to evaluate the DC bias risk for individual transformers.

2.2. Indicator P_T

Affected by the operations of metro trains, the higher the times of the neutral DC exceeding the threshold, the higher the risk of transformer DC bias. Therefore, considering the times of neutral DC exceeding the threshold, the second evaluation indicator P_T is given as follows:

$$P_T = \frac{T_{|I_i| > I_{th}}}{N} 100\% \quad (2)$$

where $T_{|I_i| > I_{th}}$ is the number of the exceeding threshold times of the neutral-point DC of the transformer; N is the sample number of transformer neutral DC in a certain period. The indicator is $0 \leq P_T \leq 1$. The larger the indicator P_T , the higher the DC bias risk level. When P_T equals 1, the transformer is always working under DC bias. The indicator can be used to evaluate the DC bias risk for individual transformers in a certain period.

2.3. Indicator P_X

In urban power grids, the number of DC bias transformers reflects the extent to which the system is affected by metro stray currents. As the number of DC bias transformers increasing, the DC bias risk level of the whole urban power grid gradually increases [7]. Therefore, considering the number of DC-biased transformers, the evaluation indicator P_X is

$$P_X = \frac{x}{K} 100\% \quad (3)$$

where x is the number of DC bias transformers in one sampling; K is the number of transformers in the urban power system. The indicator is $0 \leq P_X \leq 1$. When P_X is equal to 0, there is no transformer under DC bias. The greater the indicator P_X is, the higher the DC bias risk level of the whole urban power grid. The indicator is used to evaluate the transformer DC bias risk for the entire urban power grid.

2.4. Indicator P_E

Affected by train operations, neutral DCs of transformers are random. Considering the cumulative effect of random stray currents, the evaluation indicator P_E is proposed to evaluate the average risk probability of the urban power grid.

$$P_E = \sum_{t=1}^N \frac{x_t}{NK} 100\% \quad (4)$$

where N is the sample number of transformer neutral DC in a certain period; x_t is the number of the DC bias transformers in the sample of t_{th} ; The indicator is $0 \leq P_E \leq 1$. The greater the indicator P_E is, the higher the cumulative effect of stray current on the urban power grid. The indicator can be used to evaluate the DC bias risk for the entire urban power grid in a period.

3. Mitigation Method of Transformer DC Bias

Using the proposed indicators, the DC bias risk is evaluated first. If the DC bias risk exists, the mitigation method is adopted. The BD is installed to mitigate transformer DC bias. To minimize the installation numbers and comprehensively mitigate the DC bias risk, a mitigation strategy method is proposed considering the operation of metro trains and the urban power grid.

3.1. Method Principle

The principle of the proposed mitigation method is shown in Figure 3. There are two parts, including establishing the optimization model of BD installation and calculating BD installation placements. In the optimization model of BD installation, the constraint is to control the risk level of transformer DC bias less than the setting. The objective is to minimize the BD installation. In the calculation process of BD installation, the operations of metro trains and the urban power system are sampled with the Monte Carlo method. In each sampling, the genetic algorithm (GA) is used to optimize the BD installation. Then, by merging the optimization results, the installation placements of BDs are obtained.

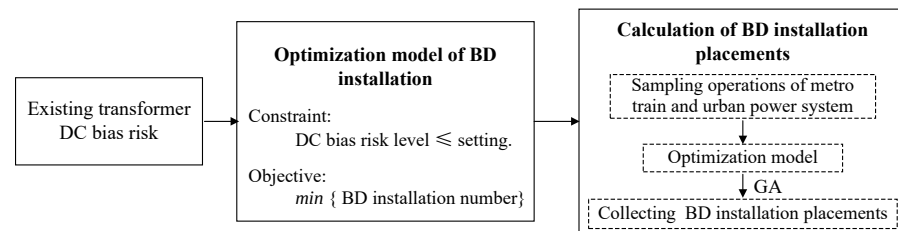


Figure 3. Principle of the proposed mitigation method.

3.2. Optimization Model of BD Installation

In the optimization model, the objective is to minimize the BD installation and mitigate the DC bias risk level of transformers. Assume that the total number of transformers is K . The transformer neutral point DCs are $I = \{I_1, I_2, \dots, I_k\}$. If all neutral points have BDs installed, the risk of DC bias really can be reduced. But, the higher the number of BD installations, the higher the installation cost of BDs. Thus, all neutral points installing BDs is a costly and wasteful strategy. Under one sampling condition of metro train operation, the optimized objective is to minimize the BD installation as follows:

$$\min f_j = \min J_{i,j} \quad (5)$$

where $J_{i,j}$ is the installation number of the BDs. i is the i_{th} operation scenarios of urban power grid. j is the j_{th} sampling scenarios of train operations. Meanwhile, we use the proposed indicators to evaluate the transformer DC bias risk. We require that the indicators P_i and P_X are less than their corresponding thresholds of transformer DC bias. The constraint conditions are, respectively,

$$P_i \leq P_{i.th} \quad (6)$$

$$P_X \leq P_{X.th} \quad (7)$$

where $P_{i.th}$ and $P_{X.th}$ are thresholds of the indicators that are all greater than or equal to 0. If the optimization objective is to eliminate transformer DC bias risk, the two thresholds are both 0. If the objective is to reduce the transformer DC bias risk to an acceptable scope, thresholds can be set based on the field requirements. In the field, when the max magnitude of neutral point DC is less than 10 A, the average $P_{i.th}$ is about 0.06 and the average $P_{X.th}$ is about 0.01.

3.3. Calculation of BD Installation

3.3.1. Modeling of BD Installation

Considering the flow paths of stray current and the structures of the metro system and urban power grid shown in Figure 1, the DC resistance model for calculating the neutral DCs of transformers is established as shown in Figure 4. The metro system and urban power system are equivalent to the DC resistance network model considering the DC resistance parameters of devices [2,3,19]. In the urban power grid, the grounding grids of substations are connected by neutral-point-grounded transformers and grounding systems. The 500 kV and 220 kV transformers are grounded through neutral points. The 110 kV

transformers are commonly ungrounded. Thus, only grounding wires or grounding cable armoring are modeled in 110 kV substations.

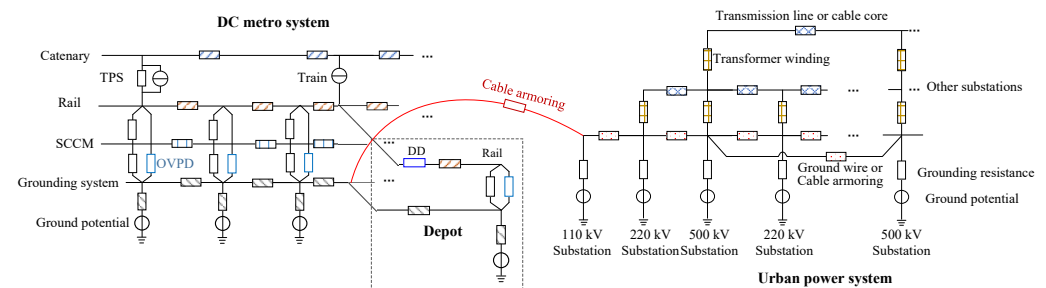


Figure 4. Schematic drawing of transformer neutral DC model.

After installing BDs at transformer neutral points, the BD installation models are shown in Figure 5. After installing BDs, the nodes i are disconnected to j in 500 kV substation. And the node $i + 1$ and node $j + 1$ are disconnected in the 220 kV substation. Therefore, when the BDs are installed at neutral points, the admittances $Y_{i+1,j+1}$, $Y_{j+1,i+1}$, Y_{ij} , and Y_{ji} change to 0. Using Kirchhoff's laws, the distribution of transformer neutral DCs after installing BDs can be obtained. Based on the model of BD installation, the operations of the metro train and urban power system are sampled first.

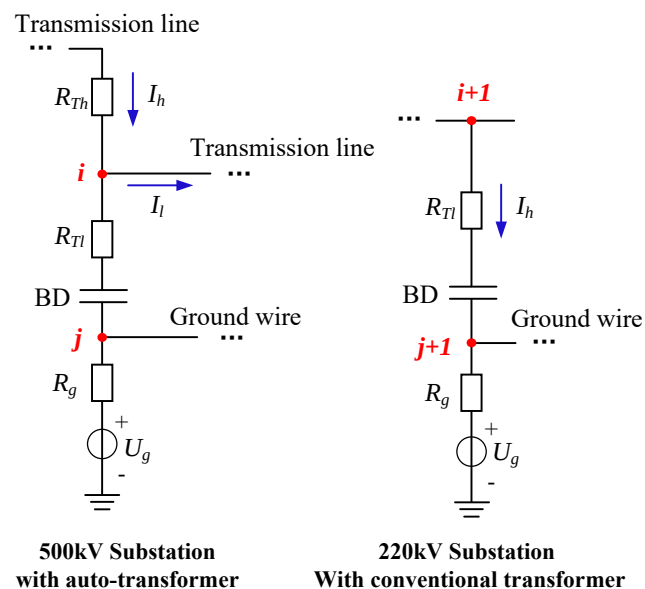


Figure 5. Model of BD installation.

3.3.2. Sampling Operation of Metro Trains

In the metro system, the train current and speed are obtained through the traction calculation method. The real train current and position in the field are tested and shown in Figure 6. There are two kinds of train operation periods, including dwell time and operation time. During the dwell time, the train stays in the station. During the operation time, the train operates between two stations at an average speed. The segmented linear relationship between train current, position, and time is obtained by a linearization process. The slope of the position linearization line during operation time corresponds to the train's average speed.

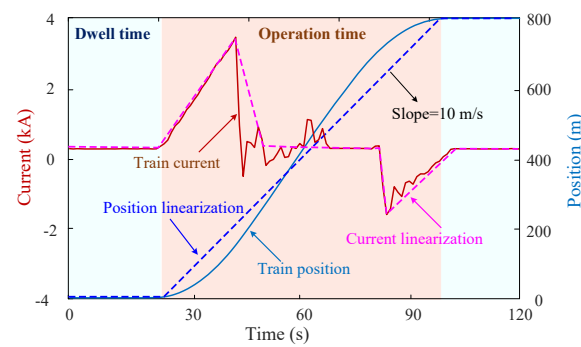


Figure 6. Train current and position data.

Based on the segmented linear relationship of train position and time, the probability distribution of train position between two stations can be obtained, as shown in Figure 7. A and B are the probability distributions of the train position at the stations (i.e., 0 and L). The two probabilities are calculated with the ratios of dwell time and total time. In the field, the dwell time and total time of each train are determined by the train timetable, which is pre-designed prior to the operation of the metro train. Thus, the probability distributions of A and B can be calculated based on the train timetable. In Figure 7, the C and D are the first and last samplings of train positions between the two stations. The two positions are determined by sampling time. For example, if the sampling time is 1 s and average speed is 10 m/s, C is 10 m, and D is $L-10$ m, considering the average speed. Using the Monte Carlo method, the train position can be sampled [7]. Then, based on the relationship of train current and position, the train current can also be sampled.

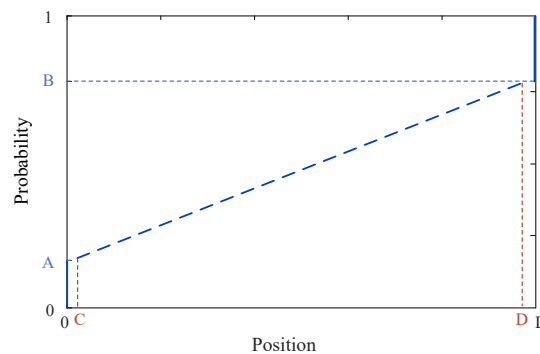


Figure 7. Probability distribution of train position between two stations.

3.3.3. Sampling Operation of Urban Power Grid

In the urban power grid, neutral-point-grounded transformers are connected by transmission lines. Thus, the connection relationship between transformers will change with the operation strategy of urban power grid switching. Thus, to characterize the operation strategy of the urban power grid, a connection relationship matrix is proposed. The admittance matrix Y_{power} of the urban power system is calculated

$$Y_{power} = R^T \cdot Y_{sys} \quad (8)$$

where Y_{sys} is the entire admittance matrix of the urban power system, in which all possible transmission lines are modeled. R is the connection relationship matrix including 1 and 0. When a transmission line between two transformer windings is opened, the connection relationship between the two nodes of transformer windings is 0. Thus, by changing the relationship matrix, the operation of the urban power system can be sampled.

3.3.4. Calculation of BD Installation

To rapidly calculate the optimization model, the genetic algorithm (GA) is used. The optimization process with GA is shown in Figure 8. In the optimization process, the initial vector consists of K particles randomly populations $X = \{x_1, x_2, \dots, x_K\}$. x_i is equal to 1 or 0. If $x_i = 1$, the BD is installed at transformer neutral point i . Using the populations, calculate the transformer neutral DCs and evaluate the DC bias risk. Consider that the genes replicate, cross, and mutate, forming new populations. If the number of iterations reaches the termination condition, the optimization is stopped. Finally, output the BD installation placements.

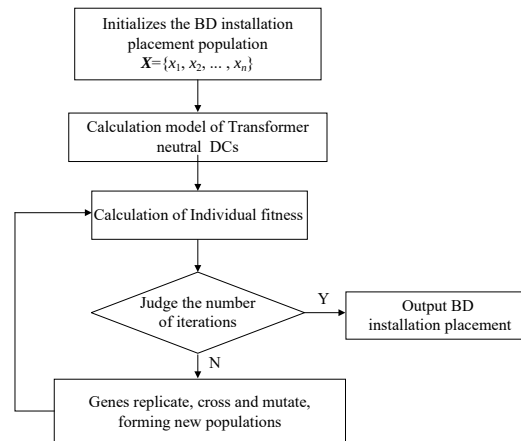


Figure 8. Optimization of BD installation placement with GA.

After calculating the optimization schemes of all the sampling scenarios of train operations, the optimization strategy is obtained by calculating the union of installation placements of BDs. The optimization strategy of BD installation placements J is calculated as follows:

$$J = J_1 \cup J_2 \cup \dots \cup J_i \cup \dots \cup J_M$$

$$J_i = J_{i,1} \cup J_{i,2} \cup \dots \cup J_{i,j} \cup \dots \cup J_{i,n} \quad (9)$$

where J is the installation placement of BD under all operation scenarios of urban power grid. J_i is the installation placements of BD under the i_{th} operation scenarios of the urban power grid. M is the total number of operation strategies of the urban power grid. n is the Monte Carlo sampling number of the operation strategies of metro trains. Based on the results, the placements J should have BDs installed, while when the urban power grid works under the operation condition i , just the BDs with placement J_i are turned on.

In the field, the existing method is to install a BD at the transformer where the neutral DC is high above the threshold, which may be a waste of BD installation, and cannot mitigate the DC bias when the metro train operation changes. However, in the proposed method, the optimization objective is to minimize the BD installation. Moreover, because the mitigation strategy is obtained by collecting the BD installation placements under each sampling condition, the optimization results can be applied to any train operating condition.

4. Method Comparison and Application

4.1. Introduction of Urban Power System

The substations of the urban power grid and the line distributions of the metro system are shown in Figure 9. There are 73 substations and 11 metro lines. The urban power grids and metro lines are intertwined at high geographic densities. In Figure 9, substations 1–7 are power factories with conventional transformers, 8–16 are 500 kV substations with auto-transformers, and 17–73 are 220 kV substations with conventional transformers. And

the transformers of 31–33, 35, 36, 38, 40, 42, 43, 45–47, 49–53, 59, 61, 62, and 72 supply power to metro lines.

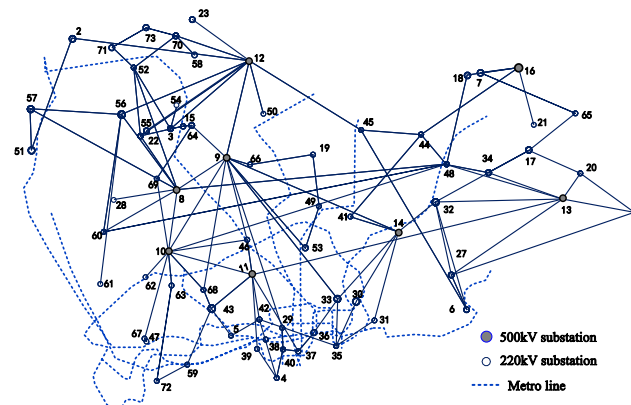


Figure 9. Topology structures of urban power grid and DC metro network.

Assume that the transformer works in the DC bias state when the transformer neutral DC exceeds 5 A. Choose a certain scenario of metro operation as the calculation condition. The DC calculation results of transformer neutral points are shown in Figure 10. There are 11 transformers that work in the DC bias state. The indicators P_i are larger than 0. The indicator P_E is 15.07%. The results show that the transformer DC bias risk exists in this urban power grid under this metro operation condition. The urban power system needs to take the measures to mitigate the transformer DC bias.

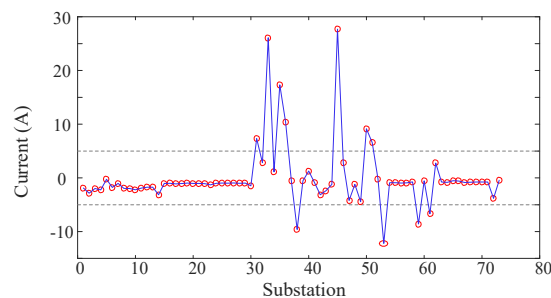


Figure 10. Transformer neutral DC under a certain operation of metro trains.

4.2. Method Comparison

In the field, the existing method used to mitigate transformer DC bias is to install a BD at the transformer neutral point, at which the neutral DC has exceeded the threshold. But, after installing the BD, the normal transformer without DC bias may experience DC bias. Thus, it is possible to install lots of BDs to mitigate transformers' DC bias. To verify that the proposed mitigation strategy can really lead to fewer BDs than the existing method, the numbers of BD installations of the different methods are compared.

4.3. Comparison in Static Scenario

In the static scenario, there are 419 metro trains operating on the metro lines, including 89 trains operating in the traction condition, 92 trains operating in the braking condition, and 238 trains operating in the coasting condition.

In the existing method, all transformers with neutral point DCs exceeding 5 A have BDs installed. After the neutral DC of the normal transformer exceeds the threshold value due to the BD installation, this new DC bias transformer also needs BDs to be installed. Until the neutral DCs of all transformers in the urban power grid are less than 5 A, the BD installations are the results of the existing method. In the proposed method, the GA

parameters are set as follows: the initial number for GA population is 500; the number of iterations is 200; the parameter for gene replication is 0.7; and the thresholds of the indicators are all set to 0. The results of the existing and proposed methods are shown in Table 1.

Table 1. Installation placements of two methods.

Method	Number	Installation Placements
Existing method	66	3, 9–73
Proposed method	44	2, 5, 6, 12, 13, 22, 23, 30–59, 61–64, 67, 70, 72

The results show that using the existing method, 66 BDs are needed to mitigate transformer DC bias risk. But under the same train operations, 44 BDs can also mitigate transformer DC bias risk based on the proposed method. Compared to existing methods, the number of placements in the proposed method is reduced by 22 under the same train operating conditions, which is only 66.7% of the existing method. And the number of BD installations is reduced by 33.3% in this urban power grid. The comparison results show that the proposed method can optimize the installation placements of BD and reduce the number of installations.

4.4. Comparison in Dynamic Scenario

In the dynamic scenario, the metro train operations are sampled by the Monte Carlo method based on the metro train timetables. For each sample, the BD installations are calculated using two methods separately. A total of 100 iterations are sampled, and BD installation placements are obtained by collecting all installations. The BD installation placements of two methods are shown in Table 2.

Table 2. Installation placements of two methods.

Method	Number	Installation Placements
Existing method	67	3, 5, 9–73
Proposed method	46	2, 5, 6, 7, 12, 13, 22, 23, 26, 30–59, 61–64, 67, 70, 72

The results show that 67 BDs are needed to mitigate transformer DC bias risk using the existing method. But, 46 BDs can also mitigate transformer DC bias risk based on the proposed method. Compared to existing methods, the number of placements in the proposed method is reduced by 21 under the same sample conditions. The results show that the proposed method can optimize the BD installation placements and reduce the number of installations.

4.5. Method Application

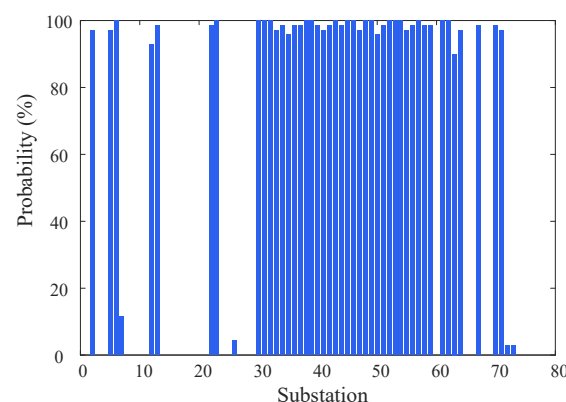
Considering the metro train dynamic operations, the BD installation placements are optimized by the proposed method. The support threshold of the transformer neutral DC is 5 A. If the BDs are not installed, after 20,000 samplings, the maximum values of indicator P_i and indicator P_T of each transformer are shown in Table 3. The maximum value of indicator P_X and indicator P_E are 31.10% and 10.74%. There are 36 substations with DC bias risk and 37 substations without DC bias risk.

Table 3. Risk indicators of transformer DC bias.

Substation	Indicator		Substation	Indicator	
	Max P_i (%)	P_T (%)		Max P_i (%)	P_T (%)
2	48.64	0.21	42	95.58	81.41
3	28.61	0.005	43	90.22	59.90
6	75.57	20.28	44	49.34	0.45
7	52.46	1.27	45	86.59	48.41
9	55.16	1.90	46	82.74	39.45
10	65.92	7.24	47	93.03	76.06
11	63.67	6.45	49	93.80	72.85
12	49.38	0.79	50	81.60	31.79
13	54.54	1.55	51	79.60	22.85
14	84.37	40.43	52	95.69	82.12
31	93.57	75.63	53	97.72	90.48
32	82.52	41.27	54	39.60	0.15
33	90.99	73.11	55	38.12	0.10
34	84.46	46.51	56	31.87	0.03
35	87.11	61.23	59	93.58	86.52
36	90.53	72.15	61	91.67	82.51
38	88.08	59.38	62	94.09	86.88
40	97.25	28.90	72	83.30	46.82

Through comparing the results of indicator $MaxP_i$, the maximum value is 97.72% in substation 53, 22 substations exceed 80%, and 13 substations exceed 90%. Comparing the indicator P_T , the maximum value is 90.48% in substation 53, 14 substations exceed 50%, and 6 substations exceeds 90%. The results show that there are 14 substations that have transformer DC bias risk during more than half the time of metro train operation. For some substations, the transformer DC bias risk is greater. The indicators $MaxP_X$ and P_E are 31.10% and 10.74%. The results show that the DC bias risk is very high. It is necessary to carry out a mitigation strategy in the urban power grid.

Using the proposed method, with thresholds of indicators set as 0, through 20,000 samplings of dynamic metro operation scenarios, the installation probabilities of optimized placement results are shown in Figure 11. Substations 2, 5, 6, 12, 13, 22, 23, 30–59, 61, 62, 64, 67, 70, and 71 need to have BDs installed, and the BD installation probability exceeds 90 % with the train operations. Among them, the probability percentage of substations 7, 26, 72, and 73 is less than 20%. The collection of BD installation placements in the power grid is shown in Table 4. Considering the dynamic train operation, a total of 48 substations need to have BDs installed. Moreover, all the 220 kV transformers supplying power to the metro system should have BDs installed.

**Figure 11.** BD Installation probabilities of optimization results.

If the low transformer DC bias risk is allowed, the thresholds of indicators can be set to a small value. When both thresholds are 0.01, the BD installations are shown in Table 4. The results show that when the low-level DC bias is allowed, the BD installations can be reduced by the proposed method. Based on the method, BDs can be installed at transformers with high DC bias risk in the field, which can help control BD installation and the DC bias risk of transformers.

Table 4. Collection of BD installation placements.

Constraint Thresholds	Number	Installation Placement
0	48	2, 5, 6, 7, 12, 13, 22, 23, 26, 30–59, 61–64, 67, 70–73
0.01	44	2, 5, 6, 12, 13, 22, 23, 30–59, 61–64, 67, 70, 71

5. Conclusions

To mitigate the transformer DC bias caused by metro stray current, an optimization method of BD installation has been proposed considering the effect of metro train and urban power system operations on the neutral DCs. Compared with the existing method, the BD installation numbers calculated by the proposed method were less than that of the existing method. Moreover, the BD installation probabilities at the transformers supporting power to the metro exceed 90%. Thus, when mitigating the transformer DC bias caused by metro stray current, the BD should be installed at the transformers supporting power to the metro first. However, the metro train operations are multitudinous and difficult to collect comprehensively. Thus, the effect of metro train operations should be analyzed deeply in the future.

Author Contributions: Conceptualization, investigation and methodology, A.W.; data curation, G.W. and X.L.; resources and supervision, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the National Natural Science Foundation of China (U2166212 and 52307139) and Science and Technology Project of CSG (090000KK52200145).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: Author Guoxing Wu was employed by the company Shenzhen Power Supply Bureau Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Lin, S.; Wang, A.; Liu, M.; Lin, X.; Zhou, Q.; Zhao, L. A Multiple Section Model of Stray Current of DC Metro Systems. *IEEE Trans. Power Deliv.* **2021**, *36*, 1582–1593. [\[CrossRef\]](#)
2. Du, G.; Wang, J.; Jiang, X.; Zhang, D.; Yang, L.; Hu, Y. Evaluation of Rail Potential and Stray Current With Dynamic Traction Networks in Multitrain Subway Systems. *IEEE Trans. Transp. Electr.* **2020**, *6*, 784–796. [\[CrossRef\]](#)
3. Xu, S.Y.; Li, W.; Wang, Y. Effects of Vehicle Running Mode on Rail Potential and Stray Current in DC Mass Transit Systems. *IEEE Trans. Veh. Technol.* **2013**, *62*, 3569–3580.
4. Wang, A.; Lin, S.; Hu, Z.; Li, J.; Wang, F.; Wu, G.; He, Z. Evaluation Model of DC Current Distribution in AC Power Systems Caused by Stray Current of DC Metro Systems. *IEEE Trans. Power Deliv.* **2021**, *36*, 114–123. [\[CrossRef\]](#)
5. Wang, A.; Lin, S.; Wu, J.; Zhang, H.; Li, J.; Wu, G.; He, Z. Relationship Analysis Between Metro Rail Potential and Neutral Direct Current of Nearby Transformers. *IEEE Trans. Transp. Electr.* **2021**, *7*, 1795–1804. [\[CrossRef\]](#)
6. Yu, K.; Ni, Y.; Zeng, X.; Peng, P.; Fan, X.; Leng, Y. Modeling and Analysis of Transformer DC Bias Current Caused by Metro Stray Current. *IEEE Trans. Electr. Electron. Eng.* **2020**, *15*, 1507–1519. [\[CrossRef\]](#)
7. Wang, A.; Lin, S.; He, Z.; Jingzhuo, Z.; Wu, G. Probabilistic Evaluation Method of Transformer Neutral Direct Current Distribution in Urban Power Grid Caused by DC Metro Stray Current. *IEEE Trans. Power Deliv.* **2023**, *38*, 541–552. [\[CrossRef\]](#)
8. Rezaei-Zare, A. Behavior of Single-Phase Transformers Under Geomagnetically Induced Current Conditions. *IEEE Trans. Power Deliv.* **2014**, *29*, 916–925. [\[CrossRef\]](#)
9. Etemadi, A.H.; Rezaei-Zare, A. Optimal Placement of GIC Blocking Devices for Geomagnetic Disturbance Mitigation. *IEEE Trans. Power Syst.* **2014**, *29*, 2753–2762. [\[CrossRef\]](#)

10. Xie, Z.; Lin, X.; Zhang, Z.; Li, Z.; Xiong, W.; Hu, H.; Khalid, M.S.; Adio, O.S. Advanced DC Bias Suppression Strategy Based on Finite DC Blocking Devices. *IEEE Trans. Power Deliv.* **2017**, *32*, 2500–2509. [[CrossRef](#)]
11. Rezaei-Zare, A.; Etemadi, A.H. Optimal Placement of GIC Blocking Devices Considering Equipment Thermal Limits and Power System Operation Constraints. *IEEE Trans. Power Deliv.* **2018**, *33*, 200–208. [[CrossRef](#)]
12. Ma, S.; Lin, X.; Li, Z.; Jin, N.; Rong, Z.; Zhang, P.; Xu, H. A System-Level Suppression Method for DC Bias Based on Reverse Unbalanced Currents in the Same Transmission Section. *IEEE Access* **2021**, *9*, 126967–126975. [[CrossRef](#)]
13. Guo, Y.; Du, Q.; Liu, Y.; Yang, F.; Chen, L.; Zhang, X.; Xiao, S.; Li, C.; Wu, G. Systematic protective scheme for mega-city power systems against stray currents caused by metro systems. *High Volt.* **2023**, *8*, 943–953. [[CrossRef](#)]
14. Liang, Y.; He, D.; Zhu, H.; Chen, D. Optimal Blocking Device Placement for Geomagnetic Disturbance Mitigation. *IEEE Trans. Power Deliv.* **2019**, *34*, 2219–2231. [[CrossRef](#)]
15. Wu, F.; Yu, S.; Zhao, Z.; Quan, W. Calculation and control of DC bias current distribution in an AC power system around a typical ± 800 kV DC grounding electrode. *J. Eng.* **2019**, *2019*, 3145–3149. [[CrossRef](#)]
16. Overbye, T.J.; Shetye, K.S.; Hutchins, T.R.; Qiu, Q.; Weber, J.D. Power Grid Sensitivity Analysis of Geomagnetically Induced Currents. *IEEE Trans. Power Syst.* **2013**, *28*, 4821–4828. [[CrossRef](#)]
17. Ma, S.; Rong, Z.; Lin, X.; Jin, N.; Wang, Z.; Xing, J.; Peifu, Z. Study on the Global Optimal Configuration of DC Bias Equipment Considering the Cooperation of Multiple Devices. *Proc. CSEE* **2020**, *40*, 4387–4399.
18. Ma, S.; Lin, X.; Li, Z.; Jin, N.; Rong, Z.; Zhang, P.; Xu, H. A Novel DC Bias Suppression Method Considering the Cooperation of Multiple Devices. *IEEE Access* **2021**, *9*, 130212–130220. [[CrossRef](#)]
19. Du, G.; Zhu, C.; Jiang, X.; Li, Q.; Huang, W.; Shi, J.; Zhu, Z. Multiobjective Optimization of Traction Substation Converter Characteristic and Train Timetable in Subway Systems. *IEEE Trans. Transp. Electr.* **2023**, *9*, 2851–2864. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.