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Influence of Resistive Coupling Between Substation Grounding Network and Peripheral Metal Pipe Network and Optimization Design Based on Field-Circuit Coupling and Multi-Software Synergy

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Abstract

With the evolution of the new power system, the importance of substation grounding network performance is increasingly prominent, the optimization of the old substation renovation work is also gradually into the right track and attention. In this paper, the impact of resistive coupling between the grounding network system and its surrounding underground metal pipe network system in the substation renovation project is explored and analyzed in depth, and the electromagnetic field model of the grounding network and the pipe network is established respectively by using the research method of field-circuit coupling and the two simulation software CDEGS and ETAP are integrated to focus on the changes in key performance parameters during the renovation of substation grounding network, and it is found that its resistive coupling effect leads to some fluctuations in the key performance parameters. Based on the above research content, a series of optimized protection measures suitable for the actual reconstruction project are further proposed, aiming at guaranteeing the safe and stable operation of the grounding system as well as the surrounding metal pipe network under fault conditions. This study provides a theoretical basis and practical technical support for the optimization of substation grounding network and similar projects.

Keywords: field-path coupling; grounding network; metallic pipe network resistive coupling

1. Introduction

With the advancement of the "dual-carbon" strategy, the traditional power system is evolving into a new type of power system that is clean, low-carbon, safe and controllable, flexible and efficient, open and interactive, and intelligent and friendly. Global electricity demand is expected to grow at an annual rate of about 2.8% between 2010 and 2020, and is expected to reach nearly 30 trillion kilowatt-hours in 2024; this growth trend is particularly significant in the Asian region, where China's electricity consumption has increased by nearly 60% over the past decade, and is now the world's largest producer and consumer of electricity. In addition, the share of clean energy sources, such as solar and wind, in the electricity mix is increasing as renewable energy technologies continue to advance and costs decrease. The global installed solar power capacity has now grown from 40 GW in 2010 to nearly 1 TW by 2024, highlighting the global trend of power systems transitioning to a cleaner and more sustainable energy mix [1].

The substation as a key hub node of the power system, its construction and operation of high standards has become an inevitable trend in the development of the industry. In the design and construction of substations, the design of grounding network is crucial, it is not only an important facility to protect the safety of equipment and operators, but also directly related to the substation in the face of lightning impact and system failure protection ability, a good performance of the

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grounding network can effectively reduce the damage brought about by lightning strikes and fault currents to ensure the normal operation of the equipment and the safety of personnel.

In some studies, for the design of conventional grounding systems, researchers tend to focus their main attention on the minimization of grounding resistance and the uniformity of potential distribution. This concern stems from the expectation that the system will be able to quickly and effectively discharge fault currents in the event of a ground fault, as well as protect the safety of operators and equipment [2–5]. However, this design method often fails to fully consider the complex metal pipe network system that may exist around the substation in the actual engineering environment during theoretical analysis and calculation; These metal pipe networks may include water supply, gas supply, heating and communications and other municipal infrastructure, they are under the action of electromagnetic fields, and the grounding network may produce resistive coupling, thus affecting the performance of the grounding network, there is a certain degree of safety hazards; Literature [6] studied the influence of metal pipe network around the substation on the resistance value of the grounding system and its measurement, based on the field-circuit coupling method to analyze the influence of the corrosion protection layer of the metal pipe network on the performance parameters of the grounding system, but lack of analysis of the influence of the pipe network in different locations and sizes; The literature [7], on the other hand, discusses the specific effects of underground metallic structures on the measurement of grounding system resistance, and proposes a series of methods to reduce the grounding resistance. However, comparative studies on the performance parameters of grounding systems have been neglected.

On the other hand, some literatures have proposed a series of methods to improve the reliability of grounding system, which provides some theoretical basis for substation grounding network design. Literature [8] proposes a new method of short-distance measurement of grounding resistance applicable to the grounding network of a large substation, and analyzes the surface potential distribution law of the grounding network in different soil structures by establishing a finite element model, which effectively improves the calculation efficiency; Literature [9] discusses the effect of underground metallic piping on grounding resistance and its measurement in high resistivity areas and proposes various measures to reduce the resistance; Literature [10] quantitatively analyzed the resistive coupling of substation grounding network to nearby building grounding network and underground directly buried metal pipeline, through the method of moments, studied the impact of resistive coupling of buildings and pipelines at different distances and locations, and put forward the corresponding protective measures. However, the literature lacks an in-depth comparative analysis of the key factors affecting the performance of grounding network, such as soil resistivity, climatic conditions, and the surrounding environment, etc., and seldom involves the application of actual engineering projects, the lack of on-site data to support and validate, which makes it difficult to fully assess the feasibility and practicability of these theoretical results in the actual engineering and recognition.

In view of the above problems, this paper explores in depth the influence of industrial frequency grounding short circuit on the grounding network and its peripheral metal pipe resistive coupling in the substation reconstruction project, and proposes the method of using the field-circuit coupling to establish the electromagnetic field model respectively, and analyzes the key performance parameters under the mutual influence of the grounding network system as well as the pipe network system; And on the basis of actual engineering project data combined with CDEGS and ETAP two simulation software comparative study of the grounding system related performance parameters change, to ensure that the substation contact voltage and step voltage and other key parameters in line with the human safety limits [11–13]; In order to further avoid the corrosion problem of pipe network due to the excessive induced voltage of the pipe network, a series of optimized protective measures are proposed, which provide certain theoretical basis and data support for the safe operation of the ground network of the substation reconstruction, safeguard the personal safety of the staff in the station, and reduce the potential impacts on the surrounding metal pipe network.

2. Research Methodology and Modeling

2.1. Field-Coupled Method

In the field and road coupling method, the field is the magnetic field produced by the current; the road refers to the path through which the magnetic flow occurs. Field-circuit coupling is categorized into direct and indirect coupling, which mainly refers to the exchange of data between the field and the circuit, thus re-using it as input data for calculation; The method is developed on the basis of the magnetic circuit method, and the accuracy of the calculation is further improved by incorporating the key parameters of the steady state field analysis into the calculation process of the magnetic circuit method, and fully considering the nonlinearity of the material as well as saturation and other issues [14–16]. As for the complexity of the substation environment, field-circuit coupling analysis is a complicated process involving the interaction between electromagnetic fields generated by high-voltage equipment and the circuits in the substation as well as the numerous interconnected components and their wide range of frequencies, however, the enhancement of computer technology and the advancement of specialized software have provided the possibility to solve these problems. The specific steps between the general use of the field-circuit coupling method to analyze the influence of the substation's peripheral pipe network on the resistive coupling of its grounding network are shown in Figure 1:

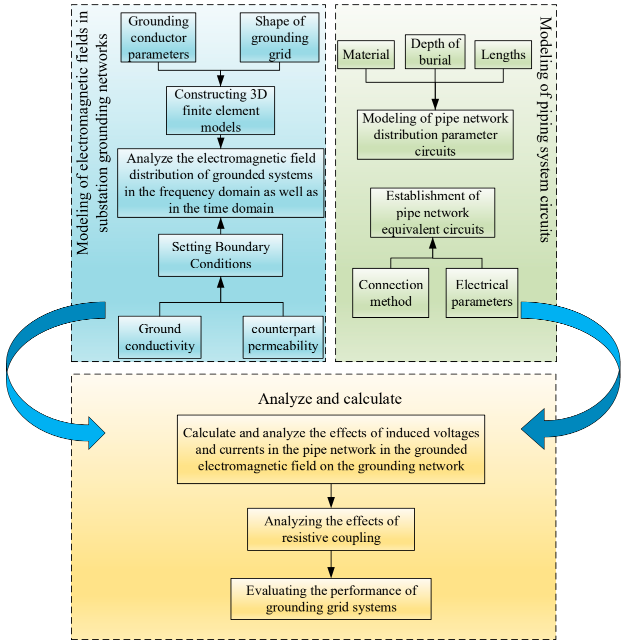

Figure 1. Steps of analyzing the impact of substation peripheral pipe network on grounding network resistive coupling.

As shown in Figure 1, in the analysis of the impact of the pipe network around the substation on the grounding network resistive coupling, it is first necessary to establish the electromagnetic field model of the grounding network and the circuit model of the pipe network system through the basic performance parameters of the grounding network and the pipe network, respectively

2.2. Resistive Coupling Analysis Method

For the case where underground metal pipes exist around the substation grounding network, the effect of the metal pipes on the potential needs to be considered when fault currents flow in the

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grounding network. The potential vector equations for the midpoints of each section of the grounding grid and the metal pipe are established separately:

$$\begin{aligned} U_0 &= R_{00} I + R_{A0} I_A \\ U_A &= R_{0A} I + R_{AA} I_A \end{aligned} \quad (1)$$

where U_0 and U_A represent the potentials of the grounding network and the surrounding metal pipe network; R_{00} and R_{AA} represent the resistance coefficient matrices of the grounding network and the metal pipe network itself; I and I_A represent the stray current vectors at each end of the grounding network and the surrounding metal pipe network; R_{A0} represents the matrix of mutual resistance coefficients for the effect of metallic pipes on the grounding grid; R_{0A} represents the matrix of mutual resistance coefficients for the effect of the grounding grid on the metallic pipe.

A metal pipe equivalent circuit is modeled as shown in Figure 2.

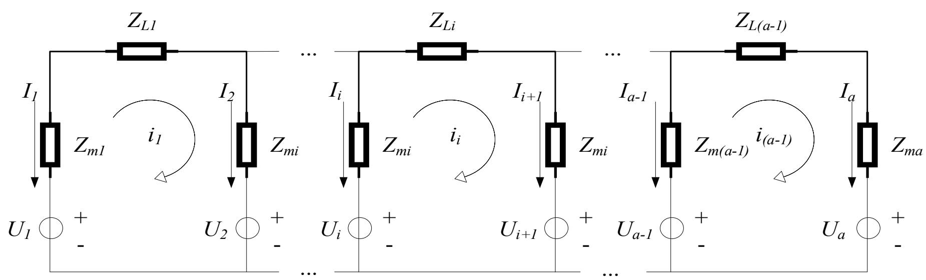

Figure 2. Pipeline equivalent circuit model.

This is obtained from Kirchhoff's law:

$$T_A U_A = I_A \quad (2)$$

where T_A represents the metal pipe equivalent circuit matrix.

The grounding network can be viewed as an isotope, and with the magnitude of the injected current i_{set} known one obtains.

$$\begin{aligned} u_0 &= U_{01} = U_{02} = \cdots = U_{0n} \\ i_{set} &= I_1 + I_2 + \cdots + I_n \end{aligned} \quad (3)$$

The collation reduces to matrix form:

$$\begin{bmatrix} R_{00} & R_{A0} & -1 & 0 \\ R_{0A} & R_{AA} & 0 & -1 \\ 0 & -E & 0 & T_A \\ 1 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} I \\ I_A \\ U_0 \\ U_A \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ i_{set} \end{bmatrix} \quad (4)$$

And in the case of a pipe network consisting of multiple metal pipes around the substation grounding grid, the expression for the relationship between their potentials can be derived as:

$$\begin{aligned} U_0 &= R_{00}I + R_{A0}T_A U_A + R_{B0}T_B U_B + \cdots + R_{K0}T_K U_K \\ U_A &= R_{0A}I + R_{AA}T_A U_A + R_{BA}T_B U_B + \cdots + R_{KA}T_K U_K \\ U_B &= R_{0B}I + R_{AB}T_A U_A + R_{BB}T_B U_B + \cdots + R_{KB}T_K U_K \\ &\vdots \\ U_K &= R_{0K}I + R_{AK}T_A U_A + R_{BK}T_B U_B + \cdots + R_{KK}T_K U_K \end{aligned} \quad (5)$$

where $U_0 \ldots U_K$ is the potential distribution of the grounding network and metal pipe network; $T_A \ldots T_K$ is the equivalent circuit matrix of the metal pipe network; R_{ij} (i, j=0, A, …, K) is the matrix of resistance coefficients formed by the grounding network and the metal pipe network itself and by each other; K is the number of pipes in the metal pipe network.

Similar to the case of a single metal pipe, the derivation yields the final matrix equation as:

$$\begin{bmatrix} R_{00} & R_T & -1 \\ R_P & GT - E & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} I \\ U \\ u_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ i_{set} \end{bmatrix} AK \quad (6)$$

where i_{set} is the total dissipation value of the grounding grid; E is a unit array of order m; m is the number of pipe segments after dissecting the metal pipe network.

$$R_T = \begin{bmatrix} R_{A0}T_A & R_{B0}T_B & \cdots & R_{K0}T_K \end{bmatrix}$$

(7)

$$R_P = \begin{bmatrix} R_{0A} & R_{0B} & \cdots & R_{0K} \end{bmatrix}$$

(8)

$$G = \begin{bmatrix} R_{AA} & R_{BA} & \cdots & R_{KA} \\ R_{AB} & R_{BB} & \cdots & R_{KB} \\ \vdots & \vdots & \ddots & \vdots \\ R_{AK} & R_{BK} & \cdots & R_{KK} \end{bmatrix}$$

(9)

$$T = \begin{bmatrix} T_A & 0 & \cdots & 0 \\ 0 & T_B & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & T_K \end{bmatrix}$$

(10)

$$U = \begin{bmatrix} U_A & U_B & \cdots & U_K \end{bmatrix}$$

(11)

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Solving this m+n+1 dimensional matrix equation yields the grounding network bulk current distribution I, potential U_0, and the metal pipe network potential distribution.

The grounding grid potential-dispersion relation matrix when there is no metal pipe network influence around the grounding grid can then be expressed as:

$$\begin{bmatrix} R_{00} & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} I \\ u_0 \end{bmatrix} = \begin{bmatrix} 0 \\ i_{set} \end{bmatrix} \quad (12)$$

The potential u_0 of the grounding grid and the bulk flow distribution vector I are obtained by solving for the absence of pipe influence. Then the grounding resistance of the grounding grid can be further solved:

$$R = \frac{u_0}{i_{set}} \qquad (13)$$

3. Engineering Simulation Analysis

In this paper, according to the actual transformation project of a substation grounding network in Shandong, the basic parameters of the substation grounding network and the surrounding soil resistivity to establish an equivalent model of substation grounding network and the surrounding metal pipe network system, and to study the impact of resistive coupling between the two.

3.1. Project Overview

According to engineering information, the substation is currently set up in the station 4 deep well grounding body, vertical grounding body using Φ20mm copper-plated steel rods, depth of 40m, the horizontal grounding body using 40 × 5 flat copper, to take the unequal spacing of the laying, the depth of burial of 0.8m or so. Unlike common rectangular grounding grids, the overall shape of this substation grounding grid is close to a right triangle. When a short-circuit fault occurs in the substation, the fault current into the ground through the grounding grid is about 15kA (short time, 0.4s). In the southeast direction of the grounding network, there are two old and new gas pipelines, the old gas pipeline distance from the nearest grounding network is about 15m or so, the new pipeline distance from the grounding network is about 24m, does not meet the requirements of GB50028 in the underground gas pipeline and 220KV substation grounding body not less than 30m distance. The old pipeline crossing section placed in DN700 ductile iron casing, new and old pipelines are Φ529mm spiral seam welded steel pipe, wall thickness of 8.0mm, using a 3-layer PE anticorrosion layer, the thickness of the anticorrosion layer of 3mm, resistivity of 1 × 1013Ω-m, the pipeline burial depth of 1.2m. The length of the new and old pipes parallel to the grounding grid is about 120m.The model of grounding network and pipeline is shown in Figure 3.

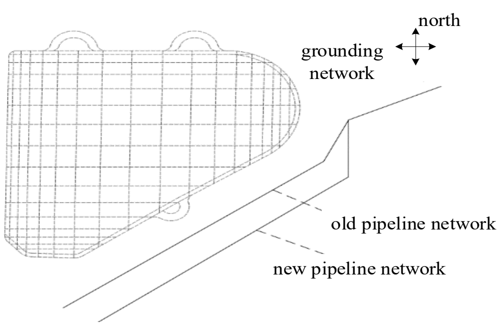

Figure 3. Model of grounding grid and pipeline.

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In the feasibility study stage of this project, the soil resistivity was measured on site, and the measured data were analyzed and interpreted to obtain a two-layer soil resistivity model of the geographic environment in which the substation is located, and the specific soil stratification is shown in Table 1.

Table 1. Soil Model Around Substations.

Layer of soil	Depth(m)	Resistivity(Ω·m)
1	3.0	120.3
2	∞	82.0

According to the measured underground soil resistivity data of the substation, CDEGS and ETAP power system analysis software are used to model and analyze the substation grounding network and the surrounding underground metal pipe network structure, and simulation calculations are made to obtain the potential rise of the substation and the metal pipe network as well as other safety parameters, and study and analyze the impact of resistive coupling between the grounding network system and the metal pipe network system.

3.2. CDEGS Simulation Analysis

The CDEGS package is a power system analysis program written by Safety Engineering Canada (SES) based on the method of moments. Based on the two-layer soil model in the previous section, the substation grounding network and the surrounding underground metal pipes are modeled and analyzed using the CDEGS simulation program, which combines the material and structure of the grounding system and the metal pipes [17].

First, ten equal measurement points are set up in the center of the grounding network along the path perpendicular to the direction of the metal pipe, and a 15KA fault current is passed, and the changes of scalar potential, contact voltage, and step voltage on the path are simulated and calculated as shown in Figure 4.

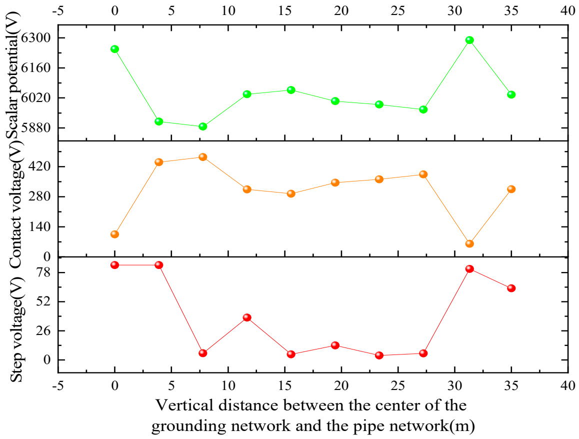

Figure 4. Variation of basic performance parameters of measurement points within the grounding network(CDEGS).

As shown in Figure 4, when a short-circuit fault occurs in the substation generating a fault current of 15 KA, the scalar potential from the center to the edge of the grounding grid shows an uneven distribution trend; The contact voltage is lower at the center point at 104.62V and fluctuates above and below 400V on the rest of the path; The step voltage can be as high as 84.6V at the center

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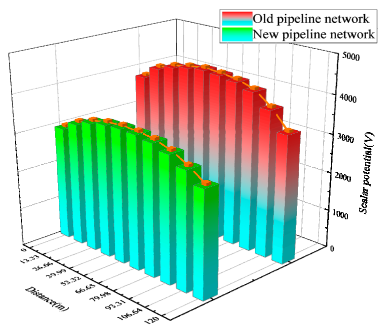
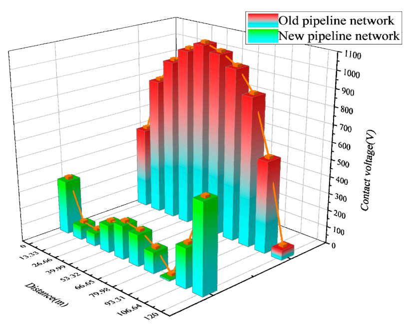
point, with all other locations on the path below that value, reaching a low of 3.98V, with a tendency for the step voltage to pick up closer to the pipe.

On the other hand, the old and new metal pipes are parallel to the grounding network from the northeast, and the parallel length is about 120 m. Under the condition of 15 KA fault current, the old pipes are parallel to the grounding network from the northeast of the map as the starting point, and the trend of the relevant performance parameters of the new and old pipes under the parallel distance of 120 m is simulated and calculated as shown in Figure 5.

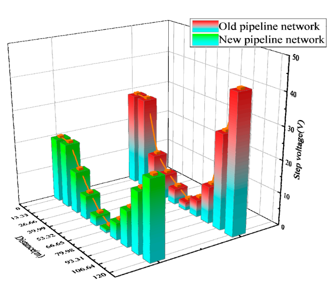
As shown in Figure 5, when the fault current flows in, for the old and new pipe networks the scalar potential shows a trend of high in the middle and low at both ends. For the contact voltage, the trend of the old pipe network is close to the scalar potential, while the trend of the new pipe network fluctuates more, showing high at both ends and low in the middle. For the step voltage, both old and new pipe networks show a trend of low center and high sides. The performance parameters of the old network show a higher trend compared to the new network.



(a) Variation in scalar potential



(b) Variation of contact voltage



(c) Variation of step voltage

Figure 5. Changes in key performance parameters of old and new pipelines (CDEGS).

The main reason for the above trend is due to the presence of low-resistance grounding conductor reduces the equivalent soil resistivity near the conductor, so that the grounding network center to the edge of the ground potential rise shows an uneven distribution trend. The surface of the metal pipe network with high-resistance corrosion protection layer, so that the equivalent soil resistivity in its vicinity increases, which in turn makes the grounding network near the metal pipe network at a higher ground potential rise. The old pipeline is closer to the grounding network, the old pipeline is affected by the coupling effect when the substation short-circuit fault is greater than the new pipeline, making the old pipeline three voltage parameters are higher than the new pipeline.

3.3. ETAP Simulation Analysis

ETAP software is a full graphical interface power system simulation and analysis software developed by OTI [18–20]. Based on the double-layer soil model in the previous section and the data of substation and pipeline, the finite element method modeling and analysis module of ETAP analysis program is used to model and analyze the irregular grounding grid system and metal pipeline, and to study the trend of ground potential rise, contact voltage, and step voltage change from the center of the grounding grid to the edge of the grounding grid that is parallel to the metal pipeline, and along the old and new metal pipelines. Twelve equal points from the center to the edge of the grounding network, the old pipeline, and the path of the new pipeline were selected to calculate the relevant safety parameters as shown in Figure 6.

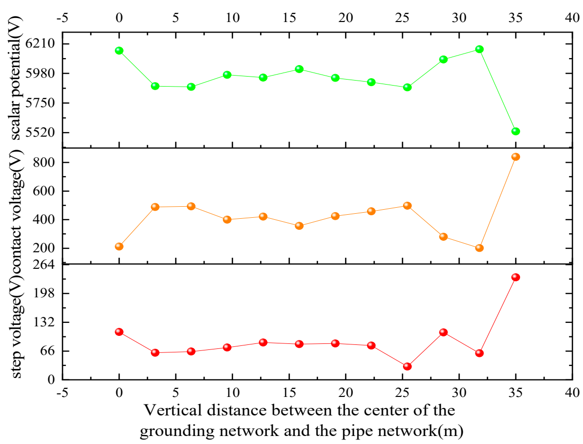
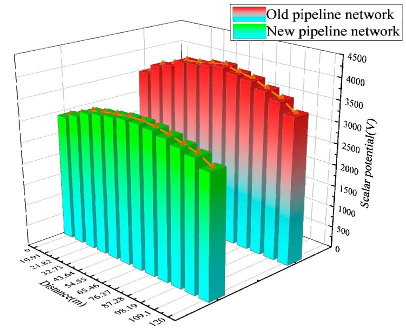


Figure 6. Variation of basic performance parameters of measurement points within the grounding network(ETAP).

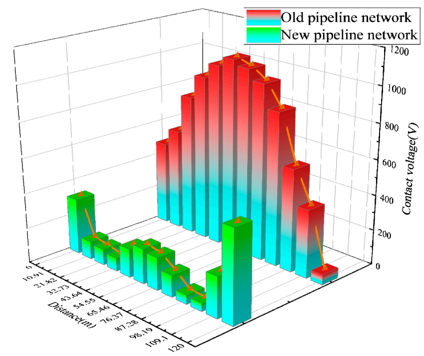
As shown in Figure 6, the scalar potential reaches its highest point at 0 m, and then the voltage fluctuates slightly with the increase of distance, but remains stable in general. The voltage starts at 0 m, and then rises and then fluctuates with the increase of distance, showing a certain degree of fluctuation. The step voltage decreases and then fluctuates with the increase of distance, with a relatively smooth overall trend.

The same old pipeline in the northeast of the map began to parallel with the grounding network as a starting point, the use of ETAP software simulation to calculate the 120m parallel distance, the trend of the relevant performance parameters of the new and old pipeline is shown in Figure 7.

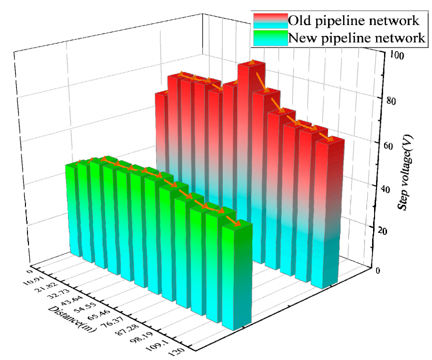
As shown in Figure 7, the scalar potential and contact voltage trends obtained using the ETAP software are basically similar to those obtained in the previous section, but the trend of the step voltage is significantly smoother and shows a high middle and low sides.



(a) Variation in scalar potential



(b) Variation of contact voltage



(c) Variation of step voltage

Figure 7. Changes in key performance parameters of old and new pipelines (ETAP)

Comprehensive simulation of the above, it can be found that the simulation results of the two software are more clearly show the changes in the key performance parameters of the grounding network and pipe network under the influence of resistive coupling. Compared with the simulation of CDEGS, in the ETAP simulation, the change of performance parameters of the grounding network is basically consistent, but the trend of its change is gentler, the scalar potential distribution from the center to the edge of the grounding network is more uniform without large fluctuations, the contact voltage and step voltage are lower at the center point, and there is a certain upward trend near the pipeline, with a large fluctuation of the change. The key performance parameters of the old and new pipe networks clearly showed an increasing trend at closer linear distances from the grounding network, and the fluctuations in changes were significantly smaller for the new pipes than for the older ones. However, there is a certain difference between the two in the simulation value, which is mainly due to the ETAP for irregular grounding network modeling and analysis of the finite element algorithm, the calculation of grounding system related parameters, the geodetic structure of the mesh partition, while the CDEGS software based on the method of moments calculations, only for the region of grounding network and its underground geodetic stratification structure of the engineering

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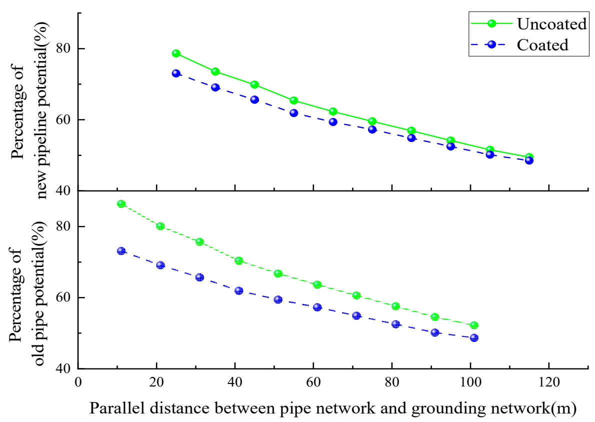
simulation. On the other hand, CDEGS software makes it easy to set observation points in the construction of grounding network and pipeline models and facilitates the optimization design, so CDEGS software is used to model the resistive coupling analysis and other influencing factors in the following analysis [21–25].

4. Optimized Design of Protective Measures

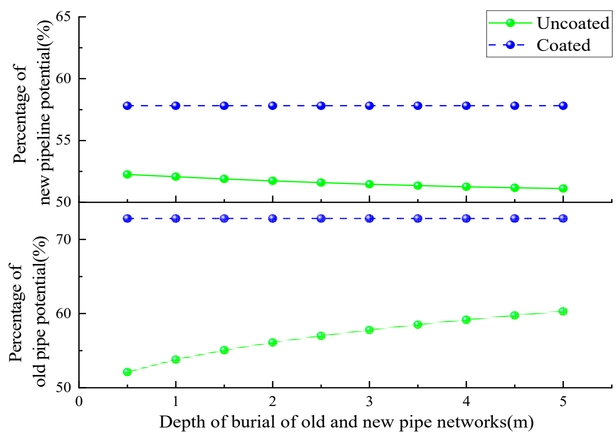
In order to further optimize the transformation of the substation grounding network in the project, the influence of the surrounding metal pipe network on the grounding network is now explored from various aspects.

4.1. Analysis of Influencing Factors

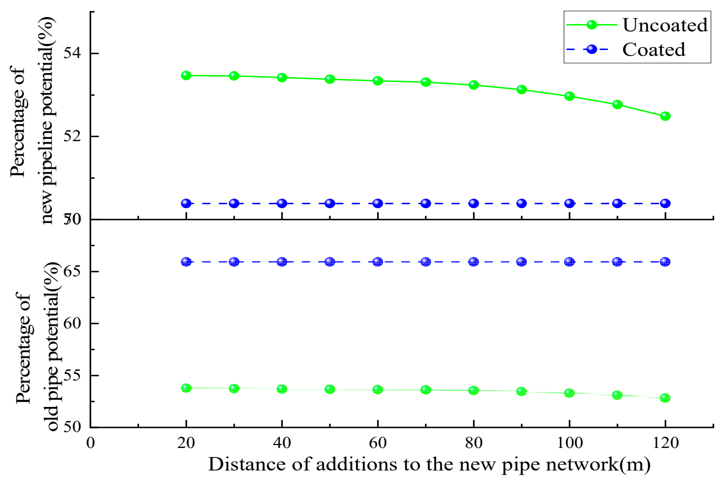
On the basis of the substation grounding network and the surrounding metal pipe network model in the previous section, the same fault current of 15KA is passed, and the potential of the grounding network is used as a benchmark, and the new and old metal pipe networks are analyzed as a whole, and the new and old grounding networks are studied respectively by changing the parallel distance between the pipe networks and the grounding network, the laying length of the new and old pipe networks and the degree of depth of the burial, and by considering the influence of the layers of the pipe networks based on the 3-PE corrosion layer. The percentage change of the potential is shown in Figure 8.



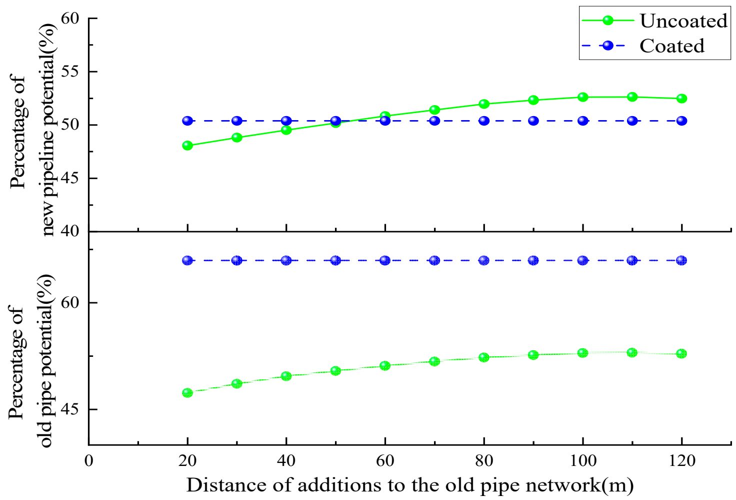
(a) Distance between old and new piping and grounding grid



(b) Depth of burial of old and new pipelines



(c) Length of new pipe laying



(d) Length of old pipe laying

Figure 8. Percentage of potential for new and old pipes.

As can be seen from Figure 8(a), with the increase in the distance between the pipe and the grounding network between the impact of the resistive coupling between the two becomes smaller, the percentage of the potential of the pipe decreases, the addition of the coating can be reduced to a certain extent to reduce the impact of the resistive coupling. From Figure 8(b), it can be seen that the percentage of potential of the pipe with additional coating is almost unaffected as the depth of the pipe increases, whereas without additional coating, the percentage of potential of the old pipe close to the grounding grid with respect to the grounding grid gradually increases, and the percentage of potential of the new pipe away from the grounding grid with respect to the grounding grid gradually decreases. From Figure 8(c), it can be seen that in the case of no coating, as the length of the old pipe decreases, the percentage of potential between the old and new pipes and the grounding grid gradually decreases, while after adding the coating, changing the length of the old pipe has basically no effect on the percentage of potential between the old and new pipes and the grounding grid. From Figure 8(d), it can be seen that in the case of no coating, as the length of the new pipe decreases, the percentage of potential between the old and new pipes and the grounding grid increases slightly,

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while after adding the coating, changing the length of the new pipe has basically no effect on the percentage of potential between the old and new pipes and the grounding grid.

4.2. Installation of Additional Vertical Grounding Electrodes

The original grounding network contains 4 vertical grounding body, now on the grounding network added 2 to 12 vertical grounding body, grounding body conductivity of 100S/m, thermal conductivity of 234, melting temperature of 1083 ℃, resistivity of 1.72Ω-m, heat capacity of 3.42J/K, length of 40m, fault clearing time of 0.4 seconds, body weight of 50kg. The changes in the performance parameters of the grounding system after adding different numbers of vertical grounding bodies are analyzed and shown in Figure 9:

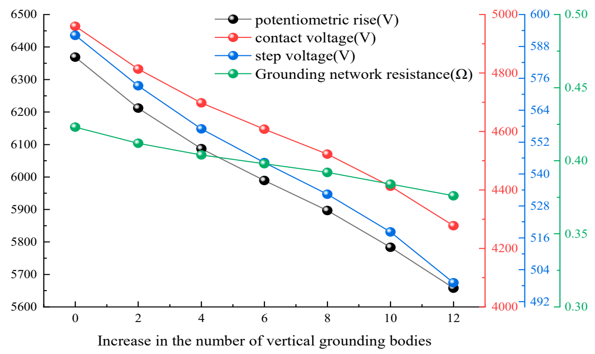
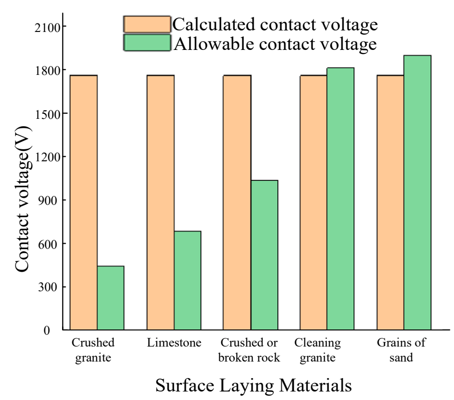


Figure 9. Changes in safety parameters with the addition of a vertical grounding body.

As can be seen in Figure 9, with the increase of vertical grounding body, the ground potential rise, contact voltage, step voltage, and grounding resistance of the grounding network all show a decreasing trend, and when the increase of 12 vertical grounding poles, the ground potential rise is reduced by 6.8%.Therefore, in the construction conditions allow, can be considered in the grounding system to increase the amount of vertical grounding body to reduce the grounding resistance.

4.3. Addition of Surface Material

Due to the new vertical grounding body construction in the completed substation is difficult, is now analyzed in the substation as well as the pipeline above the surface laying 0.2m thick five kinds of high-resistance materials, to get the laying of different materials after the material above the contact voltage calculated value and the corresponding permissible value is shown in Figure 10 (a), the different materials above the calculated value of the step voltage and the permissible value is shown in Figure 10 (b):



(a) Contact voltage variation

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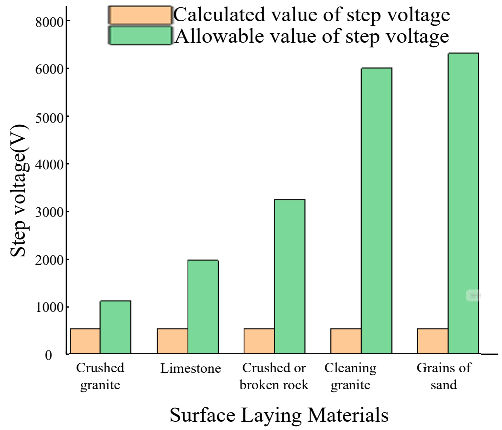

(b) Cross-step voltage variation

Figure 10. Changes in safety parameters with the addition of different surface materials.

As can be seen from Figure 10, with the increase in the resistivity of the surface of the additional surface material, close to play an insulating role, so that the material above the contact voltage and the permissible increase in the safety voltage is obvious, can effectively ensure the personal safety of staff. Among the five materials, the 0.2 m thick, crushed gravel layer with a resistivity of 8534.4 Ω-m has the most significant effect on the improvement of the permissible values of contact voltage and step voltage, and a comparison of the specific values is shown in Table 2:

Table 2. Contact and Step Voltages Before and After the Addition of a Gravel Layer.

	Contact voltage(V)	Step voltage(V)
Calculated value in the absence of a surface layer	1746.1	597.8
Allowable value without surface layer	193.1	282.5
Calculated value with surface layer	1746.1	597.8
Permissible value when there is a surface layer	1883.8	7043.2

From Table 2, the safe contact voltage limit is 1883.8 V and the safe step voltage limit is 7043.2 V when the station is paved with a 0.2 m layer of crushed sand and gravel. When the station is not paved with a gravel layer, the safe contact voltage limit is 193.1V and the safe step voltage limit is 282.5V. Laying a high-resistance crushed sand and gravel layer on the ground surface above the grounding network and metal piping can effectively reduce the step voltage and contact voltage below the safety limit, and safeguard personal safety.

5. Conclusions

This paper combines engineering practice, applies the calculation method of field-circuit coupling to establish a mathematical model, combines CDEGS and ETAP engineering software, studies the fault current flowing through the substation grounding network, the surrounding metal pipe network on the grounding network of the resistive coupling influence, and obtains the following conclusions and outlook:

1) When the fault current is injected into the grounding network system, the impact of resistive coupling between the grounding network and the metal pipe network makes the fault current form a complex flow path between the two, which has a certain impact on the current distribution of the grounding network and the metal pipe network, and ultimately leads to fluctuations in its key performance parameters.

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2)When CDEGS and ETAP software simulate the performance of the grounding system, the trends of the data obtained from the simulation show a high degree of consistency, but there is a deviation of about 5% in the values.

3) For grounding network renovation projects, the addition of high-resistance coatings and vertical grounding electrodes to the grounding network can effectively optimize the key performance parameters of the grounding system, while for the grounding network renovation project is not convenient for large-scale excavation, it can be used to optimize the performance parameters of the grounding network and the metal pipeline by the surface of the surface of the grounding network and the high-resistance layer of crushed sand and gravel.

4) The work done in this paper can also provide certain reference value and guidance for the design of DC transmission project grounding pole and converter station grounding network.

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Abbreviations

The following abbreviations are used in this manuscript:

CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure
ETAP	Electrical Transient and Analysis Program

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