Diagnosis for Conductor Breaks of Grounding Grids Based on the Wire Loop Method of the Transient Electromagnetic Method

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1. Introduction

The grounding grid offers public ground for many kinds of electrical equipment. When an equipment malfunction or a lightning strike occurs, a grounding grid can diffuse the malfunction current and the lightning current into the ground, limiting the ground potential rise (GPR) and ensuring the safety of people and facilities [1]. Steel grounding grids are buried in soil; thus, they are significantly affected by corrosion, which causes conductor breaks [2]. Therefore, it is important to develop an effective conductor break detection method that does not cause power outages or require digging or corresponding measures.

Recently, many scholars have examined the conductor breaks of grounding grids. Diagnosis methods can be classified into the following three categories: electric network parameter identification, electrochemical detection, and electromagnetic detection [3–5]. Based on the principle of the electric network, grounding grids are regarded as resistance networks that can determine conductor breaks through the resistance change between two ports. However, sometimes the resistance will not change even though conductor breaks exist, so this method often fails. The corrosion of grounding conductors can be estimated by electrochemical detection, but this method is invalid for conductor breaks detection. The electromagnetic detection method includes two main categories. Dawalibi proposed a method that injected current into a down-lead wire and measured the surface magnetic field to explore the conductor breaks of grounding grids based on electromagnetic theory [6,7]. Fu proposed transient electromagnetic apparent resistivity imaging for the conductor breaks diagnosis of grounding grids [8–10]. The method can determine the existence of conductor breaks but cannot accurately locate them because the effects of loop size and detecting depth are not considered. Moreover, this method is complex because of apparent resistivity inversion.

In this paper, the wire loop method of the transient electromagnetic (TEM) method is used to nondestructively detect conductor breaks of grounding grid. For this purpose, the grounding grids serve as the underground wire loop, and...
the measuring points are arranged on the ground. At each measuring point, a receiving loop is employed to detect the electromagnetic response, which is generated by transmitting the current of the transmitting loop. The receiving loop is centered on the transmitting loop as shown in Figure 1. By analyzing slices of the electromagnetic response, conductor breaks can be diagnosed directly. We study the effects of loop size and height difference through simulation of an intact 2×2 grounding grid and confirm that it is easier to obtain the topological structure while using a small transmitting loop at a low height. Furthermore, simulations of an intact 4×4 grounding grid and grids with different conductor breaks locations are also conducted using a small transmitting loop. This method can clearly distinguish the location of conductor breaks and the topological structure of the grounding grid. Finally, the detection method is applied experimentally. The experimental results confirm that the proposed method is an effective technique for conductor breaks diagnosis.

2. Electromagnetic Response of Wire Loop

The detection process of the transient electromagnetic method (TEM) is presented in Figure 2. A primary field is generated by the variation of the transmitting current. The primary field will induce current in the wire loop, and the electromagnetic response (secondary field) is caused by changing the induced current. We use a receiving loop to collect the secondary field. The main components of the secondary field can be divided into the following three parts [12–14]: TER (transmitting-earth-response, the electromagnetic response of the ground caused by the primary field); and LER (loop-earth-response, the electromagnetic response of the ground caused by the induced current of the wire loop). Usually, TER is treated as the background field in data processing. When the transmitting current is more than 100A, the induced current of the wire loop is usually less than 10 mA, and so LER is such a weak signal that can be ignored in engineering practice [14]. Therefore, only TLR is examined in this paper.

The transmitting current is presented in Figure 3, and the formula for TLR is defined as [15]

\[
V_{\text{AL}}(t) = -\frac{M_{\text{RL}} M_{\text{TL}} I}{L_{\text{AL}}} e^{-t/\tau_\text{L}} \left[ \frac{1}{T_1} \left( e^{T_1/\tau_\text{L}} - 1 \right) - \frac{1}{T_2 - T_3} \left( e^{T_2/\tau_\text{L}} - e^{T_3/\tau_\text{L}} \right) \right] (1)
\]

where \( I \) is the peak current, \( R_{\text{AL}} \) is the resistance of the wire loop, \( L_{\text{AL}} \) is the inductance of the wire loop, \( \tau_\text{L} \) is the time constant of the wire loop, \( T_1, T_2, \) and \( T_3 \) are inflection points of the current, \( T \) is the half cycle, \( M_{\text{RL}} \) is the mutual inductance between the receiving loop and the wire loop, and \( M_{\text{TL}} \) is the mutual inductance between the transmitting loop and the wire loop. When it comes to computing secondary field, it is an approximate formula.

From the above formula, for one wire loop, \( \tau_\text{L} \) is constant. The attenuation curves at each measurement point are parallel in semilog coordinates. Therefore, data measured concurrently can be used to draw the slice of the induced voltage to diagnose the conductor breaks. When the waveform and
value of transmitting current are the same, the induced voltage of each measuring point is determined by $M_{RL}$ and $M_{TL}$.

The formula of mutual inductance [16, 17] between the square loop and circular loop, shown in Figure 4, is defined as

$$M = \frac{N_1 N_2 \mu_0}{4\pi} \int_{l_1} \int_{l_2} \frac{dl_1 \cdot dl_2}{R}$$

where $N_1$ and $N_2$ are turns of the two loops, $\mu_0 = 4\pi \times 10^{-7}$ H/m, $2a \times 2b$ is the side length of square loop, $r$ is the radius of circle loop, $dl_1$ and $dl_2$ are the vector elements for the two loops, $(x_1, y_1, z_1)$ and $(x_2, y_2, z_2)$ are the coordinates of $dl_1$ and $dl_2$, respectively, $R$ is the distance between $dl_1$ and $dl_2$, and $\theta$ is the angle between $dl_2$ and the X-axis.

For the square and circular loops in Figure 4, the center of the square loop is set at the original point, and the Z-axis is perpendicular to the plane of the two loops. The circular loop moves from (-15, 0, 0) to (15, 0, 0). The mutual inductance between two loops is calculated via two conditions: different radius and heights. Figure 5(a) shows that the radius of the loop will affect the shape of the mutual inductance curves. The parameters are as follows: $a = b = 5$ m; $h = 0.6$ m; and $r = 1$ m, 2 m, 3 m, 4 m, and 5 m. If the sizes of the two loops are close, the whole effect is more likely to show. The mutual inductance curves appear to be convex, as shown in Figure 5(a), when $r = 2$ m and $r = 3$ m. If the sizes of the two loops differ greatly, the edge effect of the larger loop is more likely to show. A convex shape will appear at the edge of the larger loop, as shown in Figure 5(a), when $r = 1$ m. When we change the height difference between the two loops, the curves are as presented in Figure 5(b). The height difference can also affect the shape of the mutual inductance curves. The parameters are as follows: $a = b = 5$ m; $r = 1$ m; and $h = 0$ m, 0.5 m, 1 m, 1.5 m, and 2 m. If the height difference of the two loops is small, the edge effect of the larger loop is more likely to show. A convex shape will appear at the edge of the larger loop, as shown in Figure 5(a), when $h = 0$ m and $h = 0.5$ m. If the height difference between the two loops is large, the whole effect is more likely to show. The mutual inductance curves appear to be convex, as shown in Figure 5(b), when $h = 1.5$ m and $h = 2$ m.

When the transmitting current is same, the shape of the voltage simultaneously measured at the receiving loop is determined by $M_{RL} \times M_{TL}$ at every measuring point. The shape of the mutual inductance changes with loop shape, size, and height difference. Therefore, when the shape and size of the grounding grids are fixed, changing the size of
the transmitting loop and the height difference can lead to different types of the induced voltage.

3. Numerical Simulations

The configuration of the grounding grids is presented in Figure 6. The paper simulated the electromagnetic response ($H_z$) of the grounding grids with no conductor breaks using COMSOL Multiphysics. The actual side length of the grounding grid varies several meters, and the burial depth varies from 0.6 m to 2 m. The sizes of meshes of the grid are 2m×2m. The cross section of each conductor is 0.04 m×0.004 m. The conductivity of the grounding grids is $5.618\times10^6$ S/m. The soil is presumed to be homogeneous with a conductivity of 0.02 S/m. The transmitting loop above the surface of the earth is excited by a 5A step current. There are 11 measuring lines, and two adjacent lines are 0.5 m apart. There are 11 measuring points in each line, and the distance between two adjacent points is 0.5 m. The sampling frequency is 51.2 kHz; then numerical simulations consider the data at time instant of 19.53125μs.

3.1 Effect of Loop Size and Height Difference. In Figure 7, the black lines represent the actual location of the grounding grids as a reference in the induced voltage slice. The grounding grids are buried 0.6 m under the surface of the earth. The radius of the transmitting loop is either 0.1 m, 0.5 m, 1 m, or 2 m, and the turn number of the transmitting loop is 100. The induced voltages slices are presented in Figure 7. When the height difference between the grounding grids and the loop is constant, loop size will determine the amplitude and shape of the induced voltage slice. When the loop size is small, the shape of the induced voltage slice is close to the topological structure of the grounding grid.

For calculations shown in Figure 8 the transmitting loop radius is 0.5 m, and the turn number of the transmitting loop is 100. The grounding grids are buried 0.2 m, 0.6 m, 1 m, or 2 m under the earth surface. Slices of the induced voltage are presented in Figure 8. When the size of the loop is constant, the height difference between the grounding grids and the loop will determine the induced voltage slice. When the height difference is small, the shape of the induced voltage slice is close to the topological structure of the grounding grid.

Both the size of the loop and the height difference between the grounding grids and the loop impact the shape of the induced voltage slice. The smaller the loop size and the shorter the height difference, the closer the shape of the induced voltage slice is to the topological structure of the grounding grid.

3.2 Classification of Breakpoint. According to their position, we classify conductor breaks into four types.

1. A-type: The conductor break is located at the edge conductor of the grounding grids so that the induced voltage of the meshes of the grid with the conductor break will disappear. Examples include the conductor breaks located at positions 1, 2, 3, 4, 13, 14, 15, and 16 in Figure 6.

2. B-type: The conductor break is located between two grids. The induced voltage of the grounding grid appears instead of that of the two small grids. Examples include the conductor break at positions 5, 6, 7, and 8 in Figure 6.

3. C-type: The conductor break is located at a node at the edge of the grounding grids, and so the induced voltage of the two small grids disappears. Examples include conductor breaks located at positions 9, 10, 11, and 12 in Figure 6.
Figure 6: Configuration of the grounding network (2x2).

Figure 7: Induced voltage slices of various transmitting loop radius. (a) $r = 0.1$ m; (b) $r = 0.5$ m; (c) $r = 1$ m; (d) $r = 2$ m.
(4) D-type: The conductor break is located at the intersection of four small grids. The induced voltage of the four small grids will disappear, but the induced voltage of the large grid remains. Examples include the conductor breaks at position 0 in Figure 6.

3.3. Breakpoint Diagnosis of Grounding Grids. To verify the effectiveness of the conductor breaks diagnosed with small loops in a further step, this paper takes the grounding grids (4×4) as an example and simulates the electromagnetic response with the intact grounding grid and various conductor breaks locations (A, B, C, and D).

A configuration of the grounding grids is presented in Figure 9. The meshes of the grid are 2m×2m. The grounding grids are buried 0.6 m under the surface of the earth. There are 19 measuring lines, and two adjacent lines are 0.5 m apart. There are 19 measuring points in each line, and two adjacent points are 0.5 m apart. The other parameters are the same as mentioned above.

An induced voltage slice of the intact grounding grids is presented in Figure 10. When the grounding grids are

Figure 8: Induced voltage slice at various heights. (a) $h = 0.2$ m; (b) $h = 0.6$ m; (c) $h = 1$ m; (d) $h = 2$ m.

Figure 9: Configuration of the grounding network (4×4).
intact, the induced voltage slice is considered the same as the topological structure of the grounding grid.

The induced voltage slice with a conductor break at locations A, B, C, and D is presented in Figures 11(a), 11(b), 11(c), and 11(d), respectively. When the grounding grids possess a conductor break, the value of the induced voltage decreases where the edge conductor of the grid is broken. The induced voltage of the grid with the conductor break disappears,
while other edges remain raised. The induced voltage slice is considered the same as the topological structure of the grounding grid.

4. Laboratory Test

To further verify the correctness of the simulation result, a laboratory test was performed. As shown in Figure 12, the side length of meshes of the grid is 0.5 m × 0.5 m, and the cross section of each conductor is 0.04 m × 0.004 m. The conductivity of the grounding conductor (10^7 S/m) and soil (0.01–0.02 S/m) varies widely, and the buried depth of the grounding grids is near surface. Thus, the effect of the upper soil can be neglected in the experiment, which was performed in the laboratory of Jilin University, and the experimental device is presented in Figure 13. Grounding grids are placed on the ground. The transmitting and receiving loops are placed on the dynamic platform. The TEM transmitting-receiving system is a Mini TEM system that was developed by Jilin University; the transmitter current waveform is shown in Figure 14. There are 13 measuring lines, and two adjacent lines are 0.1 m apart. There are 13 measuring points in each line, and two adjacent points are 0.1 m apart. The transmitting current is a trapezoidal wave, as shown in Figure 14. Specific parameters are as follows: \( I = 5 \text{ A}, T_1 = 3 \text{ ms}, T_2 = 10 \text{ ms}, T_3 = 11.3 \text{ ms}, \) and \( T = 20 \text{ ms}. \) When the transmitting current is zero, the primary field will disappear during the experiment, so we do not have to eliminate the primary field. Therefore, the experimental data shows the off-time data integrated between \( T_3 = 11.3 \text{ ms} \) and \( T = 20 \text{ ms}. \) The sampling frequency is 51.2 kHz; then this paper considers the data at time instant of 1.953125 ms to draw an induced voltage slice.

A square loop with a side length of 0.25 m and 10 turns is employed as the transmitting loop. The radius of the receiving loop is 0.07 m, and the turn number of the receiving loop is 400. The distance between grounding grids and loops is 0.15 m. The electromagnetic response of the intact grounding grids is presented in Figure 15(a). When the side length of the transmitting loop and the value of the height difference are small enough, the slice of the induced voltage shows the...
configuration of the grids. The topological structure of the grounding grids is presented clearly since the value of the induced voltage above the grounding conductor is larger than that of any other location.

A square loop with a side length of 0.75 m and 63 turns is employed as the transmitting loop. The radius of the receiving loop is 0.07 m, and the turn number of the receiving loop is 400. The distance between the grounding grids and loops is 0.5 m. The electromagnetic response of the intact grounding grids is presented in Figure 15(b); however, no topological structure can be derived when the side lengths of the transmitting loop and the value of the height difference are large. As a result, we can only obtain grounding grids effect as a whole conductor instead of the meshes effect of the grid.

The results of the experiments are comparable with those of the simulation, are presented in Figure 15. It can be stated that loop size and measuring height affect the measuring result directly. The smaller the transmitting loop is and the nearer the loops are to the grounding grids, the easier the detection will be. The topological structure of the grounding grids will be clearly shown in the induced voltage slice.

A square loop with a side length of 0.25 m and 10 turns is employed as the transmitting loop. The receiving loop has a 400-turn round loop with a radius of 0.07 m. The distance between the grounding grids and loops is 0.15 m. The electromagnetic responses of grounding grids with various types of breakpoints, which are in accordance with the results of the simulation with various breakpoint conditions, are presented in Figure 16. The topological structures of various grounding grids are obtained. Thus, it can be concluded that this method is correct.

5. Conclusion

This paper diagnoses the breakpoints of grounding grids using the wire loop method of the TEM. Grounding grids are taken as the underground wire loop. Electromagnetic response is measured using a central loop system. According to the induced voltage slice of the grounding grid, breakpoints can be diagnosed directly. We study the effect of loop size and height difference through simulation of an intact 2×2 grounding grid and confirm that it is easier to determine the topological structure using a small transmitting loop and a short height difference. Furthermore, simulations of an intact 4×4 grounding grid and grids with various breakpoint locations are also conducted with a small transmitting loop. The topological structure of the grounding grid is clear; the breakpoint locations can be seen. Additionally, we verify the effect of loop size and height difference through the intact 2×2 grounding grid; the detection results at various breakpoint locations are derived with a small transmitting loop. The result of the experiment is in accordance with the simulation, which verifies the effectiveness of the method. In conclusion, we can derive the induced voltage signal using a near-surface experiment with a small transmitting loop. By analyzing the slice of the induced voltage, we can obtain the topological structure of the grounding grid and determine the breakpoint locations. For other transformer substations, the burial depth and size of the grounding grid differ. Therefore, setting the parameters of the transmitting and receiving systems is a problem that remains to be solved, as it still lacks a quantitative calculation method.

Data Availability

The XLSX data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
Figure 16: Induced voltage slice of the experiment with various breakpoint locations. (a) Breakpoint location is A; (b) breakpoint location is B; (c) breakpoint location is C; (d) breakpoint location is D.

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