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Topological measurement and characterization of substation grounding grids based on derivative method

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ABSTRACT

Derivative method, which avoids pathological solution of the magnetic field inverse problem, was proposed to solve the problem of drawing loss or unknown of grounding grids. First, a shape function was introduced to describe the distribution of magnetic field which is perpendicular to the surface of grounding grids. Since its odd-order derivatives contain main peaks, the 1st-, 3rd- and 5th-order derivatives were chosen to solve the topology of substation grounding grids and measure the branch current of the grid by determining the position and value of main peak, respectively. Numerical example and experimental result show that the 1st- and 3rd-order derivative method works well with low error and less computation.

Introduction

The main objectives of grounding systems are to guarantee personal safety, equipment protection and power supply continuity [1]. A grounding system comprises all the interconnected grounding facilities in a specific area, but its main element is the grounding grids. In general, most grounding grids of electrical substations consist of a mesh of interconnected cylindrical conductors, which are horizontally buried and supplemented by vertically thrusting ground rods in certain places of the substation [2]. Typically the conductors made of bare copper or iron are buried 0.3–2 m deep underground. The meshes are usually spaced 3–7 m apart and the ratio of the sides of a mesh is 1:l–1:3 [3].

The electromagnetic field theory (EMF) and the electric circuit theory (with lumped or distributed parameters) are both widely used to diagnose the corrosion status of the grounding grids in a power substation [4]. The electric circuit theory establishes and solves the diagnosis equation that describes the nonlinear relationship between branch resistance and node voltage based on the application of Tellegen's Theorem [5,6]. However, the method needs to know the topology of grounding grids. The electromagnetic field theory, which was proposed by Dawalibi [7], measures the surface electromagnetic field and establishes the magnetic field inverse equations to judge the topology and corrosion status of the grounding grids [8,9]. However, the solution to the inverse problem usually is not unique and stable, the solution process is complex.

In geophysical prospecting, the topology and burial depth of the target can be detected by the resistivity prospecting [10], electrical prospecting [11], seismic refraction tomography [12], gravity and magnetic prospecting [13], gamma radiometric prospecting [14], electromagnetic prospecting Hedley et al. [15]. The geophysical prospecting methods are mainly for large size and deeply buried targets, for example, the faults shear zones, iron ore deposit, buried cavity, water table, and have shortcoming to detect the small size (cross section less than 1 cm $*$ 10 cm) and shallow buried (0.3–2 m deep underground) branch conductors of grounding grids.

In the paper, a method is developed for calculating the topology and branch current of grounding grids and avoids pathological solution of the magnetic field inverse problem. First, the theoretical analysis of the method is discussed. Then a numerical example is used to test the viability of the method. Finally experimental result is used to test the reliability and precision of the method by a small grounding grid model in the lab.

Modeling of single current-carrying conductor by using derivative method

Most grounding grids are composed by a lot of branches in finite length. We can analyze the characterization of every single branch, and draw the topology of grounding grids by measuring

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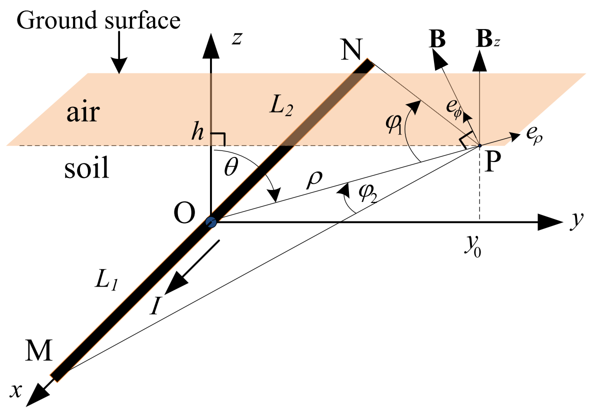

Fig. 1. The magnetic flux density caused by a finite-length current filament on the x axis is $B = \mu I/4\pi\rho(\sin\varphi_1 + \sin\varphi_2)\mathbf{e}_\phi$; the ground surface is at $z = h$ plane.

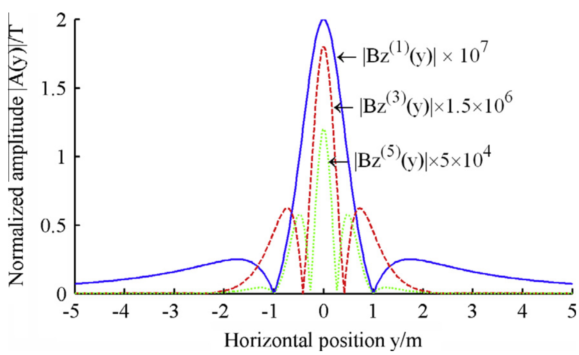

Fig. 2. Graph of $B_z^{(1)}(y)$, $B_z^{(3)}(y)$ and $B_z^{(5)}(y)$.

the position of the each branch. The process of derivation method is introduced by analyzing the current-carrying conductor in finite length.

Derivative method

The derivative method (or differential technique) is mainly used to improve the resolution ratio of seismic records, and compensate the frequency loss and amplitude loss of seismic waves during propagation [16,17].

Let $f(x)$ be a differentiable function, and let $f^{(n)}(x)$ be its n-order derivative.

$$F^{(n)}(\omega) = (j\omega)^n F(\omega) \quad \text{with} \quad n \in \mathbb{N} \tag{1}$$

where

$$F(\omega) = \int_{-\infty}^{\infty} f(x)e^{-j\omega x}dx, \quad F^{(n)}(\omega) = \int_{-\infty}^{\infty} f^{(n)}(x)e^{-j\omega x}dx \tag{2}$$

In Eq. (1), the n-order derivative of the function is equivalent to filtering it with a filter characteristic $(j\omega)^n$.

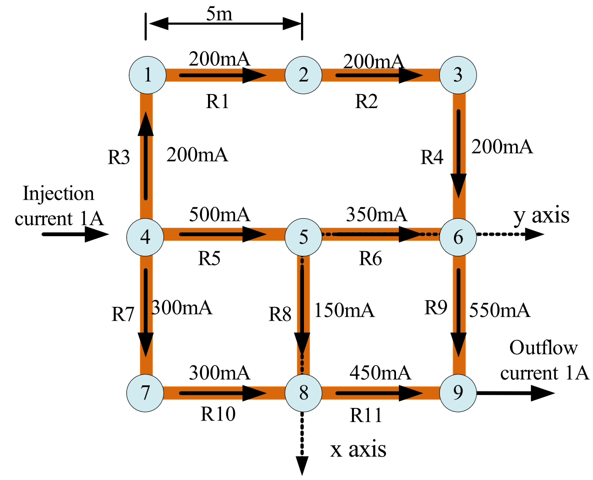

Fig. 3. Grid current-carrying model. The grounding grid model depicts the topology, branch length, point position, branch name, branch current and current direction of the grid, then the model is applied to test the viability of the Derivative method.

The application of derivation method in magnetic field distribution analysis

As shown in Fig. 1, a current carrying conductor MN in length L is buried in the uniform monolayer soil with permeability μ. The conductor is on the x-axis. The ground surface is at $z = h$ plane and the current I along the positive x-axis flows through the conductor. For point P at position $(0, y_0, h)$, its vertical distance from the conductor is ρ. The angles between segment OP with the z-axis, segment NP, and segment MP are θ, φ_1 and φ_2, respectively. The length of OM and ON is L_1 and L_2, respectively. The conductor's leakage current in the soil is ignored.

Based on Biot–Savart law, the *magnetic flux intensity* **B** at point P is

$$\mathbf{B} = \frac{\mu I}{4\pi\rho}(\sin\varphi_1 + \sin\varphi_2)\mathbf{e}_\phi \tag{3}$$

At the point P the unit vector $\mathbf{e}_\phi$ is in the direction perpendicular to the $\mathbf{e}_\rho$. Since $\rho^2 = h^2 + y^2$, the *magnetic flux density* B_z in the $\mathbf{e}_z$ direction is

$$B_z(y) = \frac{\mu I}{4\pi}\frac{y}{h^2 + y^2}(\sin\varphi_1 + \sin\varphi_2) \tag{4}$$

And $\sin\varphi_1 = \frac{L_1}{\sqrt{h^2+y^2+L_1^2}}$, $\quad \sin\varphi_2 = \frac{L_2}{\sqrt{h^2+y^2+L_2^2}}$.

Magnetic field distribution of the single current-carrying conductor in the $\mathbf{e}_z$ direction can be described by Eq. (4), called the shape function. The magnetic field distribution of the grounding grids is equivalent to the superposition of the shape functions of each current-carrying branch.

Because the higher order derivative of Eq. (4) has a more complex expression, the odd-order derivatives contain main peaks, the

Table 1
The comparison table of the three shape functions' graph characteristics.

Shape function	Graph characteristics				Widess Resolution
	Influence sphere (m) (1%)	Main peak width (m)	Side peak width (m)	Total number of peaks	
$B_z^{(1)}(y)$	19.72	2	8.86	3	1.2796
$B_z^{(3)}(y)$	4.052	0.8284	1.5858	3	2.0308
$B_z^{(5)}(y)$	3.8	0.2679	0.7321	5	2.5699

Annotation: $I = 1$ A; $h = 1$ m.