Research on Computer-Aided Design Software for Wind Farm Grounding Systems (Postprint)

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Abstract

Wind farm grounding must satisfy not only power-frequency short-circuit current requirements but also lightning impulse requirements. Defects in the design of wind farm grounding systems can lead to severe consequences, including system oscillation, equipment damage, complete plant shutdown, and even casualties. Parameter evaluation of substation grounding systems constitutes a critical component of power system design, and performing accurate and detailed simulation calculations of grounding grid parameters is of paramount importance. The wind farm grounding design software developed in this study primarily employs numerical calculation methods, enabling comprehensive consideration of practical influencing factors and providing effective support for the design, construction, and operation of wind farms.

Full Text

Preamble

Development of Computer-Aided Design Software for Wind Farm Grounding Systems

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Abstract

The grounding of wind farms must satisfy requirements for both power-frequency short-circuit currents and lightning impulse currents. Defective design of wind farm grounding devices can lead to severe consequences, including system oscillations, equipment damage, complete plant shutdown, and even personnel casualties. Parameter evaluation of substation grounding systems constitutes a critical component of power system design, making accurate and detailed simulation calculations of grounding grid parameters essential. The wind farm grounding design software developed in this paper employs numerical calculation methods that comprehensively account for practical influencing factors, providing effective assistance for the design, construction, and operation of wind farms.

Keywords: High soil resistivity, wind power plant, grounding design software, parameter simulation, numerical calculation method

1 Introduction

Wind power generation, as a vital component of new energy, has experienced rapid development in recent years. According to China' s 13th Five-Year Plan, wind power capacity is projected to exceed 210 million kW by 2020. Despite this rapid growth, China has long lacked effective solutions for wind farm grounding issues in high soil resistivity conditions [1]. Currently, domestic wind farm grounding resistance generally follows these requirements: per GB 51096-2015 "Code for Design of Wind Power Plants," the grounding resistance of wind turbine generators should not exceed 4Ω [2]; according to the China Classification Society' s "Wind Turbine Generator Systems Specification," the power-frequency grounding resistance should generally be less than 4Ω, which may be relaxed to below 10Ω in areas with very high soil resistivity.

This paper presents the development of a specialized design software for wind farms that accurately calculates relevant parameters of wind farm grounding systems. By evaluating different grounding schemes for wind farms in high soil resistivity environments and conducting technical-economic comparisons, the software identifies optimal grounding design solutions, providing technical support for wind farm engineering grounding design.

Calculation methods for grounding system parameters can be divided into two categories: simple estimation using theoretical formulas (referred to as the formula method) and more precise calculation using numerical methods (referred to as the numerical method) [3]. Due to its reliance on equivalent simplifications, the formula method inevitably introduces errors in calculating substation grounding parameters, with excessive simplifications potentially producing significant errors in certain cases—representing its primary limitation. With recent breakthroughs in grounding theory, substantial improvements in computer hardware performance, and advances in numerical computation technology, researchers worldwide have applied various numerical methods to grounding parameter calculations, including finite difference methods, finite element methods, charge simulation methods, boundary element methods, and method of moments [4]. Compared to the formula method, numerical methods can better simulate actual conditions, yielding more accurate results. Therefore, this paper adopts numerical methods for the design of wind farm grounding software.

2 Overview of Wind Farm Grounding Algorithms

According to references [5-6], numerical calculation methods can comprehensively account for factors that formula methods cannot handle, including: (1) complex soil models such as layered soils (common site soil models), block soils (hydropower station models), or combinations of layered and block soils; (2) actual shapes and structures of grounding grids and the real conditions of fault current dissipation, considering the non-uniform current distribution along different parts of the grounding grid to meet calculation requirements for arbitrarily complex grounding grid shapes; (3) complex asymmetric grounding fault current distribution and calculation of maximum ground current; (4) consideration of internal impedance of grounding conductors and mutual coupling between conductors, as well as injection points of ground current into the grounding system; (5) transient current excitation conditions; (6) calculation of maximum step and touch potential differences; (7) analysis and calculation of spatial potential, electric field, and current density distributions; (8) optimal design of grounding systems; and (9) other special cases.

According to references [7-8], wind farm grounding parameters include grounding impedance, touch potential difference, step potential difference, mesh potential difference, and ground surface potential distribution above the grounding grid. Grounding grid parameter calculations generally require consideration of three essential elements: (1) the grounding system itself, including material properties, cross-sectional shape and dimensions of grounding conductors, as well as the shape, size, burial depth, and layout of the grounding system; (2) the resistivity distribution characteristics of the large-scale soil surrounding the grounding system, such as layered/block conditions within a breadth and depth ten times the size of the grounding system; and (3) characteristics of the current source injected into or flowing out of the grounding system, including frequency, amplitude, and waveform.

The numerical solution system for these three essential elements of grounding grid parameter calculation is relatively complex [9-10]. This paper discusses only the numerical processing and solution methods for the grounding system itself, without addressing numerical methods for soil resistivity and current sources. Additionally, since impulse grounding problems are not discussed herein, the numerical calculation method for the grounding system is based on constant current field theory. When DC or AC current flows through the grounding system, the potential at any point satisfies Poisson’ s/Laplace’ s equation. By discretizing the conductors comprising the grounding system, the complex integral for calculating spatial potential can be transformed into a summation form.

The leakage current distribution of the grounding grid can be obtained by calculating the self-resistance and mutual resistance of each discretized branch, thereby determining the potential at any point in space. The numerical processing and solution method for the grounding system primarily involves solving resistance coefficients and the leakage current distribution along the grounding system, with research focusing on calculation accuracy, complexity, computation time, and memory usage. With current hardware technology, computer processing speed and memory size are no longer obstacles to numerical method application; thus, numerical methods should be improved in terms of calculation accuracy and correspondence with actual conditions, such as considering the layered/block conditions of soil where the grounding grid is located rather than analyzing only uniform soil structures with equivalent resistivity.

3 Grounding Simulation Method

The first step in the numerical method for the grounding system itself is discretization—dividing the grounding system into a collection of multiple nodes and branches. The microscopic branch model is shown in Figure 1 [Figure 1: see original paper].

In the analysis of grounding parameters, uniform soil is considered a semi-infinite, isotropic medium whose properties are generally represented by conductivity or resistivity. The local range of a grounding system is much smaller than the penetration depth of AC 50Hz or 60Hz power-frequency currents, allowing propagation time to be neglected. Under AC or DC conditions, grounding system characteristics can be analyzed based on constant current field theory. When current flows into a grounding device buried in the ground, the potential at any point p produced by electrode leakage current can be obtained using Green' s function principles, with the infinite distance point as reference.

After discretization, the grounding system is subdivided into a sufficiently dense collection of branches R. "Sufficiently dense" means all branches in R can approximate S(l) as being equal everywhere. The collection of two endpoints of branch conductors is called nodes N. The equivalent model of the discretized grounding grid consists of r branches and n nodes. A schematic diagram of a grounding grid model is shown in Figure 2 [Figure 2: see original paper].

The voltage V(j) of node number j is defined as the potential of node j. Since branch conductors are sufficiently dense, the voltage U(k) of branch k is approximated as constant at the average potential of its two endpoints:

$$U(k) = \frac{V(m) + V(n)}{2}$$

where m and n are the numbers of the two endpoints of branch k. In matrix form:

$$U = KV$$

where U is the branch voltage column vector; V is the node voltage column vector; and K is the branch-node incidence matrix, where K(i, j) = 0.5 when branch i is connected to node j, otherwise 0.

Considering all branch voltages and branch leakage currents I:

$$I = SU = H^{-1}U$$

where S is the branch leakage current matrix; H is the branch mutual resistance matrix.

For H:

$$H(i,j) = \int_{l_i}\int_{l_j} RG(l_i, l_j)dl_i dl_j$$

Let the branch leakage current I be divided into two parts, equally distributed to the connected nodes:

$$J(b) = \sum I(i)$$

where J(b) is the leakage current at node b; c_{i,b} = 1 if node k is connected to branch i, otherwise zero. In matrix form:

$$J = K'I$$

where J is the node leakage current column vector; K is the transpose of K.

Applying current conservation law:

$$F - J = YV$$

where F is the fault current injection column vector; Y is the node admittance matrix.

$$F = (K'SK + Y)V$$

The node admittance matrix Y of the grounding grid is solved by:

$$Y = AZ^{-1}A'$$

where A is the incidence matrix: A(j,k) = 1 when branch k is associated with node j and its direction is away from the node; A(j,k) = -1 when branch k is associated with node j and its direction is points to the node; otherwise zero; A is the transpose of A; Z is the branch impedance matrix of the grounding grid conductors.

The elements of Z are:

$$Z(i,j) = R(i,j) + j\omega M(i,j)$$

where M is the conductor external self-inductance matrix; M(i, j) is the mutual inductance between conductors i and j; z is the conductor internal impedance vector. The internal impedance z(i) of the ith cylindrical conductor segment can be expressed as:

$$z(i) = \frac{j\omega\mu_c}{2\pi a}\frac{I_0(a\sqrt{j\omega\mu_c\sigma_c})}{I_1(a\sqrt{j\omega\mu_c\sigma_c})}$$

where _c and _c are the permeability and conductivity of conductor i respectively; a is the radius of the cylindrical conductor; I_0 and I_1 are modified Bessel functions of the first kind of order zero and one respectively.

The mutual inductance M(i, j) between conductors is expressed according to electromagnetic field theory as:

$$M(i,j) = \int_{l_i}\int_{l_j}\frac{\cos\theta_{i,j}}{4\pi R}dl_i dl_j$$

where _{i,j} is the angle between conductors i and j.

Since the injected node current vector F is known, the node voltage vector V can be conveniently obtained through the equation above, followed by the branch voltage vector U and branch leakage current vector I. This allows resolution of the equivalent grounding impedance Z_g and surface potential distribution V_p.

$$V = (K'SK + Y)^{-1}F$$

$$Z_g = \frac{\max(V)}{I}$$

$$V_p = H_p I = H_p SKV$$

where H_p is the mutual resistance matrix between branches and observation points, with elements calculated using the same formula as equation (1).

4 Software Development

The architecture of the wind farm grounding auxiliary design software is shown in Figure 3 [Figure 3: see original paper]. Following the software design concept, it is divided into a DXF wind farm grounding system CAD data import module, a preprocessing module (wind farm soil resistivity test data processing and inversion module), a grounding numerical calculation module (grounding resistance calculation, surface potential/step potential difference/touch potential difference analysis module, resistance reduction scheme analysis), and a post-processing module (surface potential/step potential difference/touch potential difference visualization, comprehensive grounding calculation results, and automatic report generation).

4.1 DXF Wind Farm Grounding Data Import Module

Grounding design is typically performed using software such as AutoCAD. Figure 4 [Figure 4: see original paper] shows the CAD drawing of a wind farm grounding system. The software' s data import module can import data from such drawings, significantly reducing the workload of grounding system modeling. Note that the DXF format drawing of the wind farm grounding system shown in Figure 4 is two-dimensional and cannot be directly used for three-dimensional grounding system modeling; manual editing of grounding conductor burial depth is required after importing the 2D data. Additionally, the software requires specification of conductor parameters for different components, such as material properties and cross-sectional area, to prepare for subsequent calculations.

Figure 5 [Figure 5: see original paper] displays the software' s CAD interface, showing the grounding system model from Figure 4 (located in Yichang, Hubei). The software also provides functions for editing conductor geometric parameters to facilitate more refined modeling and includes tolerance functions for conductor connection defects to repair imprecise connections in CAD data.

4.2 Soil Parameter Inversion Module

Wind farm earth resistivity measurement employs the traditional Wenner four-electrode method used in power systems. Since standard [2] does not provide inversion calculation methods, field-measured earth resistivity is often equivalent to uniform soil, which undoubtedly contradicts the complex earth parameters at wind farm sites. The software' s soil parameter inversion module was developed to address this deficiency. As shown in Figure 6 [Figure 6: see original paper], by inverting apparent resistivity corresponding to different electrode spacings, layered earth parameters with minimum root-mean-square inversion error can be obtained, greatly ensuring calculation accuracy.

4.3 Grounding Calculation Module

Due to the complex geometric structure of wind farm grounding systems, simplifying them into basic geometric models would result in calculation errors exceeding engineering tolerances, posing risks to safe wind farm operation. The software' s grounding calculation module employs precise grounding simulation methods consisting of three steps: (1) grounding conductor mesh discretization, as illustrated in Figure 7 [Figure 7: see original paper]; (2) calculation of leakage and conduction admittance (see equation 9); and (3) human safety calculation and verification (maximum step and touch potential differences).

4.4 Post-Processing Module

Upon software completion, Word-format calculation reports are automatically generated without manual preparation, significantly improving office efficiency for grounding design personnel.

4.5 Software Application and Verification

Earth resistivity measurements were conducted at the site of a wind farm unit in Hubei shown in Figure 4, with results presented in Table 1 . Running the software' s soil parameter inversion module yielded two-layer earth parameters shown in Figure 6 and Table 2 , with a root-mean-square inversion error of 11.31%. Using the commercial software CDEGS' s RESAP module for inversion produced a root-mean-square error of 11.68%, as shown in Figure 8 [Figure 8: see original paper]. The similar results demonstrate that the developed software achieves high precision in soil parameter inversion.

CDEGS has DXF import functionality, but the results are unsatisfactory, as shown in Figure 9 [Figure 9: see original paper]. Commercial grounding software may encounter problems when importing complex wind farm drawings, resulting in incomplete conductor information. For comparison with the developed software, correct geometric data was exported from our software and input into CDEGS for grounding parameter calculation. The software calculated a wind farm grounding resistance of 9.65Ω, while CDEGS yielded 9.72Ω and the field measurement was 9.3Ω. The comparison shows that the developed software' s results closely match both CDEGS calculations and measured values with small errors, demonstrating accuracy and reliability. Compared to foreign commercial software, this software is specifically designed for wind farm grounding, offering greater flexibility and convenience for Chinese wind farm grounding design. Additionally, the software features powerful visualization capabilities, with surface potential visualization shown in Figure 10 [Figure 10: see original paper]. This enables designers to easily identify locations of maximum step and touch potential differences and accurately install high-resistance layers in non-compliant areas to ensure personnel safety.

5 Conclusion

Grounding systems are critical components of wind farms, providing fundamental guarantees and important measures for maintaining safe and reliable system operation while protecting personnel and electrical equipment. When high-voltage equipment experiences ground faults, the grounding system must provide a reliable return path for fault current. Wind farm grounding devices play a vital role in ensuring safe power system operation. With China’ s rapid wind power development, increasingly higher demands are placed on system safety, stability, and economic operation. To ensure safe and stable wind farm operation and improve power supply reliability, wind farms require well-designed grounding devices that guarantee compliance with regulatory requirements for grounding resistance, step voltage, and touch potential.

The wind farm grounding design software developed in this paper features a user-friendly interface, simple operation, and reliable performance. Taking Figure 4 as an example, the software calculated a wind farm grounding resistance of 9.65Ω. The software can consider multiple factors in calculations, offers strong practicality, and can simulate different wind farm grounding grid design models based on actual engineering conditions to identify technically and economically optimal solutions. It demonstrates particularly strong engineering application value for wind farm grounding in high soil resistivity environments.

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Note: Figure translations are in progress. See original paper for figures.