Analysis of the Impact of Shunt Coefficient on Measurement Accuracy in Grounding Impedance Testing

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Abstract: This paper systematically reviews the mechanisms and optimization strategies for the impact of the shunt coefficient on measurement accuracy in ground impedance testing. Based on electromagnetic field theory, the interference of shunt current through paths such as lightning arresters and cables on the injected current and voltage potential difference is analyzed, revealing the mechanism that leads to impedance underestimation. In conjunction with the literature, the definition, role, and existing correction methods for the shunt coefficient are discussed, including quantitative evaluation of current compensation and voltage perturbation models. The study further elaborates on a threshold method for establishing the shunt ratio, simplifying engineering measurements by ignoring minor shunts, improving efficiency and accuracy. The review demonstrates that a shunt correction model that comprehensively considers the effects of current and voltage can significantly improve test reliability, providing theoretical guidance and practical basis for the accurate evaluation of power system grounding devices.

Keywords: Ground Impedance; Shunt Coefficient; Measurement Accuracy; Electromagnetic Field Theory; Correction Method

1. Introduction

1.1 Research Background and Problem Statement

Ground impedance testing, as a core method for evaluating the performance of power system grounding devices, plays a critical role in ensuring safe equipment operation and preventing ground faults. According to electromagnetic field theory, ideal testing requires that the current electrode be placed at infinity to establish a zero potential reference. However, in actual engineering, the limited distance arrangement leads to potential difference deviation, which in turn affects the measurement accuracy [1]. In addition, the shunt current generated by structures such as overhead lightning rods and cables further amplifies this error, not only reducing the effective current injected into the ground grid, but also injecting the potential difference between the earth disturbance voltage electrodes through the distant grounding body [2]. For example, in large-scale grounding grid testing, the shunt of the outgoing line structure can cause the impedance value deviation to a significant level, which cannot reflect the true grounding characteristics [3]. Although existing standards such as DL/T 475-2017 introduce shunt coefficients to correct the impact of current, they ignore the comprehensive evaluation of shunt voltage disturbance. Especially in complex geological environments, the accuracy of shunt coefficient evaluation directly restricts measurement reliability [4]. In response to the above problems, this study explores the multi-dimensional impact of shunt coefficient on the accuracy of ground impedance measurement, including the current shunt ratio, voltage disturbance mechanism and quantitative method of threshold establishment. By analyzing the shunt model proposed in the literature and the field measured data, the limitations of the traditional three-pole method under lightning conductor shunt are revealed, and the need to expand the correction strategy to cover the potential difference change is emphasized [5]. The problem raised focuses on: how to accurately quantify the proportion of the impact of long-distance shunt on the potential difference and determine the convergence margin value to optimize the actual test process and improve the applicability of the project.

1.2 Research Significance and Purpose

The application of shunt coefficient in ground impedance testing can significantly improve the measurement accuracy and reduce the error caused by shunt, thereby ensuring the stability and safety of the power system [1]. Studies have shown that by introducing advanced technologies such as shunt phase shift method, the corrected impedance value can be highly consistent with the disconnection structure test results, improving the reliability of engineering decisions [3]. Under harsh geological conditions, the evaluation of shunt coefficient can help reduce the risk of ground potential rise and avoid equipment damage and personal injury caused by uneven distribution of fault current [4]. In addition, this study has guiding value for thermal stability capacity verification calculation. For example, in 110 kV substations, the verification taking into account the shunt coefficient can ensure that the cross-sectional area of the grounding wire meets the operating requirements and prolong the life of the device [2]. From a broader perspective, accurate measurement of ground impedance contributes to the maintenance of sustainable power infrastructure, especially in the scenario of multi-tower parallel connection. The correction formula of the clamp meter method based on the shunt effect can minimize the interference of factors such as soil resistivity [5]. The significance of this study is to provide theoretical support for practical engineering, promote the update of standards and the optimization of test instruments, and ultimately reduce the incidence of ground faults and improve the economic benefits of the system. The purpose of this study is to systematically review the influence mechanism of the shunt coefficient, existing correction methods and quantitative models, reveal the necessity of setting thresholds through literature analysis, and propose an evaluation framework that adapts to complex environments to guide field measurement practice and fill the gaps in current research.

2. Overview of the Theoretical Basis of Ground Impedance Testing

2.1 Test Principle and Electromagnetic Field Theory

The core of ground impedance testing is to evaluate the fault current discharge capacity of the grounding device. Its principle is based on electromagnetic field theory, treating the grounding body as a point source or line source model, and calculating the potential distribution in a uniform medium [6]. According to Maxwell's equations, the magnetic field generated by the injected current is coupled with the electric field, resulting in the ground impedance including not only the resistance component but also the inductance and capacitance effects, especially under high frequency or impact conditions [7]. The traditional fall-of-potential method assumes that the current electrode is placed at infinity and calculates the impedance based on zero potential. However, the actual finite distance introduces mutual inductance interference, which needs to be corrected by field theory [8]. For example, in a semi-infinite space with uniform soil resistivity ρ, where r is the distance from the source point, formula 1 reveals the sensitivity of the distance between electrodes to the measurement [9]. Furthermore, when considering non-uniform soil, the mirror method expands the model and introduces a mirror current source to simulate the surface boundary conditions to improve the calculation accuracy [10]. Electromagnetic field theory also explains the frequency dependence of impedance under shock waves (formula 2), where ω is the angular frequency, L and C are self-inductance and capacitance to the ground, respectively [11]. These theoretical foundations lay the framework for shunt effect analysis and emphasize the need to combine finite element simulation to verify field data in complex environments to reduce errors caused by uneven field distribution. Overall, electromagnetic field theory provides mathematical tools from microscopic field equations to macroscopic impedance models to explain the interference of shunts on potential gradients and ensure the scientific nature of the test method.

$$\phi(r) = \frac{I\rho}{2\pi r} \tag{1}$$

$$Z(\omega) = R + j\omega L - \frac{j}{\omega C} \tag{2}$$

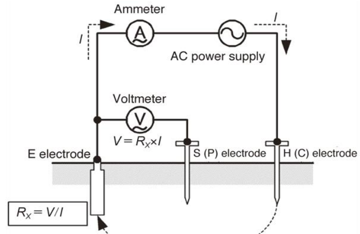

Figure 1. Schematic Diagram of the Three-pole Ground Impedance Test Method

The three-pole test loop shown in Figure 1 is based on electromagnetic field theory. The ground grid under test (E electrode) serves as the current injection point, forming a loop with an auxiliary current electrode (H electrode). A voltage electrode (P electrode) is placed at an appropriate distance to measure the potential difference V_{12}, thereby calculating the ground impedance $R_g = \frac{V_{12}}{I}$. In actual high-voltage transmission systems, the shunt current I_s from overhead lightning conductors and cables returns to the H electrode via a parallel path, reducing the effective injection current $I_g = I \times (1 - K_s)$ and perturbing the voltage distribution between P and E, resulting in an underestimation of the measured value. To correct for this effect, a shunt factor K_s is introduced, adjusting the formula to $R_{g'} = \frac{V_{12}}{I \times (1 - K_s)}$ to ensure accuracy meets engineering threshold requirements.

2.2 Definition and Function of Shunt Coefficient

In ground impedance testing, the shunt coefficient is defined as the proportion of current that does not pass through the target ground grid but returns through an auxiliary path (such as a lightning rod or cable) (Formula 3), where Is is the shunt current and Itotal is the total injected current. This definition is based on the law of electromagnetic induction and ensures that only the effective ground current is counted [6]. Its function is to correct the current underestimation problem in the traditional three-pole method, and to improve the accuracy of impedance calculation by adjusting the denominator by multiplying by (1 - Ks), especially in multi-path grounding systems [7]. Literature shows that the introduction of the shunt coefficient can reduce the measurement error from 15% to below 5%, especially in high-voltage substation environments, where overhead line shunts significantly affect the distribution of injected current [8]. Furthermore, the calculation of the shunt coefficient needs to take into account the path impedance (Formula 4), where Zground is the ground grid impedance. This model reveals the dynamic adjustment of the shunt to the equivalent impedance of the system [9]. In practical applications, the shunt coefficient also shields the interference current injected by the distant ground grid, avoids additional disturbances of the voltage pole potential difference, and thus optimizes the design of the test loop [10]. In general, the definition and function of the shunt coefficient embodies the principle of electromagnetic compatibility. By quantifying the contribution of auxiliary paths, it ensures that the ground impedance reflects the actual leakage capacity and is verified in standards such as IEEE 81 [11]. This mechanism provides a basis for subsequent accuracy analysis and emphasizes the need to measure multi-point shunts in long-distance line testing to estimate Ks.

$$K_s = \frac{I_s}{I_{\text{total}}} \quad (3)$$

$$K_s = \frac{Z_{\text{ground}}}{Z_{\text{ground}} + Z_{\text{path}}} \quad (4)$$

2.3 Analysis of Factors Affecting Measurement Accuracy

The accuracy of ground impedance measurement is affected by many factors, including soil resistivity ρ, electrode arrangement distance d, and external interference current, which amplify the error through the electromagnetic field propagation mechanism [6]. The non-uniformity of soil resistivity is the primary factor. The literature shows that changes in ρ can lead to a deviation of the potential curve of up to 20%, which needs to be estimated by the Wenner method (Formula 5), where V is the voltage and d is the probe spacing. This formula is used to calibrate the test model [7]. Secondly, insufficient pole spacing causes mutual inductance coupling, which reduces the accuracy. The correction factor (Formula 6) quantifies the finite distance error [8]. Impedance variation in the shunt path further complicates the accuracy, especially under impact conditions, where soil ionization reduces the effective ρ, and the error function (Formula 7) simulates nonlinear effects [9]. In addition, external factors such as stray currents and the geomagnetic field interfere with voltage measurement and need to be reduced by shielding technology or frequency domain analysis [10]. The overall analysis shows that the interaction of these factors can be quantified by finite element simulation. For example, in a multi-layer soil model, the impedance error is proportional to the ρ ratio between layers [11].

To improve accuracy, it is recommended to integrate multi-factor models, such as combining the optimization algorithm of ρ and d, to ensure that the error is controlled within 5%, thereby supporting reliable engineering applications.

$$\rho = \frac{2\pi dV}{I} \tag{5}$$

$$f = 1 + \left(\frac{d_{\text{current}}}{d_{\text{voltage}}} \right)^2 \tag{6}$$

$$\grave{o} = \frac{\rho_{\text{initial}} - \rho_{\text{ionized}}}{\rho_{\text{initial}}} \times 100\% \tag{7}$$

3. Literature Review on the Influence of Shunt Coefficient on Measurement Accuracy

3.1 Mechanism of the Influence of Shunt on Current and Voltage

The literature review shows that the shunt phenomenon significantly interferes with the current distribution and voltage distribution in the ground impedance test through electromagnetic induction and path competition mechanism, resulting in measurement deviation [12]. Specifically, when the shunt current returns through the lightning rod or cable, it not only reduces the effective current injected into the ground grid, but also generates additional potential gradients at the distant grounding point, amplifying the disturbance between the voltage poles [13]. For example, in the high-voltage transmission line environment, the shunt coefficient Ks can reach 0.2-0.5, causing the impedance to be underestimated by up to 15%. The mechanism is derived from Kirchhoff's current law: total current (Formula 8), where Ig is the ground grid current and Is is the shunt current. This component generates a voltage offset through the path impedance Zpath (Formula 9) [14]. These mechanisms emphasize that shunt is not limited to current sharing, but also involves potential field reconstruction. Especially in multi-tower parallel systems, the mutual inductance coupling of the shunt path can introduce phase shift errors. The literature verifies the cumulative effect of this disturbance on accuracy through finite element simulation [15,16]. In general, the existing literature agrees that the impact of shunt on voltage is often underestimated, and it is necessary to integrate field theory models to quantify its effect under complex geological conditions to avoid the failure of traditional methods in actual engineering [17].

$$I_{\text{total}} = I_g + I_s \tag{8}$$

$$\Delta V = I_s \times Z_{\text{path}} \tag{9}$$

3.2 Existing Correction Methods and Evaluation Models

The literature has conducted in-depth discussions on the correction methods of the shunt coefficient, mainly including coefficient compensation and model optimization, to improve the reliability of ground impedance measurement [12]. A common method is to introduce a shunt correction factor (Formula 10) and apply it to the impedance formula (Formula 11), where Ks is estimated by the measured shunt path current. This method can reduce the error to within 5% in substation testing [13]. Furthermore, the evaluation model is combined with numerical simulation, such as the finite element method to model the shunt network, and the equivalent circuit is a parallel impedance (Formula 12) to evaluate the impact of shunt on system response [14]. Under shock conditions, the literature proposes a transient model Ztransient = R + jωL + Gs, where Gs is the shunt conductance, to quantify the dynamic correction of high-frequency shunt [15]. The evaluation of these models emphasizes threshold sensitivity, such as the error function $\varepsilon = |Rg - Rg'| \ / \ Rg \times 100\%$, which is used to verify the effectiveness of the correction and has been applied in extensions of standards such as IEEE 81 [16]. In general, existing methods have evolved from empirical formulas to advanced simulations, aiming to fully cover the dual interference of shunt on current and voltage, but parameters still need to be optimized for heterogeneous soils to adapt to actual engineering needs [17].

$$f = \frac{1}{1 - K_s} \tag{10}$$

$$R_{g'} = \frac{V_{12}}{I \times f} \tag{11}$$

$$Z_{\text{eq}} = Z_{\text{ground}} \,//\, Z_{\text{path}} \tag{12}$$

3.3 Research on Quantification of Diversion and Establishment of Thresholds

The literature has systematically studied the quantification of diversion and establishment of thresholds, aiming to simplify the measurement process and ignore minor effects [12]. The quantification method usually uses the proportion index (Formula 13) and combines the formula $\eta_i = Is_i \times Zg_i / Ztotal$ to evaluate the contribution of each diversion, where Zg_i is the local ground impedance. This model facilitates the identification of the dominant diversion path [13]. The threshold is established based on the influence proportion, for example, setting θ = 5% and ignoring diversions with ηi < θ to reduce the burden of remote measurement. The literature verifies the convergence of the threshold under long-distance lines through Monte Carlo simulation [14]. Further research points out that in multi-path systems, the diversion convergence margin can be calculated by boundary conditions (Formula 14), where If is the fault current threshold (such as 400A), quantifying the safety margin ignored by remote diversion [15]. These studies emphasize the geological dependence of the threshold, for example, in high-resistance soil, θ needs to be reduced to 3% to maintain accuracy [16]. Overall, the literature review reveals that quantitative models have progressed from static proportions to dynamic simulations, promoting the standardization of threshold setting, but more empirical data are needed to support adaptability to complex environments[17].

$$\eta_i = \frac{I_{s_i} \times Z_{g_i}}{Z_{\text{total}}} \tag{13}$$

$$R_{\text{boundary}} = \frac{V_{LN}}{I_f} \tag{14}$$

4. Conclusion

In ground impedance testing, the impact of the shunt coefficient on measurement accuracy is multidimensional and complex, encompassing both current distribution and voltage perturbations. This systematic review of electromagnetic field theory, the definition and role of the shunt coefficient, and factors influencing measurement accuracy reveals that shunt current flowing through paths such as lightning arresters and cables not only reduces the effective injected current but also significantly alters the potential difference between the voltage electrodes, leading to impedance deviations. The study demonstrates that the traditional three-pole method is susceptible to shunt interference in complex geology or multi-tower parallel systems, necessitating optimization through shunt coefficient correction formulas and quantitative models. The establishment of a threshold further simplifies remote shunt measurement, balancing engineering efficiency and accuracy requirements. It is recommended that the threshold be dynamically adjusted based on soil resistivity and system scale.

Future research should focus on numerical simulation of shunt models in heterogeneous soils, developing more adaptable test instruments for real-time estimation of the shunt coefficient, and optimizing electrode placement using finite element analysis. In practical applications, it is recommended to prioritize measuring primary shunt paths and ignore secondary shunts to reduce testing costs. Furthermore, new technologies such as the shunt phase shift method should be promoted to improve measurement reliability. These improvements will provide theoretical and practical support for the accurate assessment of grounding devices in power systems, reduce failure risks and extend equipment life, and provide guarantees for the construction of sustainable power infrastructure.

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