Study of the high-frequency characteristics of grounding materials

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Abstract. Long-term safe and stable grounding system is the fundamental guarantee to maintain the stable operation of equipment and ensure the safety of staff. This paper investigates the high-frequency characteristics of several common grounding materials. Due to the skin effect, the axial impedance modulus, resistance part and reactance part of the conductor are all increase as the frequency. The results could provide reference and guidance for designing long-term reliable and stable grounding systems.

1 Introduction

Long-term safe and stable grounding system is the fundamental guarantee to maintain the stable operation of equipment and ensure the safety of staff [1,2]. The key to long-term stable operation of grounding system lies in the quality and reliability of grounding materials. In order to ensure the equipment and personal safety, the reliability of grounding grid has been put forward for a higher requirement.

For grounding engineering, corrosion is the most critical factor affecting the safety and service life of the grounding system on the premise that the design meets the electrical performance requirements [3]. However, the existing design sometimes does not consider the differences in soil corrosion in different regions, resulting in a short service life of the traditional steel grounding grid, and adversely affecting the safety and reliability of the grounding system. Judging from the excavation and maintenance data of the municipal bureaus, there are a large number of substations re-laid every year in my country due to the serious corrosion of the grounding grid, and that may not be economical and effective.

In this paper, based on the CDEGS simulation and FEM [4,5], the high-frequency characteristics of several common grounding materials is analysed firstly, and the trends of skin effect and impedance with the frequencies of current are obtained. Then the influence of the high-frequency characteristics on the grounding resistance is also discussed. Finally, considering the combined effect of soil resistivity and grounding grid, the trend of impulse grounding resistance and power frequency grounding resistance are obtained when different factors change simultaneously.

2 Analysis of high-frequency characteristics of grounding materials

2.1 Skin effect

Under an AC condition, the current density is greatest near the surface of the conductor, and then decreases exponentially from the surface to the interior. Since the current is mainly in the "skin" of the conductor, this phenomenon is called skin effect. The internal current density and axial impedance of the conductor can be calculated by skin effect, and the distribution of internal current density, impedance-frequency relationship and conductivity of the conductor can be analysed. Skin depth δ is defined as a depth where the current density is only 1/e (about 37%) of the surface value, depending on the frequency of the current and the electrical and magnetic properties of the conductor. The δ of grounding conductor can be calculated by formula (1).

$$\delta = \sqrt{\frac{1}{\pi f \sigma \mu}} \tag{1}$$

σ is the electrical conductivity of the material, μ is the magnetic permeability of the material, and f is the frequency. According to formula (1), the skin depth of different grounding materials under the action of current with different frequency are given, as shown in Table.1.

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Table 1. Skin depth of the different grounding materials.

Materials	Volume resistivity ($10^{-8}\Omega\bullet m$)	relative magnetic permeability	Skin depth (mm)						
			1Hz	50Hz	100Hz	1kHz	10kHz	100kHz	1MHz
Brass	7	1	133.159	18.831	13.316	4.211	1.332	0.421	0.133
Fine copper	1.75	1	66.579	9.416	6.658	2.105	0.666	0.211	0.067
Steel	9.78	636	6.241	0.883	0.624	0.197	0.062	0.020	0.006
Zinc	5.96	1	122.869	17.376	12.287	3.885	1.229	0.389	0.123
Stainless steel	48.9	10	111.295	15.739	11.129	3.519	1.113	0.352	0.111
Carbon	1375	1	1866.257	263.929	186.626	59.016	18.663	5.902	1.866

It can be seen that the skin depth decreases with the increase of frequency. The smaller the skin depth, the more obvious the skin effect, which reduces the effective cross-section of the conductor and increases the effective resistance.

2.2 Experimental study of high-frequency impulse characteristics of grounding materials

2.2.1 Impedance-frequency characteristics of copper

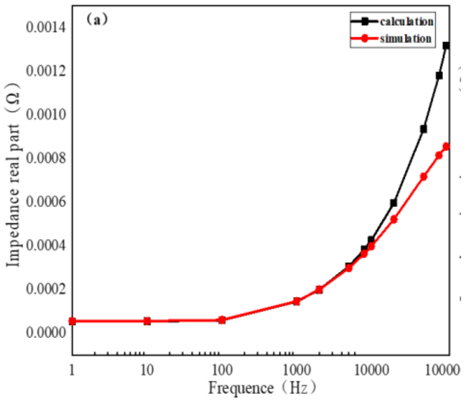
Theoretical and simulated calculations were carried out for a cylindrical copper grounding material with a radius of 10mm and a length of 1 m, and the results of the theoretical and simulated comparison are shown in Fig.1.

The impedance of the cylindrical conductor can be calculated by formula (2):

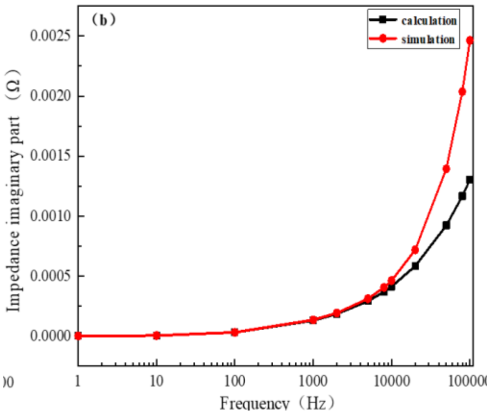
$$Z^c = \frac{j\omega\mu_c}{2\pi\sqrt{j\omega\sigma_c\mu_c}}\frac{I_0(a\sqrt{j\omega\sigma_c\mu_c})}{I_1(a\sqrt{j\omega\sigma_c\mu_c})} \qquad Z=Z^c l \qquad (2)$$

where, Z^c is impedance per unit length of conductor determined by material, l represents the length, σ_c and μ_c are conductivity and magnetic permeability, respectively. a is the respectively, I_0 and I_1 represent modified zero order and first order Bessel function of the first kind.

As can be seen from Fig.1, the copper impedance increases gradually as the frequency increases. When the simulation software is used to simulate the grounding material, the real and imaginary parts of the impedance are not much different from the theoretical values, so it is considered that this simulation model can be used to simulate the impedance-frequency characteristics of the ground material.



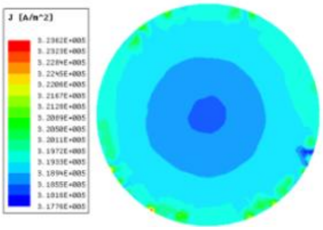
(a) real parts



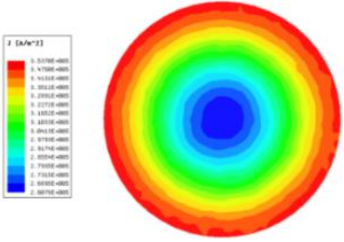
(b) imaginary parts

Fig.1. Theoretical and simulation values of (a)real and(b) imaginary parts of copper impedance

In addition, the current density distribution of copper end face at low frequencies was analyzed by the FEM to obtain the initial effective frequency of the skin effect, as shown in Fig.2. From Fig.2(a) and (b), it can be seen that the skin effect of copper starts to work from a frequency of 10Hz, and the skin effect becomes more obvious until the frequency increases to 100Hz. Meanwhile, it also can be seen from Fig.1, when the frequency increases to 100Hz, both the real and imaginary parts of the impedance start to increase more obviously.



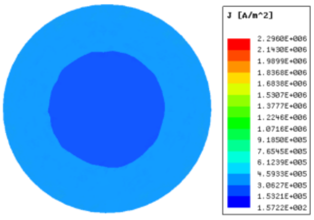
(a)10Hz



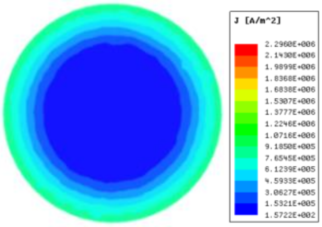
(b)100Hz

Fig.2. Current density distribution of end surface of copper at different low frequencies with (a)10Hz and (b)100Hz.

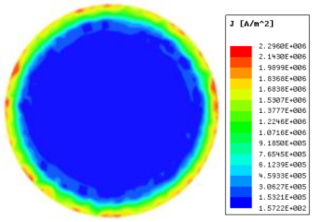
Then, the current density distribution of copper end face at different high frequencies was analysed to obtain the changing rule of copper impedance and the influence of skin effect, as shown in Fig.3.



(a)100Hz



(b)1000Hz

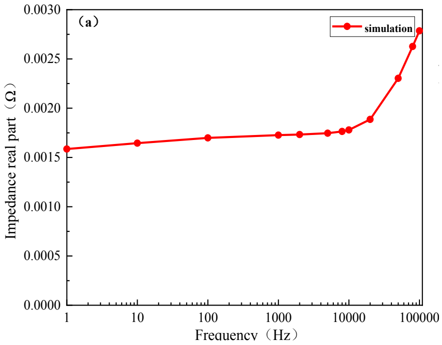


(c)10000Hz

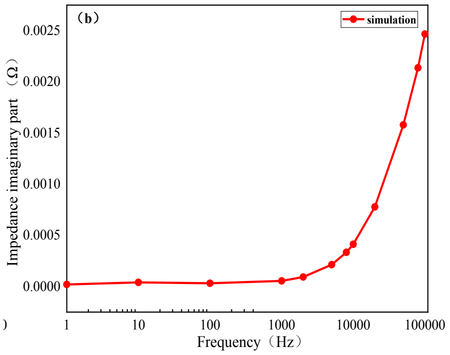
Fig.3. Current density distribution of end surface of copper at different high frequencies with (a)100Hz, (b)1000Hz and (c)10000Hz.

It can be seen that with the increase of frequency, the skin effect is gradually obvious, so that the current tends to flow near the surface. However, since the total injected current is constant, when the current flows along the edge, the current density increases, resulting in more concentrated current, which is equivalent to the equivalent area of the conductor decreases, resulting in a corresponding increase in impedance. To sum up, with the increase of frequency, the impedance of copper will gradually increase. Meanwhile, because the imaginary part of impedance has a great relationship with frequency, the imaginary part of impedance increases relatively fast.

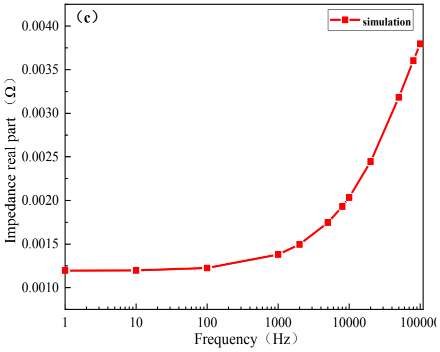
2.2.2 Impedance-frequency characteristics of copper clad steel



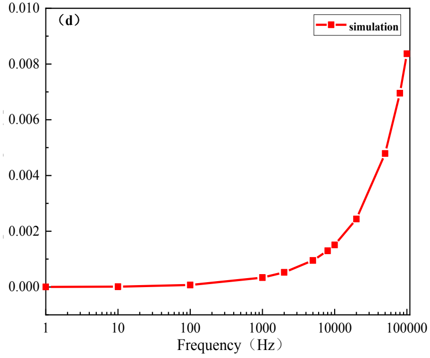
(a) real parts of cylindrical copper clad steel



(b) imaginary parts of cylindrical copper clad steel



(c) real parts of flat strip copper clad steel.



(d) imaginary parts of flat strip copper clad steel.

Fig.4. Simulation value of impedance of copper clad steel. (a) real and (b) imaginary parts of cylindrical copper clad steel. (c) real and (d) imaginary parts of flat strip copper clad steel.

Theoretical and simulated calculations were carried out for cylindrical copper clad steel (the radius of steel is 10mm, the thickness of outer copper coating is 0.7mm, and the length is 1m) and flat strip copper clad steel (steel with a cross-section of 12mm×6mm, outer copper with a thickness of 0.7mm and a length of 1 m), and the simulation results of impedance obtained are shown in Fig.4.

It can be seen that with the increase of frequency, the impedance real part and imaginary part of different shapes of copper clad steel will gradually increase, when the frequency is low, due to the current only has an impact on the impedance real part, the impedance imaginary part is basically 0. With the increase of frequency, the real part of the impedance changes little, until the frequency reaches a certain value (1000Hz), the impedance will have a significant change.

3 Influence of high-frequency characteristics of grounding materials on ground performance

The grounding resistances of three types of grounding grids, namely copper, steel and copper clad steel, were simulated and compared by using CDEGS under different soil resistivity conditions. Taking the grounding grid of a series compensation station as an example, the simulated area of the grounding grid is 278m×175m, the mesh is 15m×15m, and the grounding body is buried in a depth of 0.8m in the uniform soil. The simulation calculation results of grounding impedance are shown in Tab.2.

Table 2. Comparison of grounding resistance of copper, copper clad steel and steel grounding grids under different soil resistivity.

Soil resistivity (Ω•m)	Copper (Ω)	Copper clad steel (Ω)	Steel (Ω)
100	0.193 2	0.193 6	0.212 2
500	0.961 5	0.961 9	0.980 5
1000	1.921 9	1.922 3	1.940 9
2000	3.842 7	3.843 1	3.861 7

Tab.2 illustrate that the grounding resistance of the copper is slightly lower than that of copper clad steel and steel when the soil resistivity is the same, no matter in areas with high soil resistivity or low soil resistivity. For example, when the soil resistivity is 100Ω•m, the ground resistance of the copper is 0.1932Ω, which is 0.2% smaller than copper clad steel and 9.8% smaller than steel. Therefore, whether in areas with high soil resistivity or low soil resistivity, the grounding resistance of the grounding grid is similar when pure copper or copper clad steel are used.

4 Conclusion

In this paper, FEM and CDEGS are used to analyse the high-frequency characteristics of several common grounding materials and the influence of high-frequency characteristics on the ground performance. As the frequency increases, due to the skin effect, axial impedance modulus, resistance section and reactance section of the conductor all increase. The results could provide reference and guidance for designing long-term reliable and stable grounding systems.

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