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Realization of Harmonic Impedance Simulation Calculation Method for Grounding Grid in Substation

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Abstract. There is a difference between the actual impedance of substations' ground grid under harmonic interference and that measured under power frequency. Especially under strong harmonic interference, the difference becomes more obvious between the actual one and that measured under power frequency. A method is proposed in this paper to calculate parameters of ground grid models by measuring the ground grid impedances under power frequency and then calculate those under harmonic interference. This method is capable of solving the problem that it is impossible to measure the actual grounding impedance of substations operating under harmonic waves. The feasibility of the method is verified by means of simulating calculations. After correcting by this method, the grounding impedance modulus error becomes less than 2% and the impedance angle error less than 10%. This method may be applied to the measurement and analysis of grounding impedances of substations under harmonic interference.

1. Introduction
The currently effective methods to measure the grounding impedance are basically designed to measure those under power frequency. However, due to the complexity of actual working conditions, substations have to operate under strong harmonic waves in many conditions under which grounding impedances are different to those under power frequency, especially at DC convertor stations with strong harmonic earth currents. Strong harmonic waves can cause great disturbance to measurement signals, making the signals distorted and the accuracy of the measurement results seriously affected [1-4]. Besides, because it is required to prepare a harmonic source for field measurement and so on, it is difficult to directly measure the grounding impedance under harmonic waves. Therefore it is of great importance to find a method to compute the grounding impedance of large ground grids under harmonic interference.

2. Calculation thought and model

2.1. Basic thoughts
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The current, after being injected into the ground grid, will definitely leak into the earth while flowing in the axial direction of conductors. When using a constant current field to conduct ground grid analog computation, both the earth area and the conductor area have to be considered simultaneously for inequipotential calculation models and at the same time, the leakage current, the current in the axial direction and conductors' impedance have to be taken into account.

A lumped parameter model is used to represent ground grids. Each conductor of a ground grid is equivalent to a T-type unit composed of the equivalent impedance Z and leakage resistance Rd of the conductor [5-6]. The branch to which the equivalent impedance Z belongs is equivalent to the branch of the earth current in the ground grid; the branch to which the leakage resistance Rd belongs is equivalent to the leak current into the earth from the ground grid. See Fig.1 for an equivalent model of a single conductor in ground grids.

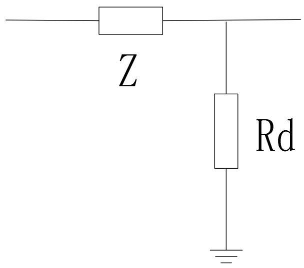


Figure 1. Equivalent model of a single conductor

What shown in Fig.2 is an equivalent model of ground grids composed of m×n meshes. Each mesh is equivalent to 4 T-type units end to end [7].

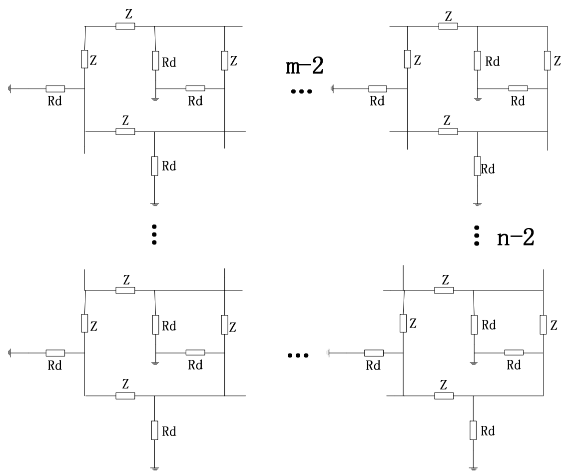


Figure 2. Equivalent model of multi mesh

In respect of the impedance measurement of large ground grids under strong harmonic interference, an equivalent model of the ground grids is established; simulation calculations in terms of the grounding impedance measured in the field under power frequency are carried out to determine the model parameters; the model is then applied to get the grounding impedance under various orders of harmonic waves. Firstly, the grounding impedance under power frequency is measured as per rules; secondly, an equivalent model of the ground grids is determined; thirdly, based on the grounding impedance measured under power frequency, the leakage resistance of the model is got; and finally the equivalent model of the ground grid is applied to get the grounding impedance under various orders of harmonic waves.

2.2. *Calculation of model parameters*

2.2.1. Calculation of equivalent impedance. The equivalent impedance Z of the conductor can be determined through basic parameter calculations of the conductor of ground grids, including the self-impedance Z_0 and the equivalent mutual impedance Z_M, i.e. $Z = Z_0 + Z_M$. Wherein the self-impedance:

$$Z_0 = R_{ac} + j\omega(L_{ac} + L_{ext}) \tag{1}$$

Due to the impact of skin effect, the AC resistance is greater than the DC resistance in the conductor. The AC resistance:

$$R_{ac} = \frac{a}{2\delta} R_{dc} \tag{2}$$

Wherein: a means the conductor's equivalent radius; $\delta = \frac{1}{\sqrt{\pi\mu\sigma f}}$ means the skin depth; $R_{dc} = \frac{\rho l}{\pi a^2}$ means the DC resistance; ρ means the conductor's conductivity; l means the conductor length.

Considering the skin effect, the interior AC self-inductance of the conductor:

$$L_{ac} = \frac{2\delta}{a} L_{dc} \tag{3}$$

The interior AC self-inductance L_{dc} can be obtained in accordance with the ampere circuit law. In $L_{dc} = \frac{\mu}{8\pi} l$, μ means the conductor's magnetic conductivity; l means the conductor length.

The exterior self-inductance of the conductor is equal to the mutual inductance between the thin section of the axis of the conductor and that of the surface of the conductor. The formula (4) to compute it is shown below:

$$L_{ext} = \frac{\mu}{4\pi} \int_{l_1} \int_{l_2} \frac{1}{r} dl_1 dl_2 \approx \frac{\mu l}{2\pi} \left(ln \frac{2l}{a} - 1 \right) \tag{4}$$

Wherein l_1 and l_2 respectively mean the route at the fine section of the axis and that at the surface; r means the distance from the source to the field point.

The formula (1-5) to compute the mutual inductance between the two sections is shown below:

$$M_{ab} = \frac{\mu_0 l}{4\pi} \int_{l_a} (\int_{l_b} \frac{1}{r} dl_b) \cdot dl_a \tag{5}$$

Wherein: la and lb respectively mean the paths of integration; r means the distance between the fine sections of conductor a and conductor b; μ_0 means the soil's magnetic conductivity.

2.2.2. Calculation of equivalent impedance. Since frequency has very little effect on the soil leakage resistance, it may be deemed as pure resistance [8]. Based on the measured grounding impedance under power frequency, the leakage resistance Rd can be calculated through simulating an equivalent model. See Fig.3 for the specific realization process. Assign Rd an initial value Rdi; apply it to an equivalent model of ground grids; conduct simulating calculations of the equivalent model to get simulation values of the grounding impedances under power frequency; compare them to those measured under power frequency; if the modulus and phase angles are within the error range, it is considered Rd=Rdi; otherwise, repeat the process above to get the value of Rd.

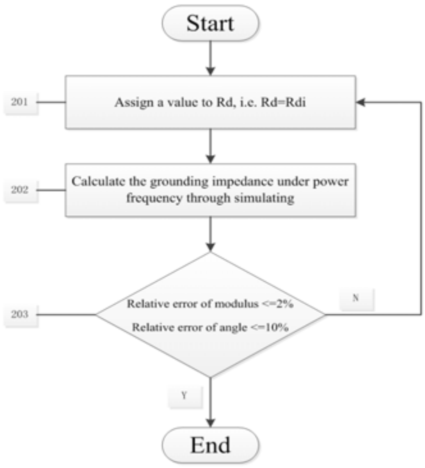


Figure 3. Solving process of leakage resistance

3. Constructing of ground grid models

In order to study measurement of grounding impedances under harmonic waves of substations' ground grids, a square measuring 100x100m^2, a ground grid with the space between ring conductors of 10m and a "7" ground grid are respectively adopted as the objects of study to calculate grounding impedances under harmonic interference. MATLAB is applied to construct equivalent models based on the structure of ground grids. See Fig.4 and Fig.5 for more details. The two models can represent most structures of substations' ground grids. The models shown in the figures are those with the current injection point around a corner; each mesh is corresponding to that of actual ground grids.

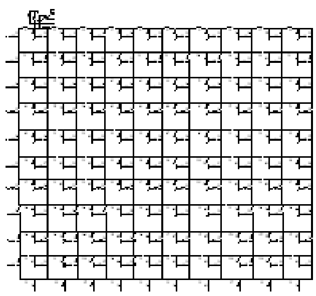


Figure 4. Equivalent model of regular ground grid

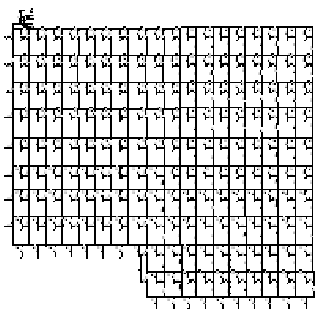


Figure 5. Equivalent model of "7" ground grid

4. Simulation and comparative analysis

Take the ground grid structures shown in Fig.4 and Fig.5 for example, after comparative analysis with the calculation results of CDEGS (a grounding analysis software package), comparative analysis is conducted for the measurement results of the grounding impedances under various orders of harmonic waves under different soil structures and those with different current injection points and the simulation results by means of CDEGS.

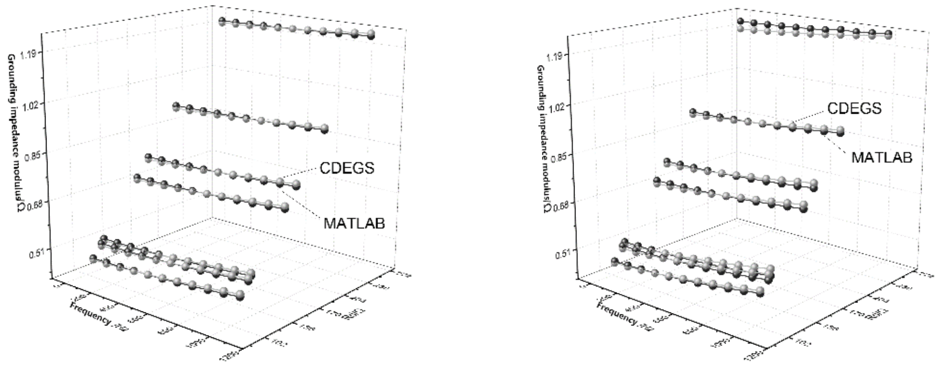
4.1. Simulation and comparative analysis under different soil structures

With the grounding impedances under power frequency calculated through CDEGS to substitute the said ones measured in the field, simulation calculations are carried out in respect of different soil structures Y. Take a three-layer soil structure for example which is classified into two types (type 1 with three layers of 50Ω•m/10m, 100Ω•m/30m and 1000Ω•m/∞; type 2 with three layers of 30Ω·m/10m, 200Ω·m/30m and 1000Ω·m/∞). Grounding impedances under power frequency in different working conditions are obtained; and then the leakage resistances Rd in different working conditions are calculated through simulation. See Table 1 for the impedances and leakage resistances of the two typical ground grid structure models. As shown in Table 1, there are obvious differences among the values of Rd calculated in different soil structures.

Table 1. Calculation of model parameters under three layer soil structure

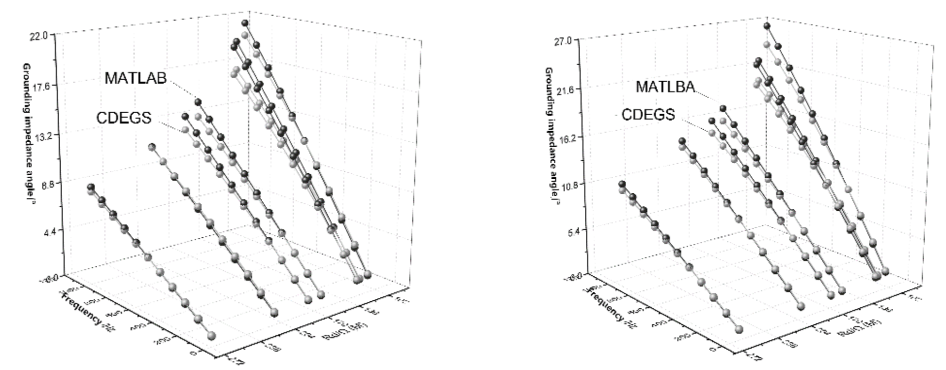
Soiltype	Grounding impedance under power frequency in regular ground grid (Ω)	Calculated value of Rd in regular ground grid (Ω)	Grounding impedance under power frequency in "7" ground grid (Ω)	Calculated value of Rd in "7" ground grid (Ω)
1	0.6998∠0.7772°	155	0.6859∠0.9662°	148.5
2	0.5173∠1.0250°	115	0.5148∠1.2722°	109.6

After determination of ground grid parameters, the grounding impedances under different harmonic waves are calculated through simulation of the constructed models; the values then are compared to the simulation results through CDEGS for analysis; the analysis tells that the grounding impedance modulus have a little error range and the absolute value of the relative errors is equal to or less than 2%. See Fig.6 for the comparison between curves of impedance modulus under various orders of harmonic waves corresponding to different leakage resistances calculated by the constructed models in the conditions with different earth resistivity and the simulation results of CDEGS.



a) Curves of regular ground grid model b) Curves of "7" ground grid model

Figure 6. Curve comparison of grounding impedance modulus under different leakage resistance



a) Curves of regular ground grid model b) Curves of "7" ground grid model

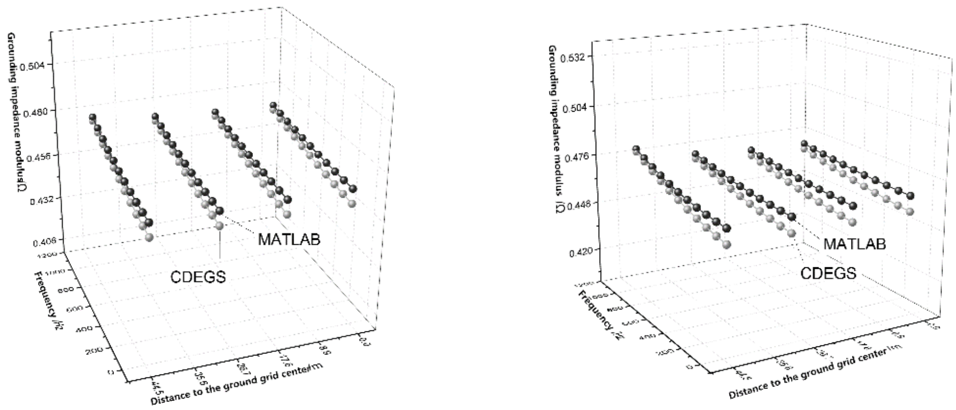
Figure 7. Curve comparison of grounding impedance angle of different leakage resistance

By comparison, it is found that the grounding impedance modules under harmonic frequency calculated by the constructed models are consistent with the calculation results of CDEGS.

Fig.7 shows the comparison between curves of grounding impedance angles under various orders of harmonic waves corresponding to different leakage resistances calculated by the constructed models and the simulation results of CDEGS in the conditions with different soil resistivity. With the increase of the harmonic order, the error of the impedance angle increases to some extent; but below the 21st harmonic waves, the relative error is less than 10%. This method may be applied to analysis of grounding impedance under general substations' harmonic waves.

4.2. Simulation and comparative analysis with different current injection points

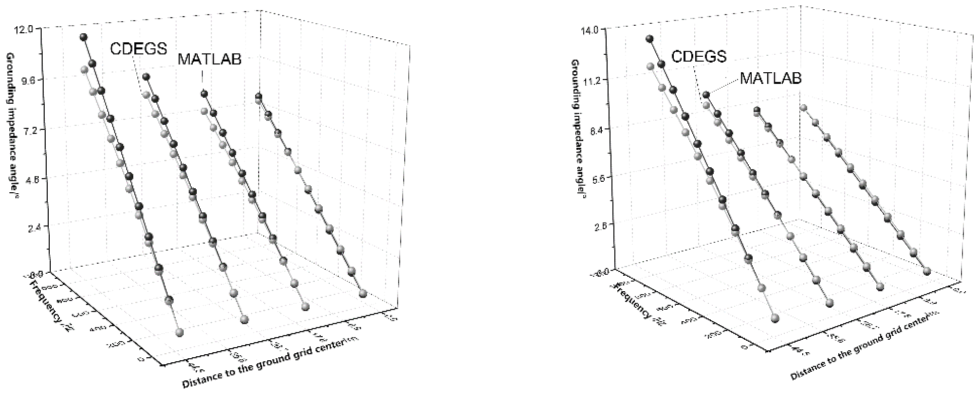
With the grounding impedances under power frequency calculated through CDEGS to substitute the said ones measured in the field, the grounding impedances under various orders of harmonic waves are calculated by means of the constructed models when changing the current injection point along the diagonal line of the ground grids and then they are compared with the simulation results of CDEGS for analysis. Fig.8 shows the comparison between the grounding impedance modulus under various orders of harmonic waves measured in the conditions of the two models and the simulation results of CDEGS with changes of the current injection point.



a) Curves of regular ground grid model b) Curves of "7" ground grid model

Figure 8. Curves of ground impedance modulus at different current injection points

By comparison, it can be told that with the increase of the distance between the current injection point and the ground grid center, the error of ground impedances under various orders of harmonic waves obtained through simulation is increasing gradually. The reason is that the error caused by edge effect of the ground grids is not taken into account in the models when the current injection point is at any edge of the ground grids. When the current injection point is at the center of the ground grids, the error is small.



a) Curves of regular ground grid model   b) Curves of “7” ground grid model

Figure 9. Curves of ground impedance at different current injection point

Fig.9 shows the comparison between the grounding impedance angles under various orders of harmonic waves measured in the conditions of the two models and the simulation results of CDEGS with changes of the current injection point. By comparison, it can be told that for the “7” ground grid model, when compared with the regular ground grid model, with the increase of the distance between the current injection point and the ground grid center, the error of ground impedances under various orders of harmonic waves obtained through simulation is increasing gradually. The reason is that the error caused by edge effect of the ground grids is not taken into account in the models when the current injection point is at any edge of the ground grids. When the current injection point is at the center of the ground grids, the error is small.

5. Conclusion

1) Ground grid equivalent models are constructed. The grounding impedances under power frequency measured in the field are applied to simulating calculations to determine mode parameters. The models are used to get grounding impedances under various orders of harmonic waves. The problem that it is difficult to measure the grounding impedances under strong harmonic waves is thus solved. By the proposed method with the regular ground grid model and “7” ground grid model as the study objects, measurement, modeling and simulating of grounding impedances under harmonic waves are conducted, which verifies that compared with the grounding impedances obtained through simulations, the error of the impedance modulus of ground grids after correction by the method is less than 2% and the error of the impedance angles is less than 10%.

2) After calculation in different soil structure conditions and with different current injection points, when measuring the grounding impedance under power frequency, if the current injection point is set at the ground grid center, the error between the grounding impedances calculated under harmonic waves and the actually measured ones is at the minimum level.

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