

Article

Effects of Introducing Confluence Rings on Ground Loss Resistance of VLF Umbrella-Type Antenna

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Abstract: In this work, we analyze the influence of introducing confluence rings on the ground loss resistance in the ground grid system of the VLF umbrella-type transmitting antenna. The geometric deconstruction model of the confluence ring, the model of the VLF umbrella-type transmitting antenna, the models of the umbrella-type antenna ground grid system, and the formulae for the average conductivity are established. The working principle of the confluence ring was analyzed, and the ground loss resistance of the confluence ring structure with different numbers of layers and varying degrees of wire damage was simulated using Feko. The simulation results demonstrated the effect of increasing the number of confluence ring layers on the ground loss resistance of a fully functional grid to be relatively weak. However, when the ground grid wire is broken, the confluence ring structure can effectively reduce the ground loss resistance, thereby improving the radiation efficiency of the antenna.

Keywords: confluence rings; ground loss resistance; umbrella-type antenna; VLF



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1. Introduction

Very-low-frequency (VLF) communications use long wavelengths and a frequency range of 3–30 kHz for transmissions. The transmitting antenna is usually electrically small, with a low radiation resistance and a large ground loss resistance, resulting in inefficient radiation [1,2]. A large-scale ground network system is laid out in order to reduce the ground loss resistance and improve the radiation efficiency of the VLF shore-based transmitting antenna. The ground grid system of the VLF umbrella-type transmitting antenna is composed of ground grid wire, confluence ring, ground well, etc. (Figure 1). The confluence ring is a safety mechanism which acts as a bridge, electrically reconnecting the functional parts of a grid when a part of it breaks or corrodes, so as to avoid a sharp loss of resistance. Arthur Watt (1973) first elaborated on the calculation method for the ground loss resistance in the ground grid system [1]. Liu Chao et al. (2008) further expounded on the calculation of ground loss resistance for the umbrella-type antenna [2]. Furthermore, Ganlai Dai et al. (2018) analyzed and calculated the ground loss resistance of the large VLF umbrella-type antenna [3]. This was followed by the derivation of the equivalent admittance for the ground grid wire of the VLF umbrella-type transmitting antenna and the conductivity of the ideal and non-ideal ground grid wire model by Li Bin (2019) [4]. They established the models through Feko for simulations, with their predictions coming very close to the actual engineering results [4]. However, currently, there exists no literature on the calculation of conductivity for the ground grid system model (referred to as the ground grid system model). It is quite necessary to deduce this formula to improve the accuracy of the simulations to produce better predictions.

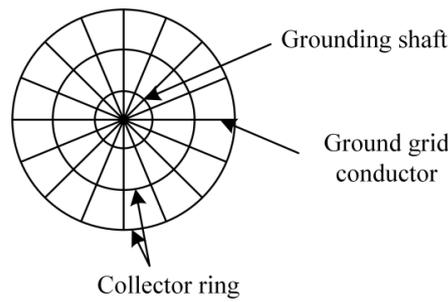


Figure 1. Structure of the ground network of the VLF umbrella-type transmitting antenna.

2. Theoretical Research on Confluence Ring and the Ground Grid System

2.1. Working Principle of the Confluence Ring

As shown in Figure 2a, the red region indicates the fully functional areas of the ground grid wire; the green area is the area where the ground grid wire cannot work normally due to corrosion or fracture; the blue area is the area where the ground grid wire cannot work normally due to the damage of the ground grid copper wire in the green area; and the inner network copper wire in the area around the green area connected with the confluence ring cannot work normally (in the antenna near field area, the current flow in the ground grid wire is from the distance to the antenna root). In the absence of the confluence ring, if the copper wire of the ground grid gets damaged at a certain point, it will, in turn, damage all the other ground grids connected to it. This greatly reduces the current conducting efficiency of this region, having a huge impact on the ground loss resistance. Through the analysis of Figure 2b,c, it can be seen that the damaged area associated with the ground grid gradually reduces after laying the confluence ring. If the two edges of the damaged ground grid area are attached to the two layers of the confluence ring, the effect of the damage becomes nullified, minimizing its influence on the ground loss resistance.

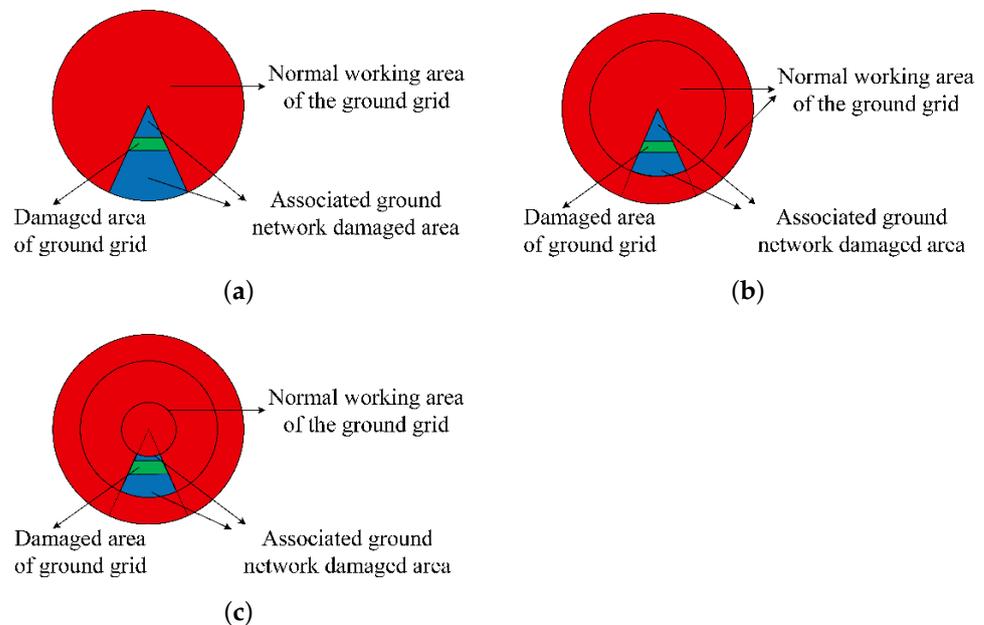


Figure 2. Schematic diagram of the different working conditions of the ground grid system. (a) In the absence of confluence rings; (b) after laying a few confluence rings; and (c) after laying multiple manifolds.

2.2. Geometric Deconstruction and Equivalent Conductivity Calculation of Flow Manifold Ring

The deconstructed geometric model of the confluence ring in the ground grid system is shown in Figure 3.

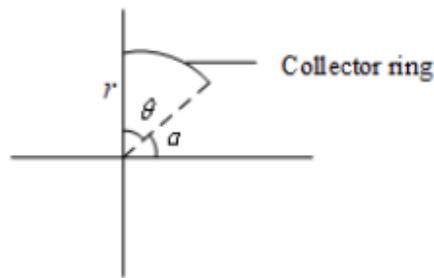


Figure 3. Geometric deconstruction of the confluence ring.

The vector magnetic potential of the confluence ring is given as

$$\vec{A} = \frac{\mu}{4\pi} I r \frac{e^{jkl}}{l} d\theta \vec{e}_\theta, \tag{1}$$

where μ is the permeability of the confluence ring, I is the current on the confluence ring, k is the wave number, l is the arc length between two points on the confluence ring, r is the radius of the confluence ring, θ is the angle between two points on the confluence ring, and e_θ is the unit angle vector in the polar coordinates.

According to Biot–Savart law, the electric field generated by the confluence ring can be obtained as

$$\vec{E} = \frac{j\omega\mu}{4\pi} I r \int \frac{e^{jkl}}{l} d\theta \vec{e}_\theta. \tag{2}$$

From Figure 2, we obtain

$$l = r\theta. \tag{3}$$

Combining Equations (1)–(3), we obtain [5,6]

$$\vec{E} = \frac{j\omega\mu\theta}{4\pi r(1 - jkr)} J(e^{jkr(\alpha+\theta)} \ln(\alpha + \theta) - e^{jkr\alpha} \ln \alpha) \vec{e}_\theta, \tag{4}$$

where J is the current density of the confluence torus.

Assuming that the confluence ring is made of an ideal conductor, due to the extremely long wavelength of VLF communication, the characteristic admittance of the non-ideal ground and the confluence ring is given as

$$Y = \sqrt{\left(\epsilon_1 - \frac{j\sigma}{\omega}\right) / \mu_t - j \frac{4\pi r(1 + k^2 r^2)}{\omega\mu(\beta - \alpha) [\ln \beta(1 - k^2 r^2 \beta) - \ln \alpha(1 - k^2 r^2 \alpha)]}}, \tag{5}$$

where ϵ_1 is the dielectric constant, σ denotes the electrical conductivity, and μ_t denotes the magnetic permeability of the soil.

$$L = \frac{4\pi r(1 + k^2 r^2)}{\omega\mu(\beta - \alpha) [\ln \beta(1 - k^2 r^2 \beta) - \ln \alpha(1 - k^2 r^2 \alpha)]} \tag{6}$$

Let the equivalent characteristic admittance of the earth and the confluence ring be Y_α such that

$$Y_\alpha = \sqrt{\frac{\epsilon_1 - \frac{j\sigma(r)}{\omega}}{\mu_t}}. \tag{7}$$

Now, Equations (6) and (7) can be used to obtain the formula for the equivalent conductivity of the Earth and the confluence ring structure as

$$\sigma(r) = \sigma + Re\left(\sqrt{\frac{\epsilon}{\mu_t} + \frac{L^2}{4}} * (2L\omega\mu_t)\right). \tag{8}$$

Substituting the obtained results for those of study [3] for calculation, the formula for the average conductivity of the ground grid system model is obtained as

$$\sigma_e = \sigma + \frac{1}{b} * Re \left\{ \int_0^b \sqrt{\frac{\epsilon}{\mu_t} + \frac{L^2}{4}} \right\} + \frac{1}{r_2 - r_1} \int_{r_1}^{r_2} \frac{\sqrt{\frac{2\sigma\omega}{\mu_t}}}{f d \ln\left(\frac{d}{2\pi a}\right)} dr, \quad (9)$$

where r_1 and r_2 specify the ground network laying range, f is the operating frequency, ω represents the angular frequency, d is the arc length between adjacent ground network lines, a is the ground network wire diameter, and b is the confluence ring wire diameter.

2.3. Umbrella-Type Antenna vs. Ground Grid System

The VLF umbrella-type transmitting antenna model is established according to the Cutler antenna in the United States. The antenna structure parameters are as follows: the heights of the outer, inner, and center ring towers are 243 m, 266 m, and 298 m, respectively, and the radius of the inner and outer ring towers are 559 m and 960 m, respectively (Figure 4). Antenna sag is considered in the modeling process, and the wire is pulled. The wire conductivity is not considered [1,2], as the actual projected data from the past suggest that the wire loss resistance is essentially negligible compared to the total resistance. The support and radiation structure of the umbrella antenna are made of PEC. The top load of the umbrella is composed of six evenly distributed rhomboid antenna curtains, with a top capacitance line running on top of each curtain. The midpoint of each top capacitance line is connected to the by-pass lines of the two inner ring towers. The end points of the top capacity line are connected with the outer ring tower and the central tower, and the arc sag of the top capacitance line is 5%. Insulators are installed at the connections between all the top capacity lines and the inner ring tower, the outer ring tower and the central tower, and the insulators are replaced by 10 pF capacitors. The non-ideal geodetic conductivity was 0.01 S/m, the relative permittivity was 20, and the magnetic permeability was 3.6×10^{-3} H/m. Each antenna group is equipped with a radiant ground grid, buried at a depth of 0.5 m under the ground. Two hundred conductors with a length of 1200 m and a diameter of 0.004 m are uniformly laid, with operating frequencies at 15 kHz, 18 kHz, 20 kHz, and 24 kHz, respectively.

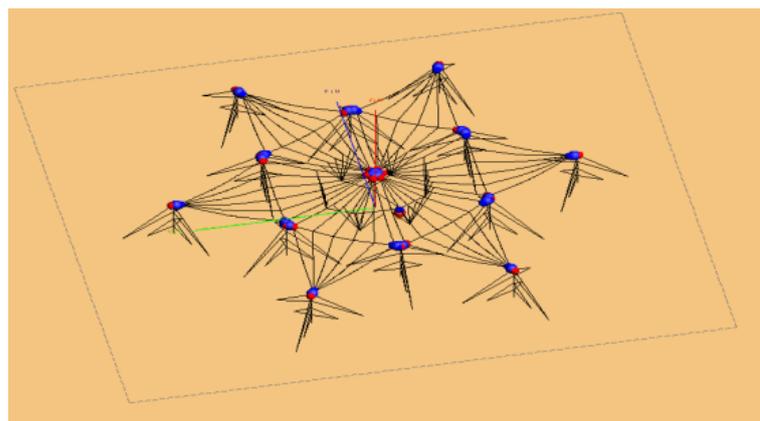


Figure 4. Model diagram of VLF umbrella-type transmitting antenna.

Eight different models were built in the FEKO software for each mentioned frequency. Firstly, under the condition that all the wires function normally, the ground grid system models with 2, 3, and 6 layers of confluence rings (referred to as the first type model) are uniformly established within a range of 1200 m, as shown in Figure 5.

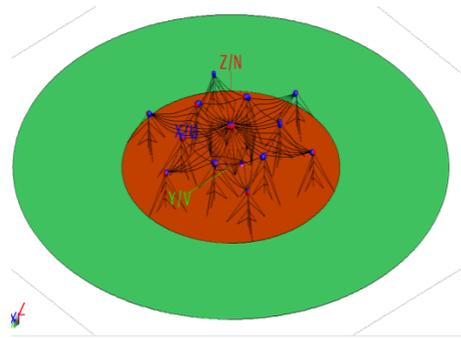


Figure 5. Schematic diagram of the first type model; the dark area is the ground network and the light area is the non-ideal ground.

With reference to Figure 3, establish a collector ring when laying the VLF umbrella antenna model (hereinafter referred to as the second category of the first model); a confluence ring when the VLF umbrella antenna model is not laid (hereinafter referred to as the second category of the second model); and the second category of the first model being laid refers to the convergence of the three layers of ring, with ground wire damage numbers of 10, 20, 30, 40 and 50. This is shown in Figure 6.

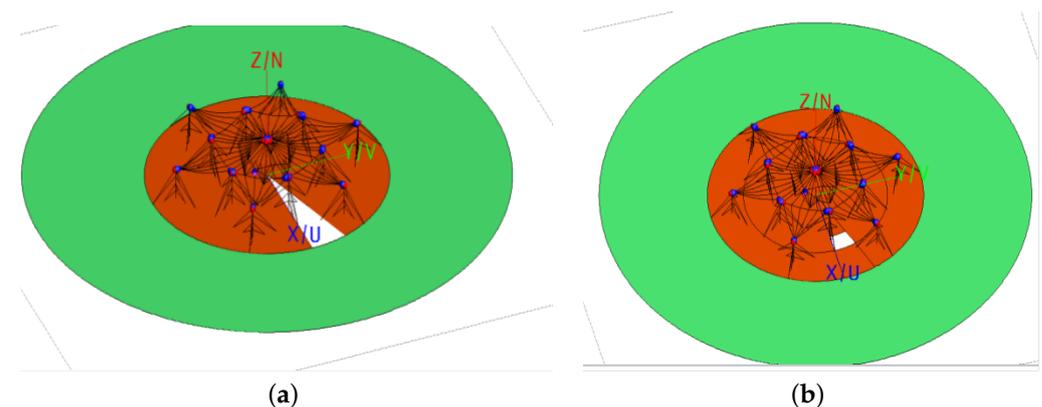


Figure 6. Schematic diagram of the second type model; the darkly colored area is the functional part of the ground network, the lightly colored area is the non-ideal ground, and the blank area is the fracture in the ground network: (a) The first model. (b) The second model.

The two-type ground grid system model consists of a circular conductive medium plane with a thickness of 0.5 m. This plane is divided into three regions: (i) the functional and (ii) the damaged area of the ground grid wire, and (iii) the non-ideal ground. The dielectric constant and magnetic permeability of the conductive media in the former two regions are the same as that of the non-ideal ground. The conductivity of the damaged area of the ground grid wire and the non-ideal ground area is 0.01 S/m, and that of the functional area is then calculated using Equation (9).

3. Simulation Prediction and Analysis

3.1. Influence of the Number of Layers of Confluence Ring on Ground Loss Resistance

According to the antenna structure parameters in Section 2.3, a 3D VLF umbrella-shaped transmitting antenna model is simulated in Feko. The antenna is constructed using PEC, and the geodetic parameters corresponding to different models are set according to Section 2.3. In the calculation of antenna radiation resistance, the earth is considered to be an infinitely ideal earth. The non-ideal geodetic model is a concentric circle composed of different conductive media planes, and the radius of the outermost circle is the wavelength corresponding to the operating frequency of the antenna divided by 2π .

When the 200 ground grid two-layer, three-layer, and six-layer convergence ring models are laid, the average conductivity is calculated to be 0.0469 S/m, 0.0471 S/m, and 0.0477 S/m, respectively. These values were imported into the FEKO simulations, and the ground loss resistance of the first type model was calculated.

According to Figure 7, under the condition that all the ground grid wires are working normally, with the increase in the number of confluence ring layers, the earth loss resistance changes weakly, and the value change is less than 1%. It can be seen that the influence of the confluence ring on the ground loss resistance is not obvious when the ground grid wire is working normally.

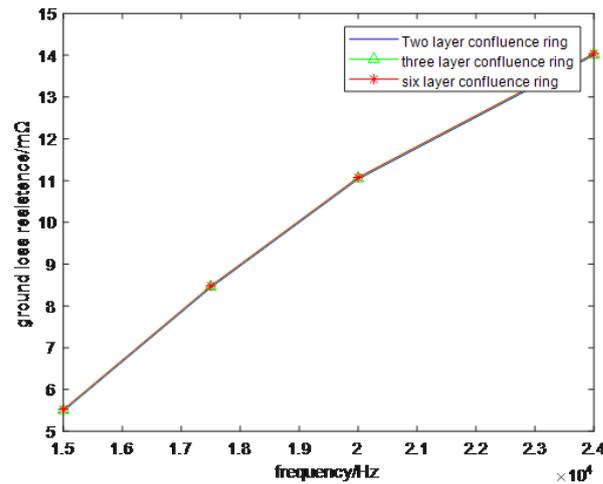


Figure 7. Ground loss resistors with different layers of manifold rings.

3.2. Influence of the Confluence Ring on the Ground Loss Resistance of Damaged Ground Grid Wires

For the second type of geodetic structure model, the calculation results of ground loss resistance are shown in Figure 8 and Tables 1 and 2. In case (A), all the ground grid wires are fully functional; in case (B), the ground grid wires are broken but the confluence ring is laid; and in case (C), the ground grid wires are broken and the confluence ring is not yet laid.

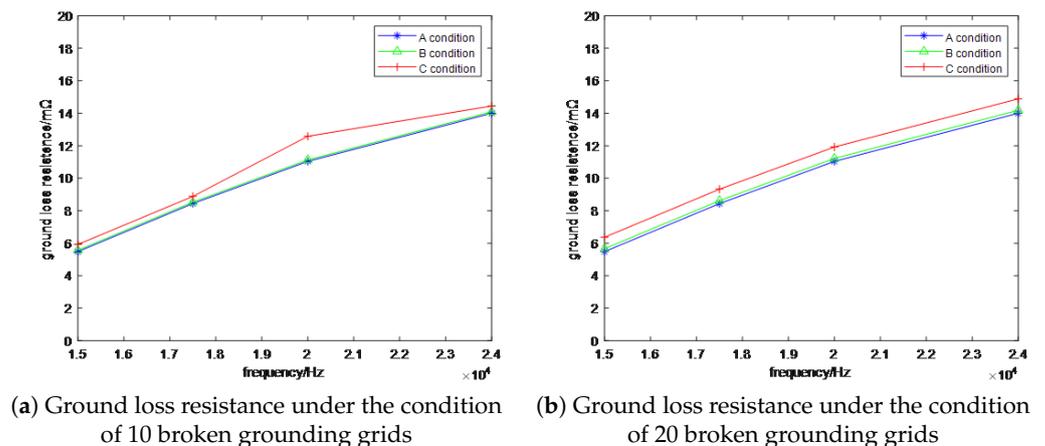


Figure 8. Cont.

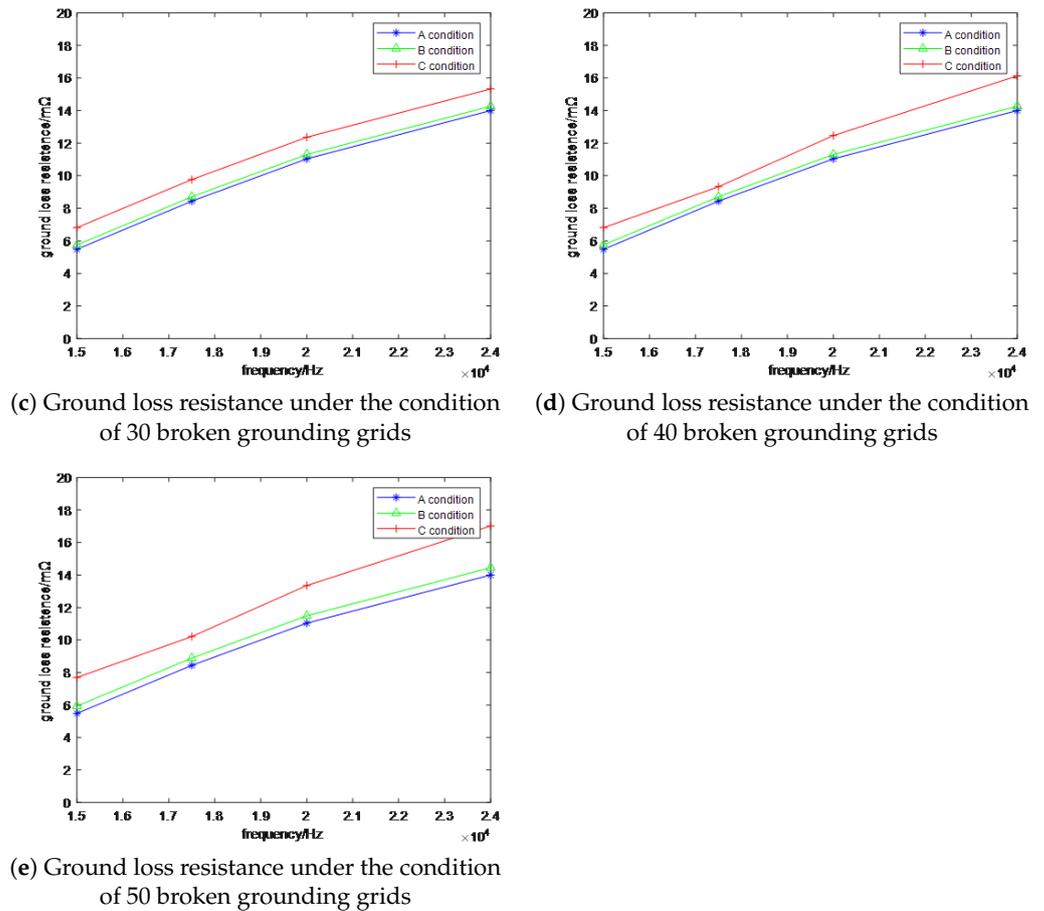


Figure 8. Earth loss resistance under the three conditions A, B and C.

When the working frequency is 20 kHz, the percentage of improvement between the ground loss resistance of the second type of model and that of the corresponding fully functional ground grid (referred to as the normal resistance) is shown in Table 1.

Table 1. Percentage increase in earth loss resistance under B and C conditions.

| | 10 | 20 | 30 | 40 | 50 |
|---|-------|------|------|-------|-------|
| B | 0.42% | 0.9% | 1.1% | 1.6% | 2.0% |
| C | 4.2% | 8.7% | 12% | 17.1% | 20.4% |

When the operating frequency is 20 kHz, the radiation efficiency of the second type of model antenna is shown in Table 2.

Table 2. The radiation efficiency of the antenna under two conditions B and C.

| | 10 | 20 | 30 | 40 | 50 |
|---|--------|--------|--------|--------|--------|
| B | 70.67% | 70.65% | 70.62% | 70.60% | 70.58% |
| C | 70.67% | 70.54% | 70.41% | 70.28% | 70.15% |

According to Table 1, when compared to the normal resistance scenario, when 10, 20, 30, 40 and 50 ground grid wires are broken, the percentage increase in the resistance of case B was 0.42%, 0.9%, 1.1%, 1.6% and 2.0%, respectively, and the radiation efficiency was 70.67%, 70.65%, 70.62%, 70.60% and 70.58%, respectively. Whereas, for the same testing

conditions, the percentage increase in the resistance of case C was 4.2%, 8.7%, 12%, 17.1%, and 20.4%, respectively, and the radiation efficiency was noted to be 70.67%, 70.54%, 70.41%, 70.28%, 70.15%, respectively. When the confluence ring is laid, the percentage increase in resistance is up to 2%, and that of radiation efficiency is down to 0.12% at most. Without the confluence ring, the percentage increase in resistance goes up to 20.4%, and that of radiation efficiency goes down to 0.52% at most. It is clear that when a multi-layer confluence ring is laid (which effectively reduces the damaged area associated with the ground grid), it reduces the ground loss resistance, and improves the radiation efficiency.

4. Summary

In this paper, the characteristic admittance of the ground grid confluence ring of the VLF umbrella-type transmitting antenna is derived, and the formula for the average conductivity of the equivalent model is obtained. The ground loss resistance is analyzed through Feko simulations for varying numbers of confluence rings and different degrees of damage to the wires. The following conclusions were drawn: (1) When the ground grid is functioning normally, the impact of the increasing number of the confluence ring layers on the ground loss resistance is minimal, and the percentage increase is far less than 1%. So, the effect of the confluence ring structure on the ground conductivity is not very obvious. (2) When the ground wire is damaged, the ground loss resistance increases with the number of damaged wires. In this case, introducing confluence ring layers into the ground grid system can substantially reduce the ground loss resistance and improve the antenna radiation efficiency.

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References

1. Watt, A.D. *Very Low Frequency Radio Engineering*; Translation; National Defense Industry Press: Beijing, China, 1973.
2. Liu, C.; Jiang, H.; Huang, J. *Very Low Frequency Communication*; Haichao Publishing House: Beijing, China, 2008.
3. Dai, G.; Dong, Y.; Kang, Y. Analysis and Calculation of Ground Loss Resistance of large VLF Umbrella-type Antenna. *Commun. Technol.* **2018**, *33*, 483–489.
4. Li, B. *Research on Radiation Characteristics of Very Low Frequency Current Antenna and Very Low frequency Umbrella-Type Antenna Array*; Wuhan Naval University of Engineering: Wuhan, China, 2019.
5. Feng, C.; Ma, X. *Engineering Electromagnetic Field*; Higher Education Press: Xi'an, China, 2011.
6. Jin, J. *Computational Electromagnetics*; Publishing House of Electronics Industry: Beijing, China, 2018.