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Research Article

Analysis of the Electrical Performance of Multituned VLF Thirteen-Tower Umbrella Antennas

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The concept of multituned thirteen-tower umbrella antenna is developed in this study to address the problem that increasing the power capacity of a single-tuned VLF transmitting antenna leads to a decrease in self-resonance. The calculation method of electrical parameters such as input resistance and radiation efficiency is theoretically analyzed based on the radiation resistance of different antenna units in a thirteen-tower umbrella antenna, and the electrical performance of the single-tuned and multituned thirteen-tower umbrella antennas is simulated and compared with the measured results of the Cutler antenna. Under the same antenna structure parameters and input power, the antenna radiation efficiency of the multituned thirteen-tower umbrella antenna is basically the same as that of the single tuned one. However, the multituned antenna has lower input current and higher self-resonance, which can effectively improve the antenna's safety and broaden its operating frequency range.

1. Introduction

Very low-frequency (VLF) communication have been widely used in areas such as maritime and submarine communication [1–3]. Generally, a VLF transmitting antenna is an electrically small antenna placed on the ground [4, 5]. Compared to other VLF transmitting antennas (such as the T-shaped antenna), the umbrella antenna has a low reactance and high radiation efficiency [6–8]. The radiation power of the antenna directly determines the distance of communication, and the power capacity of a VLF transmitting antenna is closely related to the size of the antenna [9]. When the antenna height is limited, the power capacity of the umbrella antenna can mainly be improved by increasing the area of the top load. However, increasing the top load will increase the static capacitance of the antenna, resulting in a decrease of the antenna's self-resonance [10], and increasing the power will increase the input current, which makes the antenna tuning more difficult [11, 12].

According to the technical reports of the Cutler and the NWC antenna [13, 14], the static capacitance of NWC antenna is increased by 31.2% and the radiation power is increased by 47.3% when compared to the Cutler antenna, which leads to an increase of 11.5% in input current and a decrease of 14.9% in self-resonance, and this has created a negative impact on the safety and operating frequency range of the antenna. To make the Cutler antenna the first to achieve 1 MW radiated power, Wheeler suggested using a cell approach that could be repeated to expand the antenna size as required [15], and in the final design, two identical thirteen-tower umbrella antennas were included to form the Cutler antenna, which solved the problems of excessive input current and low self-resonance of high-power VLF antenna at the cost of multiplying the construction cost. In the case of the NWC antenna, the operating frequency had been changed from 22.3 kHz to 19.8 kHz in 1991 [14]. Although it is unclear whether this change is related to the lower self-resonance, it does reduce the antenna's bandwidth and raise the security risk.

To better resolve this contradiction, the concept of multituned thirteen-tower umbrella antenna is proposed in this study. Rather than tuning the six diamond-shaped top loads of a thirteen-tower umbrella antenna as a whole, this study innovatively proposes to split the diamond-shaped top loads of a single thirteen-tower umbrella antenna into different antenna units and employ multituning to tune the antenna units. The multituned thirteen-tower umbrella antenna can maintain a lower input current and a higher self-resonance while increasing the antenna's radiated power, according to theoretical analysis and simulation, as well as comparing with the existing single-tuned VLF thirteen-tower umbrella antennas (e.g., the Cutler antenna and the NWC antenna). The high-power thirteen-tower umbrella antenna's operating frequency range and safety can both benefit from this.

2. Radiation Efficiency of Single Tuning and Multituning

The VLF thirteen-tower umbrella antenna is an electrically short top-loaded monopole antenna. The top load of the antenna is made up of six diamond-shaped panels. These panels are formed by eight wires that run out from the antenna center and one catenary wire for support [13] (see Figure 1(a)). Six groups of diamond-shaped top load and down lead are symmetrically distributed around the central tower, and each diamond-shaped top load and down lead can be used as a separate antenna unit, and the distance between each antenna unit is very small relative to the wavelength, so the currents are essentially equal in amplitude and phase, which can form a multituned antenna. The multituned antenna uses one antenna unit as the main antenna unit, which is directly fed by the transmitter, and the other antenna units as deputy antenna units, which are grounded through the tuning coils. By changing the number and electrical connection of the tuning coils at the bottom of the antenna, they can have the following tuning modes:

(1) Six diamond-shaped panels are connected in parallel to form a single-tuned antenna (see Figure 2(a)).

(2) Each diamond-shaped panel is used as an antenna unit (hereinafter referred to as 1 panel antenna unit, see Figure 1(a)), with a total of six antenna units form a "one main and five deputy" multituned antenna (see Figure 2(b)).

(3) Every two diamond-shaped panels are connected in parallel as an antenna unit (2 panel antenna unit, see Figure 1(b)), and a total of three antenna units form a "one main and two deputy" multituned antenna (see Figure 2(c)).

(4) Every three diamond-shaped panels are connected in parallel as an antenna unit (3 panel antenna unit, see Figure 1(c)), and a total of two antenna units form a "One main and one deputy" multituned antenna (see Figure 2(d)).

2.1. Radiation Resistance of Different Antenna Units. The VLF thirteen-tower umbrella antenna can be regarded as composed of six monopole antennas with diamond-shaped top load. Assuming that the radiation resistance of one single monopole antenna with diamond-shaped top load is R_r and the effective height is h_e, then there are [16]

$$R_r = 160\pi^2\left(\frac{h_e}{\lambda}\right)^2, \tag{1}$$

where λ is the free space wavelength.

The effective height h_e is related to the static capacitance C_0 of the antenna. The antenna static capacitance is mainly composed of two parts, namely, the ground capacitance C_V of the down lead and the ground capacitance C_H of the diamond-shaped top load. Because both C_V and C_H are ground capacitance, so there are

$$C_0 = C_V + C_H. \tag{2}$$

Assuming that the physical height of the antenna is h, the relationship between the static capacitance C_0 and the effective height h_e of the antenna is

$$h_e = \frac{1}{C_0}\cdot\frac{h\cdot(C_0 + C_H)}{2}, \tag{3}$$

m identical monopole antennas with diamond-shaped top load are connected in parallel to form a single-tuned antenna unit, in this study, $m = 1$, 2, 3, and 6, as shown in Figure 1.

Ignoring the difference of each monopole antenna, the static capacitance C_0' of the new antenna unit is

$$C_0' = C_V' + C_H' = C_V + mC_H. \tag{4}$$

The physical height of the newly formed antenna units is still h, and the effective height h_e' of the new antenna units can be calculated from equation (3):

$$h_e' = \frac{1}{C_0'}\cdot\frac{h\cdot(C_0' + C_H')}{2} = \frac{h}{2}\cdot\frac{C_V + 2mC_H}{C_V + mC_H} \geq h_e. \tag{5}$$

As can be seen from equations (1) and (5), the effective height of the antenna unit composed of m monopole antennas with diamond-shaped top load connected in parallel increases with the increase of m, so the radiation resistance of the antenna unit also increases with the increase of m (i.e., the increase of the diamond-shaped top load area), and the increase volume is related to the ratio of C_H and C_V. As shown in Figure 3, when C_H/C_V is greater than 7, the increase of effective height of each antenna unit is within 5%, and the greater the ratio, the smaller the increase. In the actual high-power VLF thirteen-tower umbrella antenna, the value of C_H/C_V is generally large, so the effective height of each antenna unit does not change much. It shows that increasing the area of the top load on the basis of a diamond-shaped top load does not contribute much to the improvement of the antenna's effective height. As a result, the antenna units shown in Figure 1 have a similar radiation resistance.

2.2. Input Resistance of Each Antenna Unit in a Thirteen-Tower Umbrella Antenna. A thirteen-tower umbrella antenna can be regarded as composed of multiple antenna units. The input impedance of each antenna unit is composed of two parts, one is the radiation impedance, and the other is the

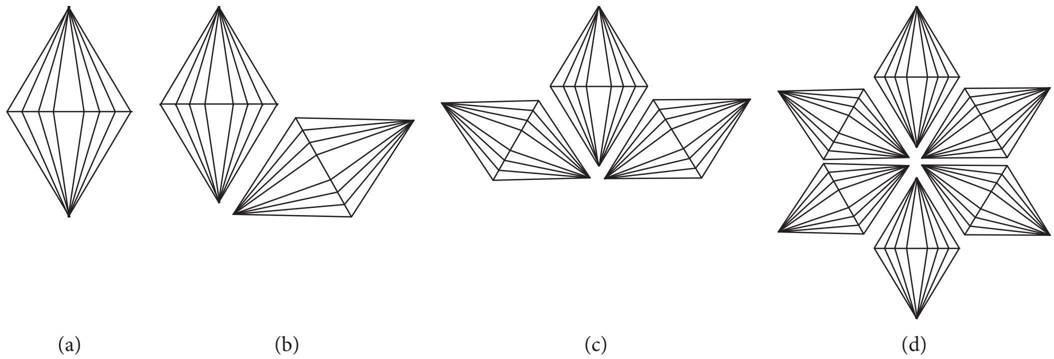

Figure 1: Schematic diagram of single-tuned antenna unit. (a) 1 panel antenna unit, $m = 1$. (b) 2 panel antenna unit, $m = 2$. (c) 3 panel antenna unit, $m = 3$. (d) 6 panel antenna unit, $m = 6$.

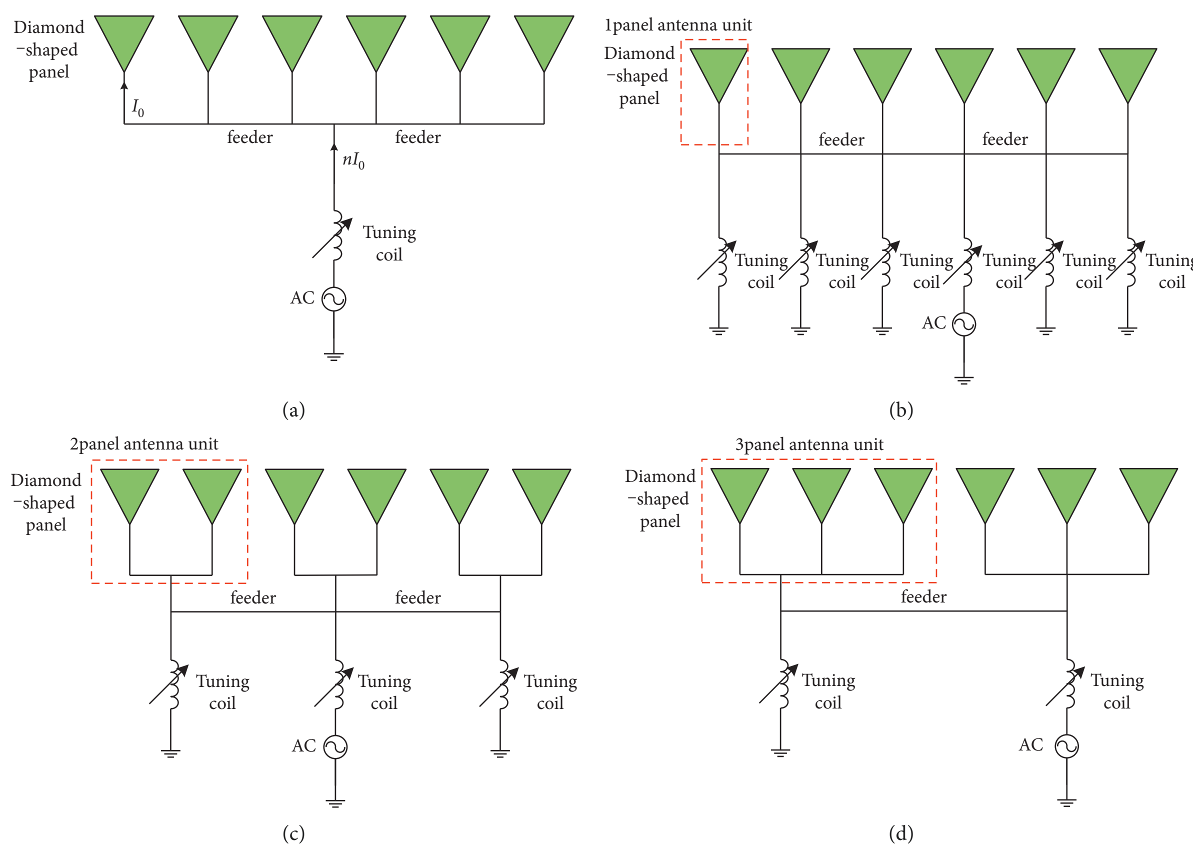

Figure 2: Electrical connection of different tuning modes of thirteen-tower umbrella antenna. (a) Single-tuned thirteen-tower umbrella antenna. (b) “One main and five deputy” multituned antenna, one unit is fed, and the other five are grounded through tuning coils. (c) “One main and two deputy” multituned antenna, one unit is fed, and the other two are grounded through tuning coils. (d) “One main and one deputy” multituned antenna, one unit is fed, and the other one is grounded through the tuning coil.

loss impedance, which mainly consists of ground loss impedance and conductor loss impedance. Due to the mutual coupling between the antenna units of the 13-tower umbrella antenna, the radiation impedance of each antenna unit can also be divided into two parts, namely its own radiation impedance (self-impedance) and induced impedance [17].

Suppose there are n antenna units, the input voltages of each antenna unit are $V_1, V_2, \ldots, V_n$, and the input current are $I_1, I_2, \ldots, I_n$, respectively, Z_{ii} is the self-impedance of the ith antenna unit, Z_{ik} is the induced impedance of the kth antenna unit on the ith antenna unit, and $Z_{\text{loss}i}$ is the loss impedance of the ith antenna unit, then:

$$\begin{cases} V_1 = I_1\left(Z_{11} + Z_{\text{loss1}}\right) + I_2 Z_{12} + \ldots + I_n Z_{1n}, \\ \ldots, \\ V_i = I_1 Z_{i1} + \ldots + I_i\left(Z_{ii} + Z_{\text{loss}i}\right) + \ldots + I_n Z_{in}, \\ \ldots, \\ V_n = I_1 Z_{n1} + \ldots + I_{n-1} Z_{n(n-1)} + I_n\left(Z_{nn} + Z_{\text{loss}n}\right). \end{cases} \quad (6)$$

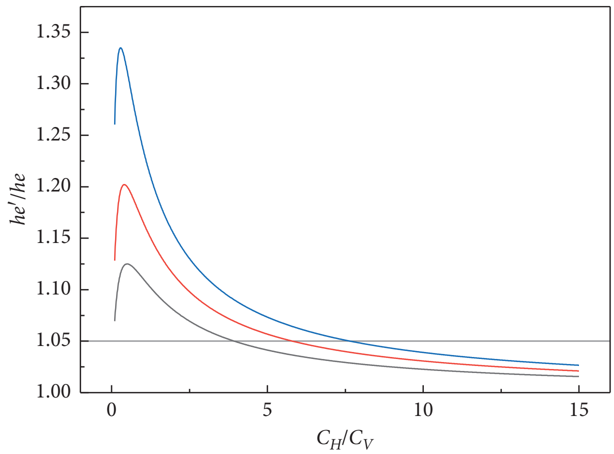

Figure 3: Variation of effective height of different antenna units with C_H/C_V. h_e' is the effective height of the 2/3/6 panel antenna unit, respectively (see Figures 1(b)–1(d)), h_e is the effective height of 1 panel antenna unit (see Figure 1(a)), C_H is the capacitance of the 1 panel antenna unit's top load, and C_V is the capacitance of the 1 panel antenna unit's down lead.

Then the input impedance of each antenna unit relative to its own input current is

$$\begin{cases} Z_1 = \dfrac{V_1}{I_1} = (Z_{11} + Z_{\text{loss1}}) + \dfrac{I_2}{I_1} Z_{12} + \cdots + \dfrac{I_n}{I_1} Z_{1n}, \\ \ldots, \\ Z_i = \dfrac{V_i}{I_i} = \dfrac{I_1}{I_i} Z_{i1} + \ldots + (Z_{ii} + Z_{\text{lossi}}) + \cdots + \dfrac{I_n}{I_i} Z_{in}, \\ \ldots, \\ Z_n = \dfrac{V_n}{I_n} = \dfrac{I_1}{I_n} Z_{n1} + \cdots + \dfrac{I_{n-1}}{I_n} Z_{n(n-1)} + (Z_{nn} + Z_{\text{lossn}}). \end{cases} \tag{7}$$

When selecting the appropriate tuning inductance, the current of each antenna unit is basically equal in amplitude and phase, so the induced resistance between each antenna unit can be approximately equal to its own radiation resistance. In practical engineering, it can be considered that the total loss resistance of each antenna unit relative to its input current is equal. Taking the real part of equation (7), it can be obtained that the input resistance R_a of each antenna unit is

$$R_a = R_{i1} + \cdots + R_{ii} + R_{\text{lossi}} + \cdots + R_{\text{in}} = nR_{r0} + R_{\text{loss}}, \tag{8}$$

where R_{r0} is the radiation resistance when the antenna unit exists in isolation, nR_{r0} is the radiation resistance of each antenna unit relative to its own input current in a thirteen-tower umbrella antenna, and R_{loss} is the loss resistance of each antenna unit.

Suppose the input current of each antenna unit is I_0, the input power of the antenna unit is

$$P_0 = I_0^2 R_a = I_0^2 (nR_{r0} + R_{\text{loss}}). \tag{9}$$

2.3. Comparative Analysis of Single-Tuned and Multituned Thirteen-Tower Umbrella Antennas. The electrical connection diagram of tuning coils of single-tuned and multituned thirteen-tower umbrella antenna is shown in Figure 2.

The single-tuned thirteen-tower umbrella antenna can be regarded as n antenna units connected in parallel at the input, the input voltage remains unchanged, and the total input current of the single-tuned antenna is n times that of each antenna unit, so the total input resistance of the single-tuned thirteen-tower umbrella antenna is

$$R_{a\text{Single}} = \frac{1}{n} R_a = R_{r0} + \frac{1}{n} R_{\text{loss}}. \tag{10}$$

The total input current of the single-tuned antenna is nI_0, and the total input power is

$$\begin{aligned} P_{0\text{Single}} &= (nI_0)^2 R_{a\text{Single}} = n^2 I_0^2 \left(R_{r0} + \frac{1}{n} R_{\text{loss}} \right), \\ &= I_0^2 \left(n^2 R_{r0} + nR_{\text{loss}} \right). \end{aligned} \tag{11}$$

The radiation efficiency of single-tuned thirteen-tower umbrella antenna is

$$\eta_{\text{Single}} = \frac{R_{r0}}{R_{r0} + 1/nR_{\text{loss}}} = \frac{nR_{r0}}{nR_{r0} + R_{\text{loss}}}. \tag{12}$$

When the thirteen-tower umbrella antenna adopts the multituning method to form a multituned antenna, n is the number of the antenna units, $n = 2$, 3, and 6, respectively, corresponding to "one main and one deputy" antenna, "one main and two deputy" antenna, and "one main and five deputy" antenna in Figures 2(b)–2(d), the total input power of the multituned antenna is

$$P_{0\text{Multi}} = nP_0 = nI_0^2 (nR_{r0} + R_{\text{loss}}) = I_0^2 \left(n^2 R_{r0} + nR_{\text{loss}} \right). \tag{13}$$

Then the radiation efficiency of multituned thirteen-tower umbrella antenna is

$$\eta_{\text{Multi}} = \frac{n^2 R_{r0}}{n^2 R_{r0} + nR_{\text{loss}}} = \frac{nR_{r0}}{nR_{r0} + R_{\text{loss}}}. \tag{14}$$

It can be seen from equations (11) to (14) that the radiation efficiency of the single-tuned thirteen-tower umbrella antenna and the multituned thirteen-tower umbrella antennas with the same input power and antenna scale are basically the same. Here, the slight differences between each antenna unit in the thirteen-tower umbrella antenna are ignored.

3. Numerical Calculation and Analysis

For the thirteen-tower umbrella antenna with different tuning modes, the modeling and simulation is carried out by FEKO software to quantitatively analyze its electrical performance [18]. First, the simulation model of dual 13-tower umbrella antenna is established with reference to the Cutler transmitting antenna to verify the accuracy and reliability of

Table 1: Cutler antenna measurement and simulation results.

	Static capacitance (nF)	Radiation resistance (Ω)	Radiation reactance (Ω)	Self-resonance (kHz)
Measured results [13]	123.9	0.1984	−35.4	40.2
Simulation results	119.4	0.1996	−38	40.6
Error	−3.6%	0.6%	7.3%	1.0%

the model. The operating frequency is 24 kHz, and the simulation results are shown in Table 1.

According to the simulation results, the performance of the antenna model is basically consistent with the measured values of the Cutler antenna, so the established thirteen-tower umbrella antenna model is accurate and effective. Based on this antenna model, the electrical performance of the antenna units and thirteen-tower umbrella antenna is simulated.

3.1. Radiation Impedance of Antenna Units. The impedance of the antenna units shown in Figure 1 is simulated, respectively, and the results are shown in Figure 4.

It shows that the larger the top load area of the antenna unit, the greater the radiation resistance of the antenna unit, but the difference of the radiation resistance between the antenna units is very small, which is basically consistent with the analysis result of equation (5) and Figure 3. Moreover, with the increase of the number of diamond-shaped top loads, the increase in antenna static becomes smaller, that is, the contribution of each diamond-shaped top load to the total static capacitance of the antenna decreases.

3.2. Analysis of Single-Tuned and Multituned Thirteen-Tower Umbrella Antennas. A single thirteen-tower umbrella antenna which is half of the Cutler antenna model is used as the simulation model, and two radial ground screens of different size are laid, respectively, in the model I and model II (see Figure 5). The parameters of antenna and ground system are shown in Table 2. In addition, the operating frequency changes between 15 and 30 kHz.

The ground loss resistance of a VLF thirteen-tower umbrella antenna can be split into H-field loss resistance and E-field loss resistance [5, 19, 20]. Because the antenna structure is extremely complex, it is very difficult to accurately solve its ground loss resistance by analytical calculation [21]. In this study, the combination of numerical simulation and analytical calculation is used to solve its ground loss resistance. First, calculate the near field of the antenna through the FEKO software [9, 22–24], then integrate the loss power of H-field and E-field, respectively, and finally, the H-field loss resistance R_H and the E-field loss resistance R_E relative to the antenna's input current are solved according to equations (15) and (16):

$$R_H = \frac{1}{I_0^2}\int_A R_H' \left|H_t\right|^2 \mathrm{d}A, \tag{15}$$

$$R_E = \frac{1}{I_0^2}\int_A R_E' (\omega\varepsilon_0)^2 E_z^2 \mathrm{d}A, \tag{16}$$

where R_H' is the equivalent surface resistance of the Earth with the ground screen, H_t is the tangential component of the magnetic field on the Earth surface, R_E' is the effective series resistance per unit area, E_z is the vertical component of the electric field on the Earth surface, ω is the operating angular frequency, ε_0 is the vacuum permittivity, A is the near-field region around the antenna, the range within a radius of 2000 meters is included in this study, and I_0 is the input current of the antenna.

The ground loss resistance R_{loss} of the antenna is [16]

$$R_{\text{loss}} = R_H + R_E. \tag{17}$$

As shown in the Table 3 and Figure 6, when the operating frequency is the same, the radiation efficiency of the antennas with single tuning and multituning is basically the same. And the radiation efficiency of the antennas increases with the increase of the operating frequency.

According to the results, the multituned antenna's radiation resistance is around n^2 times that of a single-tuned antenna, and its loss resistance has a similar multiple relationship, too. The reason for this is that when the tuning mode of the thirteen-tower umbrella antenna with the same scale and input power is changed, the input resistance, including radiation resistance and loss resistance, changes numerically. However, when the antenna's main structure and the ground system are maintained the same, the antenna's radiation power and loss power with different tuning modes are nearly the same. The input current of the multituned antenna is around $1/n$ of that of the single-tuned antenna because the current of the single-tuned antenna is dispersed to several tuning coils (see Figure 7). Thus, when solving the radiation resistance and loss resistance relative to each antenna's own input current, there is a n^2 times numerical relationship, but the radiation efficiency of various tuning modes is basically the same, and this feature is valid over the entire frequency range of 15–30 kHz, which is also consistent with the previous theoretical analysis results.

The antenna's top voltage is another important factor that limits the antenna's radiated power. Although the top voltage of the single-tuned antenna is slightly lower than that of the multituned antennas (see Figure 8), this difference does not have a significant impact on engineering applications. However, the top voltage decreases rapidly with increasing frequency for all the tuning modes. This shows the importance of increasing the operating frequency of the antenna.

Due to the instability of the antenna working near the self-resonant frequency, the self-resonant frequency is one of the main factors restricting the antenna's working frequency range, the multituned thirteen-tower antenna can effectively improve the self-resonance of the antenna (see Table 4). In

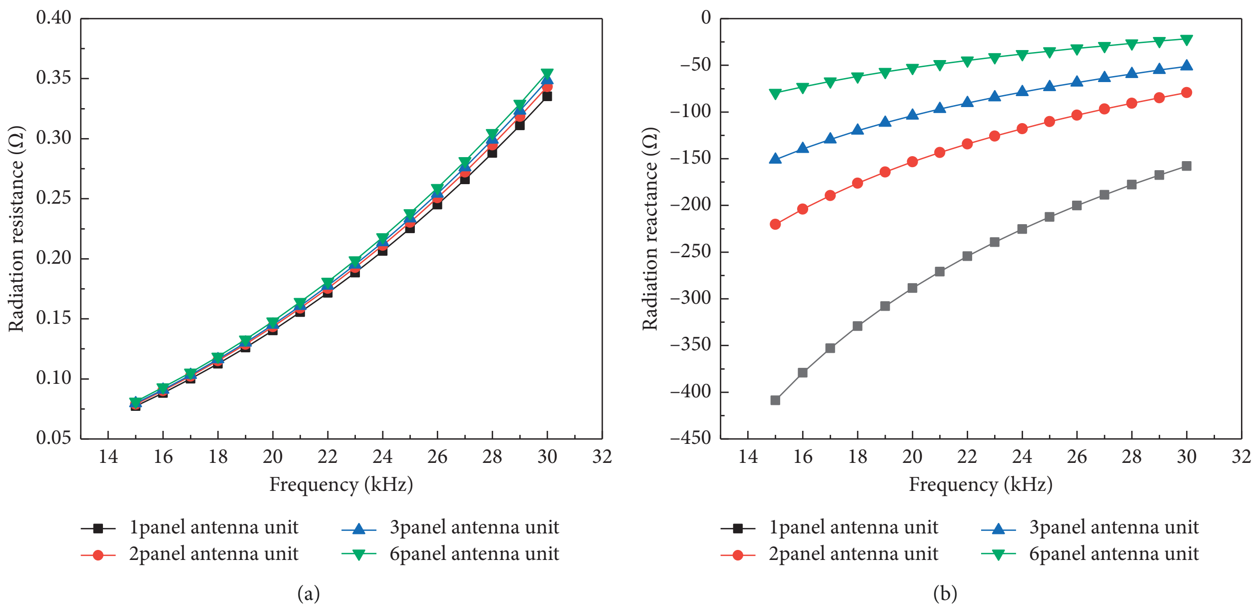

Figure 4: Radiation impedance of the antenna units. (a) The radiation resistance of the four antenna units in Figure 1. (b) The radiation reactance of the four antenna units in Figure 1. $f = 15–30$ kHz.

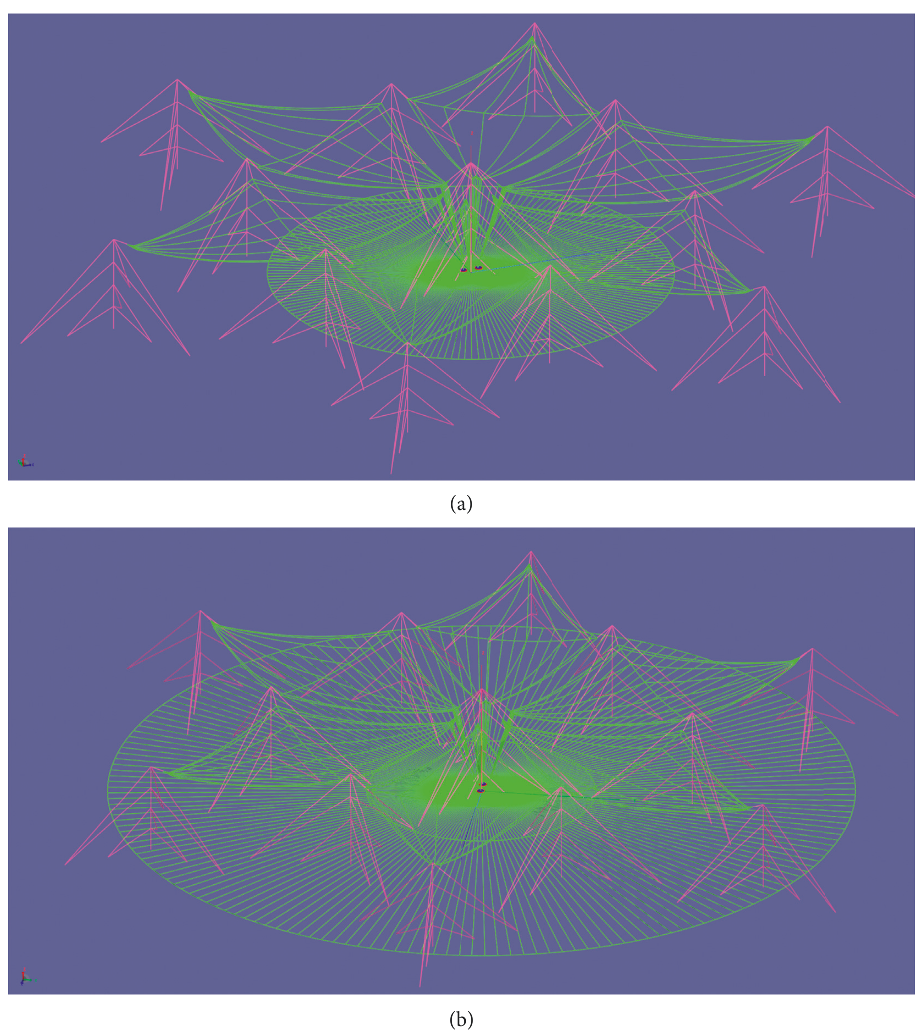

Figure 5: Antenna and ground system simulation model. The antenna structures of models I and II are identical. The ground screen of model II, however, is larger than that in model I. The ground screen for model I has a total wire length of 96 kilometers, whereas the ground screen for model II has a total wire length of 195 kilometers. (a) Model I. (b) Model II.

Table 2: Parameters of antenna and ground system.

Parameters	Value	
Center tower height (m)	298	
Inner ring tower height (m)	266	
Inner ring radius (m)	558	
Outer ring tower height (m)	243	
Outer ring radius (m)	935	
Sag of top load wires	Inner 4 wires: 4%, outer 4 wires: 5%	
Conductor conductivity ($S*m^{-1}$)	5.8×10^7	
Earth conductivity ($S*m^{-1}$)	0.01	
Input power (kW)	679	
Model	Model I	Model II
Ground screen radius (m)	500	980
Ground screen density	0–100 m: 240 wires 100–500 m: 180 wires	0–100 m: 240 wires 100–300 m: 200 wires 300–980 m: 180 wires
Buried depth of ground screen (m)	0.3	0.3

Table 3: Simulation results of the radiation efficiency.

Model	Parameters	Single-tuned antenna ($n = 1$)	"One main and one deputy" multituned antenna ($n = 2$)	"One main and two deputy" multituned antenna ($n = 3$)	"One main and five deputy" multituned antenna ($n = 6$)
Model I	Radiation resistance (Ω)	0.2064	0.8240	1.8453	7.2417
	Conductor loss resistance (Ω)	0.0096	0.0337	0.0772	0.2667
	Ground loss resistance (Ω)	0.6258	2.5034	5.6289	21.9755
	Radiation efficiency	24.5%	24.5%	24.4%	24.6%
Model II	Radiation resistance (Ω)	0.2064	0.8240	1.8453	7.2417
	Conductor loss resistance (Ω)	0.0096	0.0337	0.0772	0.2667
	Ground loss resistance (Ω)	0.0707	0.2813	0.6325	2.4200
	Radiation efficiency	72.0%	72.3%	72.2%	72.9%

Detailed simulation results of antenna model I and model II with single tuning and multituning at 24 kHz, and n is the number of the antenna units.

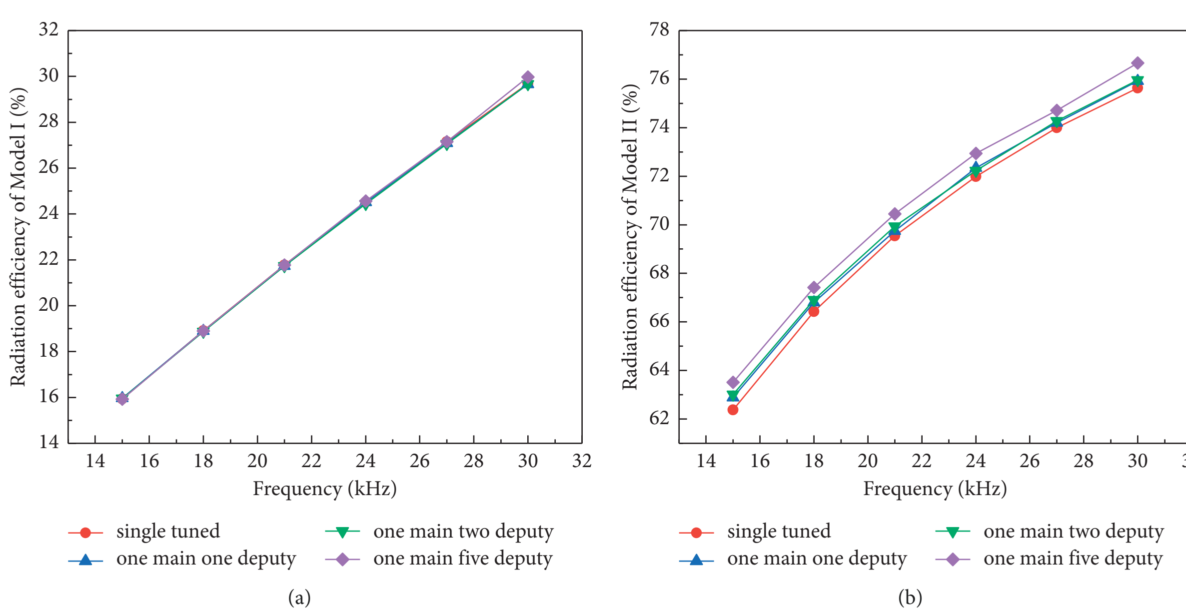

Figure 6: The radiation efficiency of model I and II with single tuning and multituning. $f = 15–30$ kHz. (a) Model I. (b) Model II.

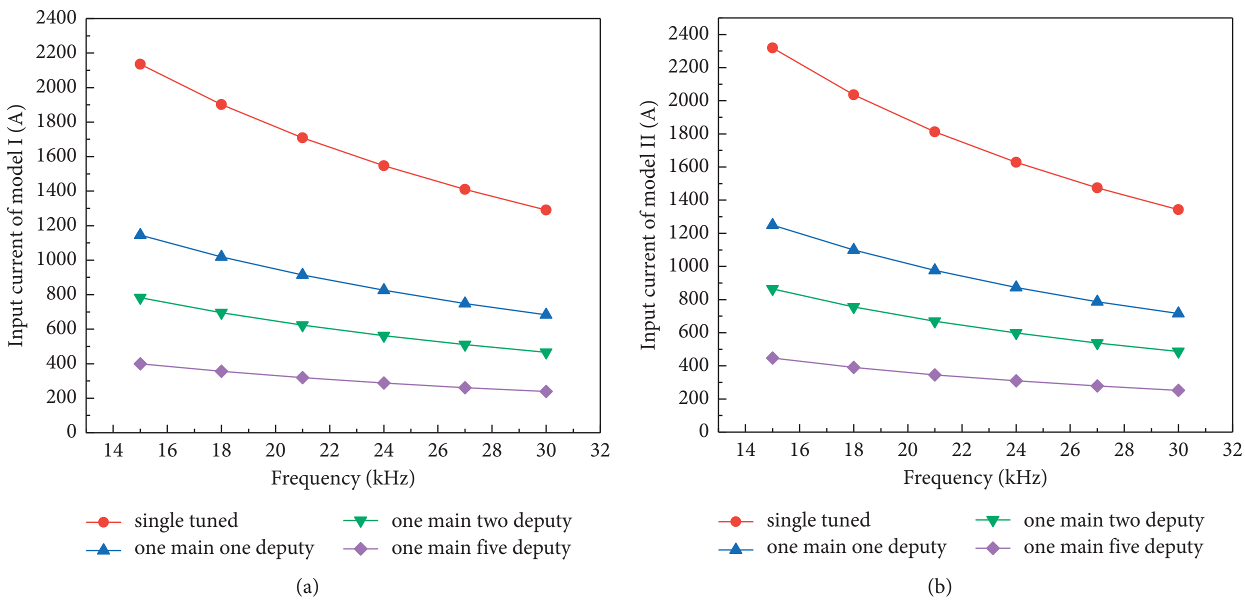

Figure 7: The input current of model I and II with single tuning and multituning. $f = 15$–30 kHz. (a) Model I. (b) Model II.

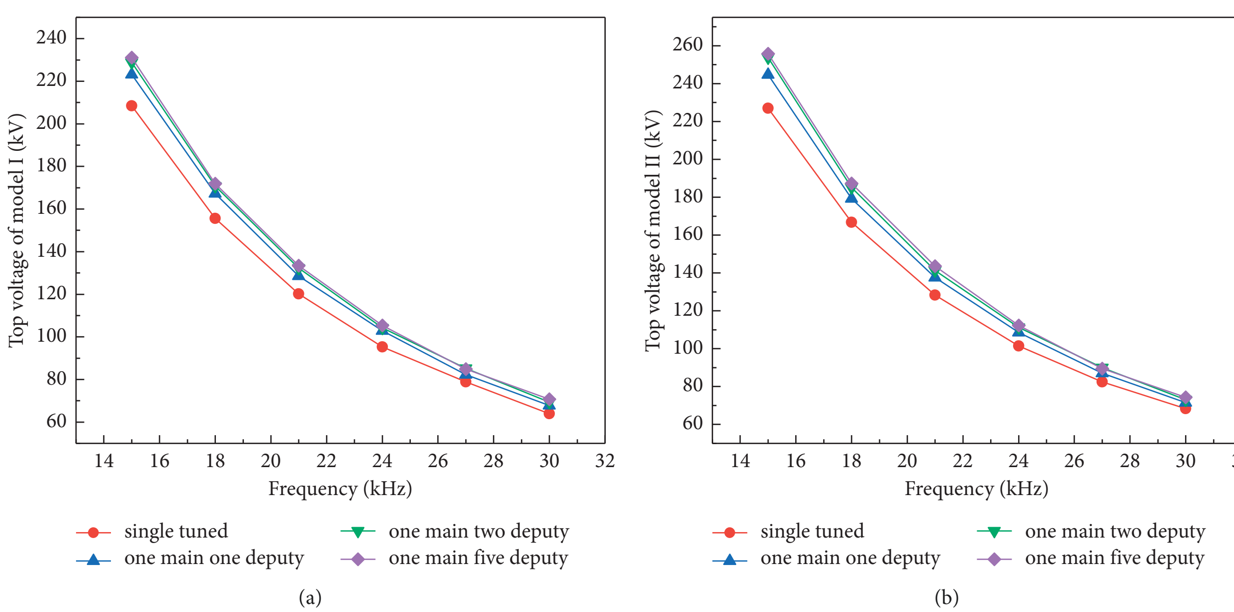

Figure 8: The top voltage of model I and II with single tuning and multituning. $f = 15$–30 kHz. (a) Model I. (b) Model II.

Table 4: Self-resonance of the thirteen-tower umbrella antennas with single tuning and multituning.

	Single-tuned antenna ($n = 1$)	"One main and one deputy" multituned antenna ($n = 2$)	"One main and two deputy" multituned antenna ($n = 3$)	"One main and five deputy" multituned antenna ($n = 6$)
Self-resonance (kHz)	40.6	43.8	44.6	45.5

n is the number of the antenna units.

terms of self-resonance, the "one main and one deputy" multituned antenna, the "one main and two deputy" multituned antenna, and the "one main and five deputy" multituned antenna are 7.9%, 9.9%, and 12.1% greater than the single-tuned antenna, respectively.

4. Conclusions

This study proposes the concept of multituned thirteen-tower umbrella antenna. By adjusting the number and electrical connection of tuning coils at the bottom of the thirteen-tower umbrella antenna, the multituned thirteen-tower umbrella antenna models are constructed. Based on simulation and analysis, when the main structure and input power of the thirteen-tower umbrella antenna remain unchanged, compared with the single-tuned antenna, the multituned antenna can effectively reduce the input current and improve the self-resonant frequency, while the radiation efficiency and top voltage maintain basically the same. This allows the antenna to operate at higher frequencies, and the input current and top voltage of the antenna will drop rapidly as the frequency rises, which will improve the safety of the antenna system and provide a novel approach for further improving the radiated power of the high-power VLF thirteen-tower umbrella antenna.

Data Availability

The data, which are produced by simulations, used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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