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This paper describes the NEC4 analysis used to evaluate proposed modifications to a Navy VLF top-loaded monopole. Charge densities are computed and used to calculate the maximum top-load gradient for two wire sizes. Although the antenna is electrically small, a large number of segments is needed to obtain the desired resolution in the charge data. Gradient values derived from the NEC4 data are shown to be in close agreement with those derived from measured data. The gradient values show that the proposed configuration does not meet the maximum gradient design limit for this antenna.

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NEC4 Analysis of a Navy VLF Antenna

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ABSTRACT

NEC4 is used to evaluate proposed modifications to a Navy VLF top-loaded monopole. Charge densities are computed and used to calculate the maximum top-load gradient for two wire sizes. Although the antenna is electrically small, a large number of segments is needed to obtain the desired resolution in the charge data. Gradient values derived from the NEC4 data are shown to be in close agreement with those derived from measured data. The gradient values show that the proposed configuration does not meet the maximum gradient design limit for this antenna.

INTRODUCTION

Electrically short, top-loaded monopoles are commonly used by the U.S. Navy for Very Low Frequency (VLF) communication. Although electrically small, the operating frequency range (typically 12 kHz to 30 kHz) results in physically large antennas requiring significant maintenance. One such antenna is the Cutler VLF Antenna System located at U.S. Naval Radio Station, Washington County, Maine. The antenna is a dual array, with each array measuring over 970' in height and 6000' in diameter. This massive structure is currently scheduled for extensive wire replacement. An economical way to evaluate the proposed changes is necessary, and using numerical modeling is one solution. This paper presents a computer-aided analysis of the Cutler antenna using the Numerical Electromagnetics Code, Version 4 (NEC4) [1]. Previous work has demonstrated the applicability of NEC-GS (NEC-Ground Screen) to similar VLF antennas [2]. Here, the objective is to use NEC4 to determine the maximum surface electric field, or gradient, on the antenna top-hat. Knowing the gradient provides a means of assessing the impact of the proposed wire replacement on antenna performance.

ANTENNA DESCRIPTION

The Cutler antenna consists of two identical arrays as shown in Figure 1. Each array is essentially a base-fed, top-loaded monopole. The top-hats of each array consist of six diamond shaped panels arranged symmetrically around a central tower. The panels are supported by one center tower (T0), six inner towers, and six outer towers. The towers range in height from 800' at the outer ring to just under 1000' at the center. Each tower is supported by a system of guy wires. All towers and guy wires are grounded, and all the panels are insulated from the towers and each other. Each panel is fed using several down lead wires extending from a connection near the center tower insulator, to a helix house at the base where they are tied together.

A plan view illustration of a single top-hat panel is shown in Figure 2. Each panel in the array is approximately 3000' long, and has eight wires running from T0 to the outer towers. The four inner wires of each panel are 1" diameter solid core cables. The four outer wires of each panel consist of 1" solid core cables connected to 1.5" diameter hollow core cables. Hollow core cables were originally used to save on weight. The 1.5" diameter is necessary to avoid corona on the antenna at lower operating frequencies.

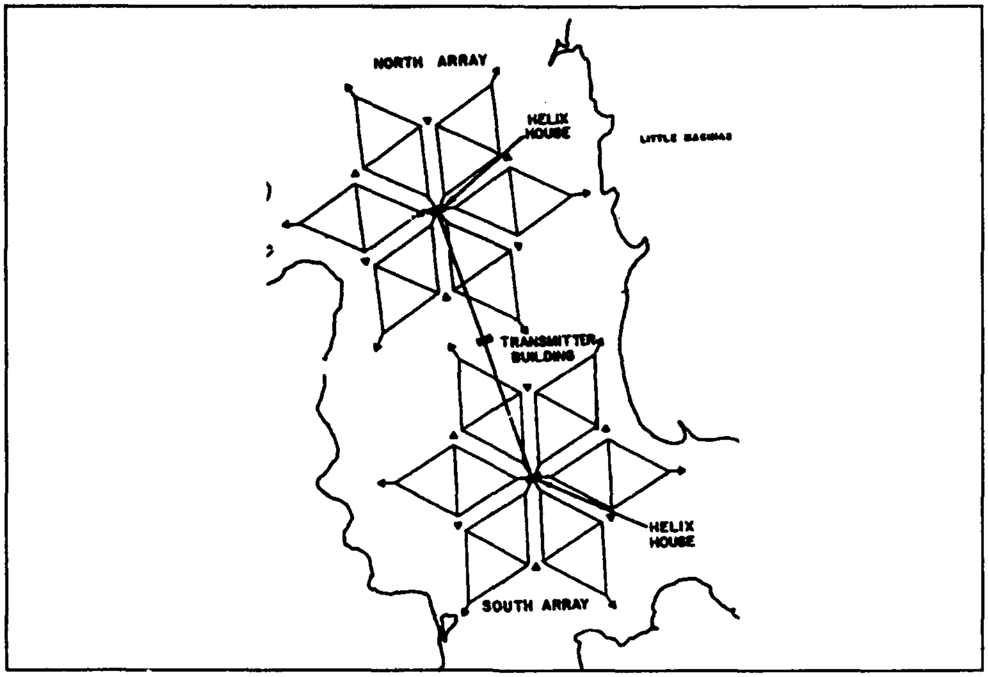

Figure 1. General layout of the Cutler antenna [3].

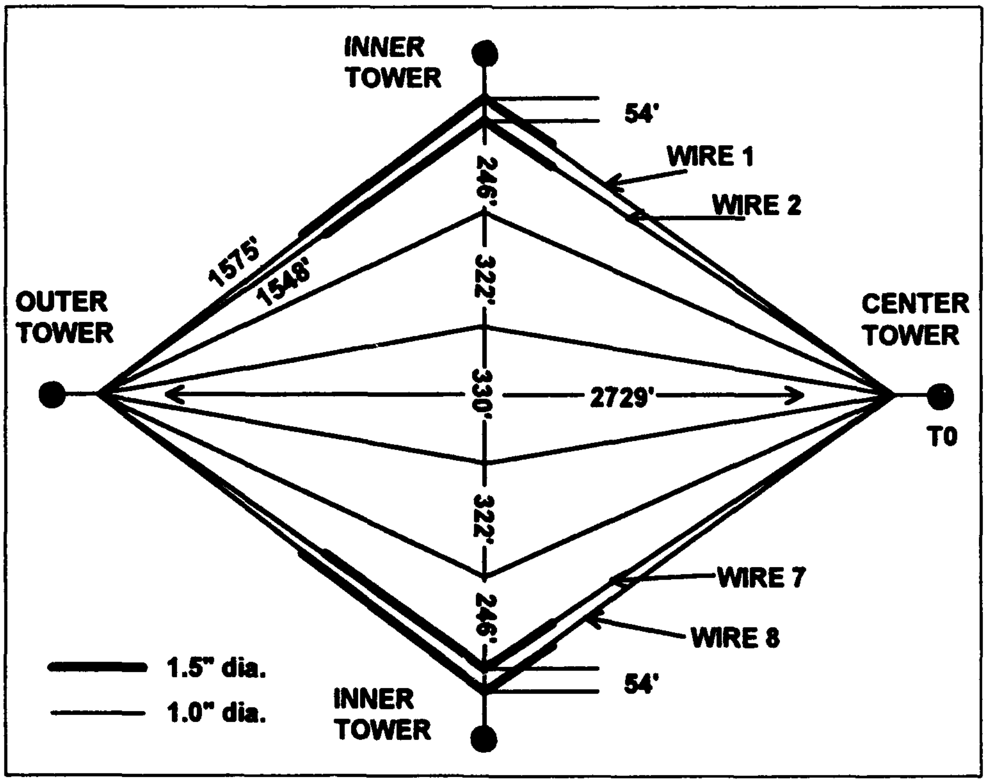

Figure 2. Plan view of a single top-hat panel of the Cutler antenna.

Corona is a discharge of electrical energy that can occur near a sharp point of a conductor raised to a high potential. Energy is discharged when the electric field strength on the conductor exceeds the breakdown voltage of the surrounding air. Since the energy is dissipated into the air, it represents a power loss in the system. Therefore, it is important to avoid corona to maintain system efficiency.

Currently, the Cutler antenna operates at 24.0 kHz. It's maximum input power is one megawatt for single array operation, and two megawatts for dual array operation. At 24.0 kHz, corona is not a problem in the 1.0" wires. However, it is desirable to operate at 17.8 kHz, and at this frequency, the 1.5" wires are needed. Unfortunately, these wires are due for replacement and the hollow core cable is no longer available. It was necessary therefore, to study different configurations to find an alternative to the 1.5" cable. Modeling the antenna using NEC4 provided a convenient way to do this.

THE NEC4 MODEL

A NEC4 model of the Cutler antenna was constructed for the computer-aided analysis. Although the antenna consists of two arrays, it is often operated using only a single array. Therefore, single array operation was assumed to simplify this analysis. Two antenna configurations were modeled. Configuration 1 models the antenna in its present state, using both 1" and 1.5" diameter top-hat wires. Configuration 2 consists entirely of 1" top-hat wires. Table 1 below gives model dimensions for both configurations. Inner panel wires refer to the panel sections from T0 to the inner towers. Outer panel refers to the sections from the inner towers to the outer towers.

Antenna Element	Configuration 1: 1" and 1.5" Wires		Configuration 2: 1" Wires Only	
	Length (ft.)	Diameter (in.)	Length (ft.)	Diameter (in.)
Center Tower	979.5	72.0	979.5	72.0
Inner Towers	875.8	72.0	875.8	72.0
Outer Towers	799.0	72.0	799.0	72.0
Downleads	550.1	1.0	550.1	1.0
Inner Panel Wires				
Wires 1 & 8	1352 223.3	1.0 1.5	1575 ---	1.0 ---
Wires 2 & 7	1216 224.9	1.0 1.5	1441 ---	1.0 ---
Outer Panel Wires				
Wires 1 & 8	800.0 774.7	1.0 1.5	1575 ---	1.0 ---
Wires 2 & 7	774.2 774.7	1.0 1.5	1549 ---	1.0 ---

Table 1. Dimensions of the NEC4 Cutler antenna model.

Since the antenna is rather complex, several approximations were made in constructing the computer models. To begin with, the top-hat elements were modeled as flat wires with no catenary. All tower guy wires were neglected and a perfect ground was assumed. Since the towers are insulated from the panels in the antenna, they were modeled as free standing monopoles in the model. On the actual antenna, several vertical feed wires fan out from the source at the base to each panel. On the computer model, each panel was fed using a single vertical lead extending from the source. Furthermore, since the center tower is not fed, the feed structure had to be made slightly asymmetric to accommodate the tower's position. That is, the distance from the source to each panel varies slightly from panel to panel. This asymmetry can clearly be seen in the center of Figure 3, which shows a view of the NEC4 wire model. Finally, since the dual outer wires on each outer panel edge are so close to each other near the panel vertices (see Figure 2), the geometry had to be altered to allow NEC4 to recognize them as separate wires. Specifically, the outer panel wire separation at the inner tower connection was less than 10^{-3} times the length of the wire segments, thus violating the separation criteria in NEC4 [1]. To get around this limitation, the outer two wires (# 1 and #8) were modeled as a single wire near the inner vertex of each panel. At a distance of two segments ($\cong$ 112 ft.) from the center tower, the wire splits into two separate wires. The angle between the wires was adjusted to achieve the specified separation at the inner tower ring. Modifying the geometry seems justified since the resulting difference in wire lengths is small compared to a wavelength. Thus, there will only be a small effect on the calculations. Also, it was felt that the charge around the inner tower region would be higher, and therefore more critical to the onset of corona, than the charge near the center tower. Hence, modeling accuracy at T0 was sacrificed in favor of maintaining the correct wire spacing at the inner towers.

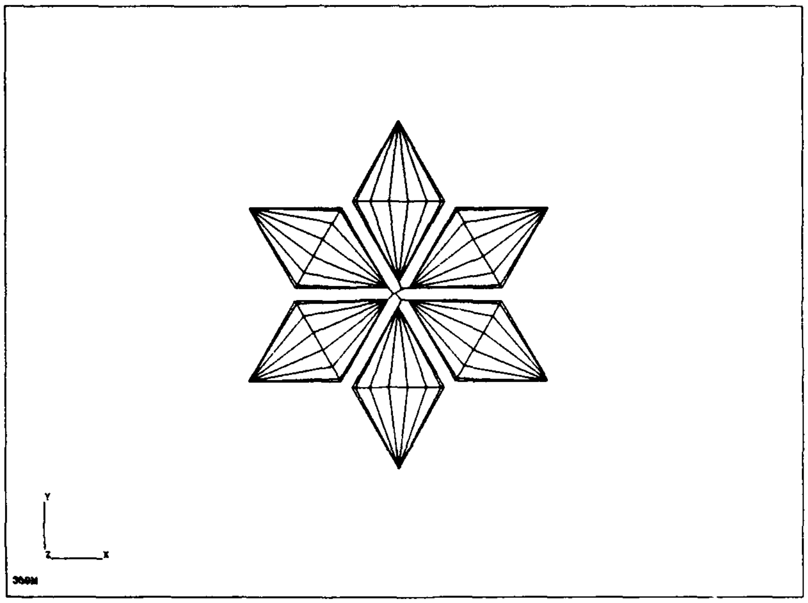

Figure 3. Plan view of the NEC4 Cutler model.

Calculations were performed using the single precision version of NEC4 on a Convex C240 Mini-supercomputer. To obtain the maximum practical resolution in the charge density, the model required approximately 3000 unknowns and five hours to run. As with all Method of Moments wire modeling, there is a trade off between model size, computation time, and the minimum segment size limit of the program. In addition, the asymmetrical feed arrangement of this particular model prevented using symmetry in the calculation. Since small segment modeling in NEC4 has been significantly improved over earlier versions [1], computation time and model size became the limiting factors for this study. Taking the factors above into account, it was decided segment lengths of approximately 55 ft. ($\cong$ 0.001 $\lambda_{17.8\ \mathrm{kHz}}$) would give the maximum practical resolution. Given the large physical size of the antenna, the resulting model contained 2997 segments.

Current and charge were calculated at 17.8 kHz and 24.0 kHz for both antenna configurations. Figures 4 and 5 show the calculated charge distribution, normalized to 1 amp input current, for the outer two panel wires (wires 1 and 2, or 7 and 8 in Figure 2) at each frequency. These are the only panel wires with 1.5" sections, and therefore show the greatest change between Configuration 1 and Configuration 2. Note the change in wire diameter is clearly seen in the data for Configuration 1. The results indicate the charge density is slightly less when only 1" wires are used. In the graphs, the data is plotted along the wires from the middle tower to the outer tower. Similar results were obtained for the wires extending from the middle tower to the center tower.

		17.8 kHz		24.0 kHz	
Configuration	Wire #1 Diameter (in.)	Q_{max} (C/m/A)	E_{max} (kV/mm)	Q_{max} (C/m/A)	E_{max} (kV/mm)
1	1.0 and 1.5	2.93×10^{-10}	0.685	2.24×10^{-10}	0.429
2	1.0	2.82×10^{-10}	0.989	2.15×10^{-10}	0.618
I_{bmax} (A)		2477		2030	

Table 2. Maximum top-hat gradients calculated using NEC4.

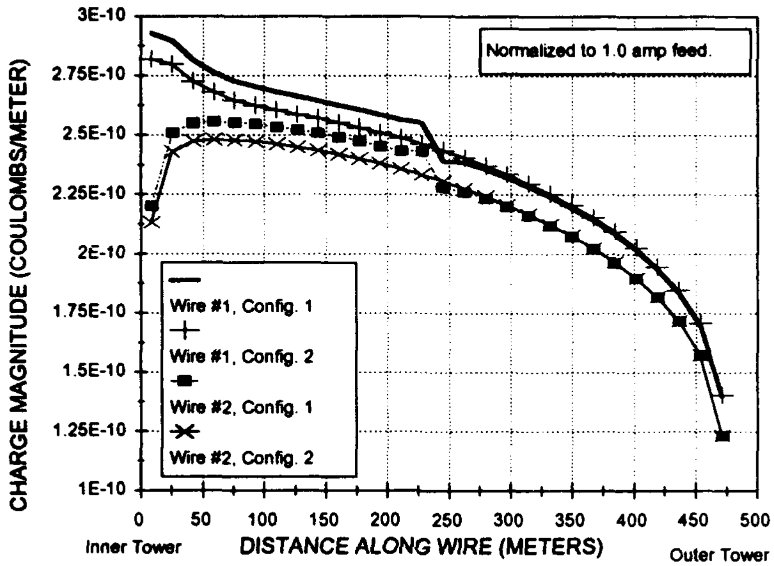

Figure 4. Calculated charge density for top-hat wires 1 and 2 at 17.8 kHz.

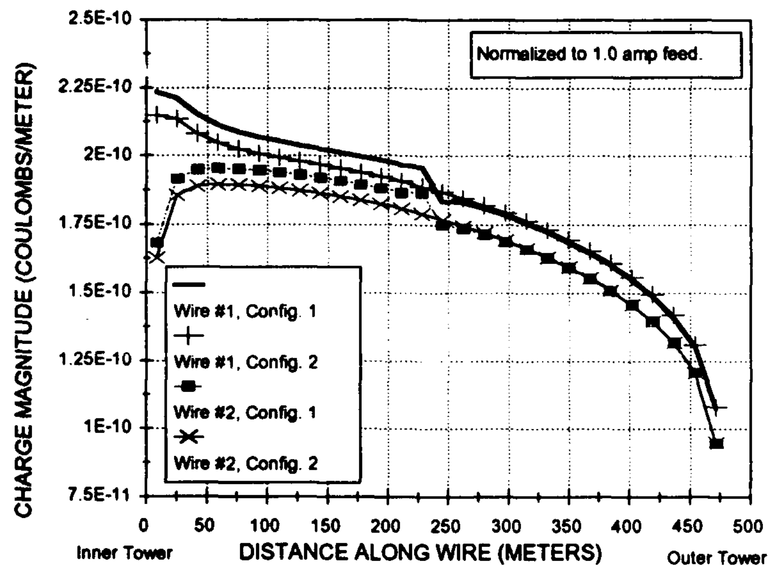

Figure 5. Calculated charge density for top-hat wires 1 and 2 at 24.0 kHz.

GRADIENT CALCULATIONS

The surface electric field, or gradient, on a conductor determines whether or not corona will occur. For this reason, it is an important parameter to consider when working with high voltage antennas like Cutler. In this case, the gradient can be used to assess the impact of replacing the 1.5" wires with 1" wires. According to [4], the maximum allowable gradient to avoid corona for the Cutler antenna is .8 kV/mm. Therefore, if the maximum gradient on the 1" replacement wires exceeds this limit they will not meet the design requirement.

For a cylindrical conductor, the gradient can be calculated from,

$$E = \frac{q_L}{2\pi\varepsilon_0 r} \tag{1}$$

where q_L is the linear charge density in coulombs per meter, ε_0 is the permittivity of free space, and r is the radius. Examination of Figures 4 and 5 shows that the maximum charge density per amp occurs on the outer wire (#1 or #8) at the inner tower connection. Multiplying these charge values by the maximum antenna input current and substitution into (1) yields the maximum gradient. The maximum antenna base currents I_{bmax}, for single array operation are 2477 A at 17.8 kHz, and 2030 A at 24 kHz [3]. Using these currents, the maximum top-hat gradients for each configuration are calculated and shown in Table 2 .

The validity of the NEC4 data was checked by comparing the results with gradients calculated from measurements. The measurements were taken during a model study of the antenna using a 100:1 scale model [4]. The model data includes the current distribution on the outer panel wires, which can be used with (1) to calculate the gradient.

To calculate the gradient from the measurements, the charge density must be derived from the current distribution. From the continuity equation, the linear charge density along a wire is related to the slope of the current distribution by,

$$Q_{Total} = \frac{\partial I}{\partial f} = \frac{I}{\omega} \tag{2}$$

and

$$q_L = \frac{\partial Q_{Total}}{\partial L} = \frac{1}{\omega}\frac{\partial I}{\partial L} \tag{3}$$

where Q_{Total} is the total charge on the wire beyond a given point, ω is the radian frequency, and q_L is the linear charge density at the point. Substituting (3) into (1) gives,

$$E_s = \frac{1}{4\pi^2\varepsilon_0 f r}\frac{\partial I}{\partial L} \tag{4}$$

where E_s is the surface electric field (*i.e.*. the gradient) on the wire. Equation (4) is a maximum when the slope of the current distribution is a maximum. From [4], the maximum slope of the measured current distribution is 0.0296 mA/m per Amp of input current. Therefore, substitution into (4) gives an equation for the maximum surface gradient as a function the antenna base current I_b:

$$E = \frac{0.0296x10^{-3} I_b}{4\pi^2\varepsilon_0 f r} \tag{5}$$

Measured input currents for various configurations of the antenna model are found in [3], including maximum currents for 1.0" and 1.5" wires at several frequencies. Substituting the currents into (5) resulted in the curves shown in Figure 6. The graph compares the measured data with the NEC4 results. The agreement between the two is very good, with the NEC4 values falling within 10% of the measurements. Note that both the NEC4 data and the measured data indicate 1.0" wires on the outer panel are unacceptable for operation at 17.8 kHz, as the gradient in this case exceeds the 0.8 kV/mm design limit.

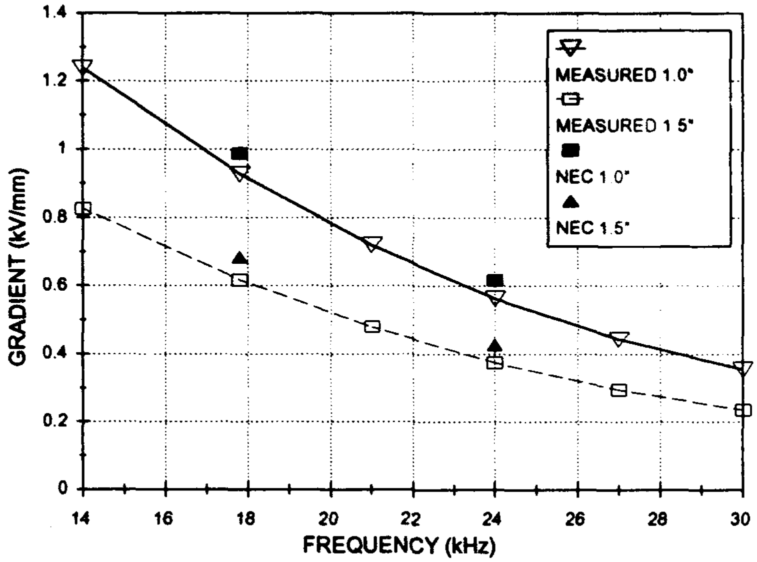

Figure 6. Measured and calculated maximum top-hat gradient for the Cutler antenna.

SUMMARY

The results of this work help demonstrate NEC4's ability to complement the antenna design process. In this particular case, it was shown NEC4 can be used to evaluate proposed changes to the Navy's Cutler, Maine VLF top-loaded monopole. Charge data from NEC4 was used to calculate the maximum top-hat gradient for the antenna. The computed results agree very well with measured model data. Both data sets indicate the gradient on the 1.0" wires exceeds the maximum design limit needed to avoid corona at 17.8 kHz.

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