THE APPLICATION OF NEC2 IN PREDICTING THE RADIATED FIELD FROM TRANSMISSION TOWER ARCING FAULTS

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Abstract - This paper describes studies performed using the Numerical Electromagnetics Code (NEC) version 2 in predicting the radiated fields from a transmission tower fault. Although widely used in antenna design and radio propagation studies, NEC2 has only recently been applied to power systems problems [1]. This investigation had two objectives: firstly to identify the optimum frequency for reception of the radiated field, and secondly, to estimate the distance from the tower at which the arcing radiation can be reliably detected.

NEC2 allows multi-element structures to be modelled using thin wire segments. A simplified tower model was therefore developed. The arc was modelled as a current source situated at the cross-arm. Due to the high frequencies needed for this study, general purpose power systems arcing models could not be used and so the frequency content was estimated based on a discontinuous current waveform.

NEC2 allowed the calculation of various results including E-field variation with frequency, distance and bearing from the tower. The results conclude that the optimum frequency for remote detection of arcing events is 10 MHz, and that the maximum distance is 36 km.

Keyword: Fault location, Arcing faults, Overhead towers, Radiated field, EMC, NEC

1 INTRODUCTION

Power transmission systems are subject to arcing faults on a regular basis. Under such conditions the avalanche ionisation at arc ignition causes non-linear currents to circulate in the fault path. In addition to the power system frequency component, the arc non-linearities can generate frequency components up to the UHF band [2].

Electro-magnetically an Extra High Voltage (EHV) transmission line tower can be considered primarily to consist of an earthing conductor, 4 vertical metallic support columns and secondary interconnecting lattice support. Under earth fault conditions, the alternating fault current will flow through the least resistive path to earth and hence flow through the earth conductor and 4 vertical supports. Since the fault current has a significant vertical component, and contains components at radio frequency (rf), the tower acts as a radio frequency transmitter and will radiate vertically polarised signals. For overhead lines of the tower construction type, parts of the tower lattice and the line itself are the most likely structures to radiate radio frequency energy [3].

Recent studies have shown that this phenomenon can be exploited as a novel method of fault location [2] using an antenna system to detect the radiated rf energy from overhead line arcing faults. A system based on this principle could remotely monitor the condition of the overhead lines without any physical connection to the power system. By accurately timing the arrival of the radiated signal at several antenna sites, the fault location can be found using an inverse hyperbolic navigational approach. By comparison, present technologies for power system fault location rely on a direct connection to the power system.

The advantage of a fault location system based on this principle is predominantly cost, since arcing faults can be located from all high voltage plant within a geographical region defined by the positions of antenna sites. This has particular relevance to lower voltage distribution plant, where the large number of circuits make the installation of fault locating equipment on a per-circuit basis economically unviable.

To date, the propagation of electromagnetic waves radiated from power system plant undergoing arcing events is not well understood. This paper reports results from an investigation aimed at explaining the properties of arc induced transient radiation and its propagation. The study used the Numerical Electromagnetics Code (NEC) version 2 software that is widely used in the field of radio communications and antenna design. NEC is a public domain computer code for three-dimensional electromagnetic modelling based on the method of moments; it is particularly effective in analysing metal structures composed of thin wires [1].

The electrically conducting elements of the system modelled by NEC are divided into line segments or short cylinders. In the present analysis, all the elements in the system are treated as perfect conductors. A transmission tower needs to be decomposed into thin wire elements, and the position, orientation and the radius of each element constitute the input data, along with the description of the source excitation and the frequency to be analysed. There are restrictions in the size and the arrangement of the individual elements in the analysis by NEC [4]. Although fairly complex tower structures can be simulated, some simplification in the geometry is required.

The broad aim of the study was to model a transmission tower, and simulate the radiation pattern produced by the arcing effect. The study had two objectives: firstly, to calculate the maximum distance of detection of radiated rf energy using conventional receiving technology. Secondly, to identify the dominant frequency of radiation in order to optimise the receiving system.

The paper, describes the modelling of the transmission line and tower, followed by the simulation results. The results include radiation pattern graphs at different frequencies, electric field distribution and effect of the overhead line. Calculations for the maximum detection range using different probability of detection are outlined. Finally, overall performance of the simulation is evaluated and recommendations are given for future work.

2 MODELLING OF TOWER

2.1 Basic Theory

A conductor system to be analysed by NEC is modelled by the composition of short cylindrical segments. A cylindrical segment is defined by the coordinates of its two end points and its radius.

Geometrically, the segments should follow the paths of conductors as closely as possible, using a piece-wise linear fit on curves. The main electrical consideration is on the segment length Δl relative to the wavelength λ, and $10^{-3}\lambda < \Delta l < 0.1\lambda$ is recommended [5].

Generally $\Delta l / \lambda$ should be less than about 0.1 at the desired frequency, so the value 0.1λ is preferred as the segment length. The current in the conductor will be computed in segments and the total current is the addition of current in these segments.

To calculate the number of segments per wire, the following information is needed:

$$\lambda = \frac{c}{f} \qquad (1)$$

$C = 3\times10^8$ m/s (speed of light)
$f =$ frequency in Hz

For example, a 1 meter conductor at 100 MHz has a wavelength given by:

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{100\times10^6} = 3\text{ m}$$

Segment length; $\Delta l = 0.1\lambda = 0.1\times3 = 0.3$ m (2)

The number of segments = 1/0.3 = 3.3. Therefore 4 segments should be used.

2.2 Range of frequency.

The range of frequency investigated in the project was 10 kHz to 10 MHz, although it is desirable to extend the range further to 100 MHz, and beyond. Using Equation (2) the segment length corresponding to each frequency can be calculated.

Frequency (Hz)	Wavelength (m)	Segment length (m)	Number of segments needed for 10m wire
10k	30000	3000	1
100k	3000	300	1
1M	300	30	1
10M	30	3	4
100M	3	0.3	34

Table 1: Segment length corresponding to each frequency.

The number of segments needed for a structure increases significantly as the frequency increases. The segment length for 100 MHz is 0.3 meter. Since the tower is a huge structure, including 100 MHz in the modelling will result in a colossal number of segments which approaches the limits of NEC's capabilities. Additionally, a large number of segments will result in long programme execution times.

2.3 Input data

The transmission tower modelled was a type ‘D’ 275/380 kV tower widely used within the UK having a height of almost 42 m. A fragment of the NEC2 input data for this transmission tower, illustrated in Figure 1, is shown in Table 2.

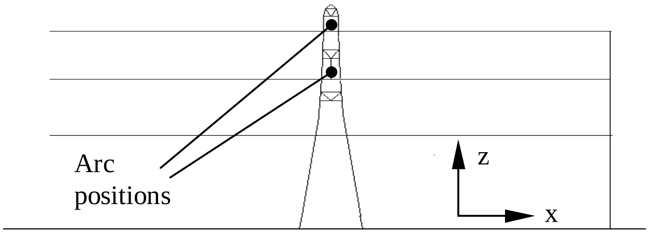

Figure 1: Tower with overhead lines and wire connection to ground.

```
CM          This is a test for model with
CM             conductor at 10MHz
CE
GW 1,5, 12.25,12.25,0, 6.5581,6.5581,40.5, 0.5
GW 2,5, 12.25,-12.25,0, 6.5581,-6.5581,40.5, 0.5
GW 3,5, -12.25,12.25,0, -6.5581,6.5581,40.5, 0.5
GW 4,5, -12.25,-12.25,0, -6.5581,-6.5581,40.5, 0.5
GW 5,4, 6.5581,6.5581,40.5, 4.25,4.25,77.75, 0.5
GW 6,4, 6.5581,-6.5581,40.5, 4.25,-4.25,77.75, 0.5
GS 0 0 .3048
GW 30901,1,9901,9901,9901,9901.0001,9901.0001
9901.0001,0.00001
GE 1
GN 1
EX 0 30901 1 00 1000 0.0
NT 30901 1 116 1 0 0 0 1 0 0
FR 0 1 0 0 10 5
EN
```

Table 2: Fragment of input data

At the beginning of each line there are two capital letters (CM, CE, GW), which are called the input data cards. They can be divided into geometry data cards and program control cards.

Firstly the input data deck must begin with comment line ‘CM’, and ‘CE’ terminates the comment lines. A line starting with ‘GW’ represents a cylindrical straight wire. The numbers following GW have special significance. The first two are a tag number, assigned to all segments of wire, and the number of segments into which the wire is divided, respectively. The following 7 numbers are the coordinates of the wire ends in

Cartesian form and radius of the wire (X_1, Y_1, Z_1, X_2, Y_2, Z_2, r).

The dimensions obtained for the tower, due to its age, are stated in imperial units. A useful feature of NEC, which works in metric units, is the ability to scale input data using the 'GS' card.

The line starting with 'GN' is the data card which specifies the ground type. Several types of grounds are available in NEC. In this project, a perfectly conducting ground has been used for simplicity.

It is useful to model the arcing current as a current source. Unfortunately in NEC a current source is not provided, although it can be created from a voltage source, a network and a point far off in space. The following three lines create a current source.

```
GW 30901,1,9901,9901,9901,9901.0001,9901.0001
9901.0001,0.00001
EX 0 30901 1 00 1000 0.0
NT 30901 1 116 1 0 0 0 1 0 0
```

The non-linear properties of the arc provide a broad range of frequencies that excite the tower into different oscillation modes. Although many models for power arcs exist, no models have been developed for the radio frequency range. In this work it has been assumed that the arcing current is discontinuous at the arc ignition and extinction, i.e. the current behaves as a step function locally to these points. Since the spectrum of a step function is of the form $1/\omega$, the frequency content at a specific frequency can be readily estimated for a known step amplitude. NEC, however, only works at one specified frequency at a time. Frequencies with amplitudes ranging from 1 A to 1000 A were modelled in NEC.

For the frequency specification 'FR', the frequency range is 10 kHz to 10 MHz. The configuration of the tower - especially the number of segments - is based on the frequency 10 MHz. This is because the tower at frequency 10 MHz will need the greatest number of segments for numerical computation accuracy. For the smaller frequencies, the model based on the 10 MHz can be utilised without loss of accuracy.

Finally, the line 'EN' is used to indicate the end of geometry data flag. A total of 141 segments are used for the modelling of the tower.

The conductors carried by the tower will affect the radiation of energy, and are modelled unattached to the tower. The arc is assumed to be the source of the radio frequency energy and is thus modelled as a current source, as described earlier. This source is sited at a position corresponding to the insulator arcing horns and is electrically connected to the tower and the relevant nearby conductor. For accuracy, the conductors have to be as long as possible and are terminated in ground connections at one side.

NEC allows the 3-dimensional computation of the electric field at an arbitrary position relative to the modelled plant. The results are given as components in mutually orthogonal x, y and z planes. The z direction represents the vertical plane whereas x and y represent the horizontal plane where the x axis is parallel to, and the y axis is perpendicular to, the line conductors.

3 ANALYSIS OF RESULTS

3.1 Variation in electric field with arc current

The arc was modelled by positioning the current source at the middle cross arm of the tower, although the effects of different positions are discussed later. The default voltage source value is 1 Volt (V). This will eventually give 1 Ampere (A), or the 'arc current'. During fault condition, the value of arc current can rise to hundreds or thousands times the nominal current.

The effect of changing the arc current can be observed in Figure 2. E_y is the y component of E-field calculated at 400 m away from the tower in the y direction. The frequency used in the calculation of the E-field is 10 MHz and the current source is varied.

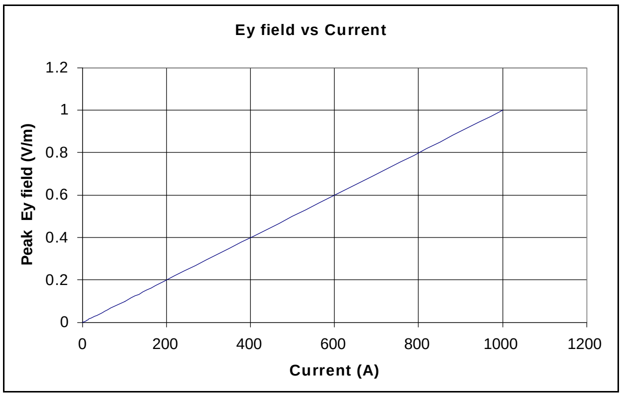

Figure 2: Graph of E_y against Arc Current

Figure 2 shows that the value of E-field increases linearly as the arc current increases. This is also true at other frequencies considered. The results can, thus, be scaled linearly. For future results, the current source is set to an amplitude of 1000 A. Although this is practically unrealistic for the frequencies considered, the value is suited to the analysis of the lower frequencies, such as 10 kHz and 100 kHz, since the E field results are generally very low and the 1000 scale provides better insight of the result

3.2 Relationship between frequency and electric field at a distance from tower

In order to find the dominant frequency of radiation within the 10 kHz and 10 MHz range modelled in NEC, a series of E-field results where obtained at varying frequencies. Experience with the software showed that the largest E-field component occurred in the vertical, or z direction. This result is consistent with the physical effect of the rf currents flowing vertically through the tower. Future results will, therefore, be for the E_z component. Two sets of results have been acquired: one set for the E_z field calculated at 1000 m from the tower and another at 5000m.

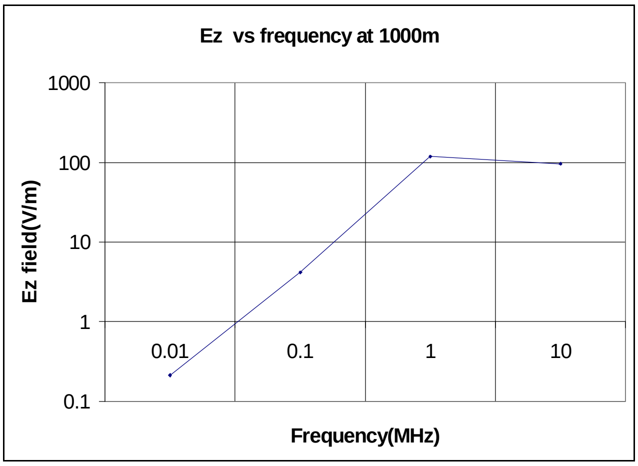

Figure 3: E_z versus frequency at 1000m from tower

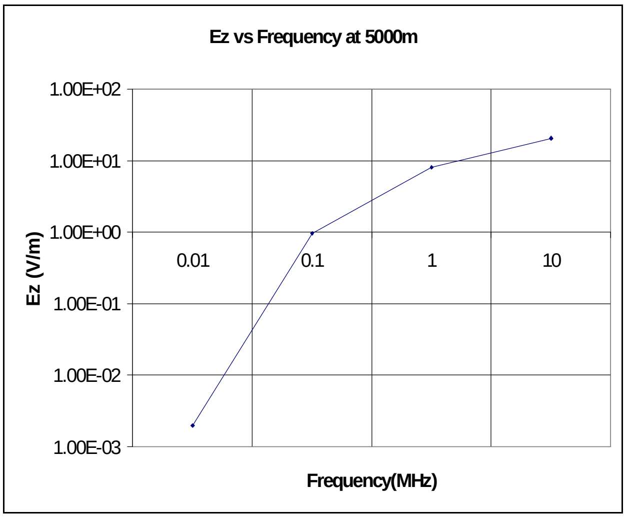

Figure 4: E_z versus frequency at 5000m from tower

Both sets of results, Figures 3 and 4, show that, generally, the E_z value increases with frequency. There is a slight exception to this in that the results at 1000 m show the peak to be situated at 1 MHz rather than 10 MHz, although the difference between the two frequencies is marginal. In terms of maximising the E-field for remote monitoring of arcing faults, this result shows that reception of either 1 MHz or 10 MHz components would be more favourable compared to the 10 kHz and 100 kHz components. Future results will concentrate on 1 MHz and 10 MHz.

3.3 *Radiation Pattern*

The radiation pattern shows a contour of constant field strength in three-dimensions. The projection of this pattern onto the x-y plane at 1 MHz and 10 MHz can be seen in Figures 5 and 6 respectively. In each figure the tower is at the centre of the plot and the conductors run from left to right.

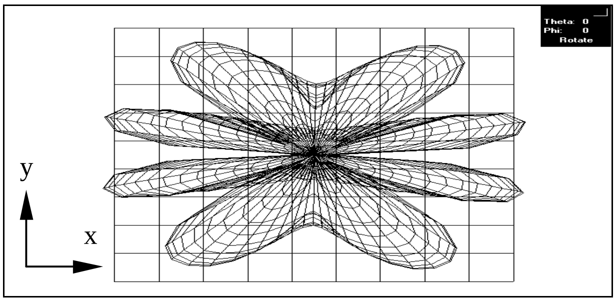

Figure 5: Radiation pattern at frequency 1 MHz

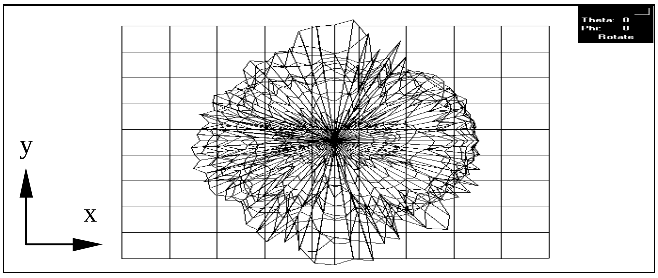

Figure 6: Radiation pattern at frequency 10 MHz

From Figure 5, 1 MHz, it can be seen that the radiation pattern has several clearly defined lobes. This is a disadvantage for remote monitoring since it is possible for the receiving antennas to be located in nulls, and thus be unable to detect the arcing event. By comparison Figure 6, 10 MHz, the radiation pattern resembles a circular pattern and the E-field appears to be evenly distributed. For this reason, it is convenient to choose 10 MHz as the dominant frequency of radiation.

3.4 *Polar plot gain*

The polar plot provides the two-dimensional plot for the gain of the modelled object (tower). Figure 7 shows the gain at 10 MHz where the direction 90° - 270° corresponds to the route of the line conductors. The lower gain on the right hand side of the plot of Figure 7 is due to the conductors being grounded on this side only.

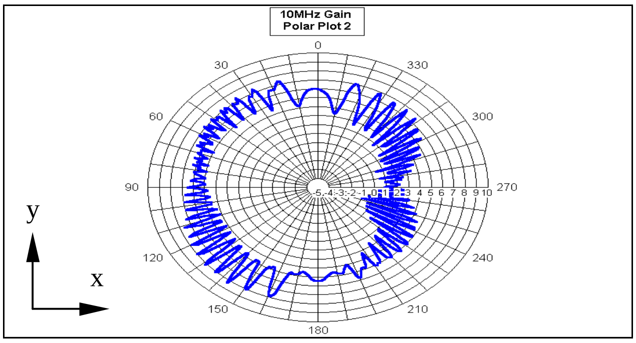

Figure 7: Polar plot of tower at 10 MHz

Figure 7 reinforces the results of Figure 6 that the radiation from the tower at 10 MHz does not contain any significant nulls and is reasonably represented at all angles. Thus, for a given distance, it is expected that the arcing event may be detected at any bearing from the tower. To prove this point it is necessary to use NEC to calculate the field at specific points.

3.5 *Effect of varying the bearing from the tower at a fixed distance*

In this test, the E_z field is computed at a fixed distance from the tower, with the bearing varied between 0° and 180° using the angle convention described in Figure 7. Figure 8 shows the variation of the E_z field with bearing, at a distance of 1000 m.

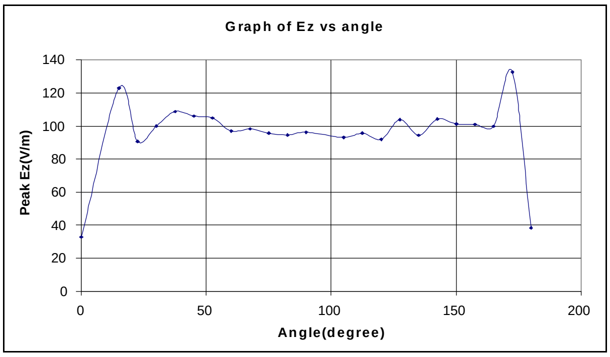

Figure 8: Graph of E_z versus bearing at 1000m

From Figure 8, it is clear that the E_z field is relatively constant over the majority of the bearing angle range. For angles of 0° and 180° the field diminishes since the observation point is under the conductors. Similarly, at 15° and 173° the E_z field has a peak caused by localised effects close to the conductors.

Figure 9 shows a similar effect where the distance is set to 5000 m. Again, it is clear that the E_z field is very well represented at all bearings. At angles in the region of 0° and 180°, Figure 9 shows different behaviour to Figure 8. This is due to the conductors being modelled with lengths of 3 km and hence at 5000 m, the radiated field not close to any conductor.

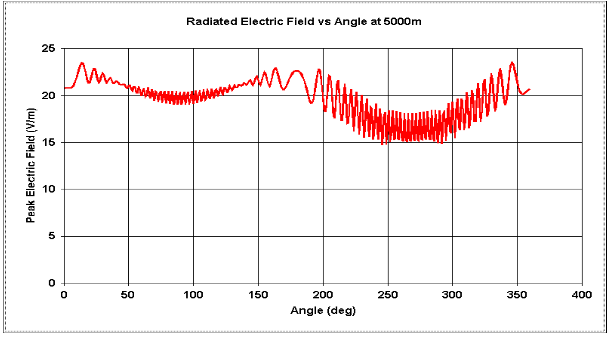

Figure 9: Graph of E_z versus bearing at 5000m

3.6 *Electric field variation with distance and height from the tower*

Figure 10 shows the peak electric field at a bearing of 90°, for a varying distance between 0 and 50 km from the tower.

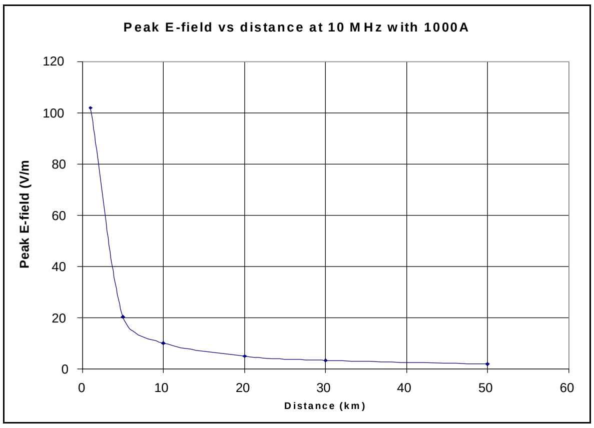

Figure 10: Peak electric field at different distances from the tower

Figure 10 shows that the E_z field decreases rapidly with increasing distance. In this result, the E_z field is calculated at 1 m above the ground plane. Varying this height made virtually no difference to the E_z field. Figure 11 illustrates this effect further for the E_z field, at a distance of 5000m, as the height is varied from 1 to 20 m. It is clear that the height of the receiving antenna makes little difference to the reception of the radiated signal from the tower.

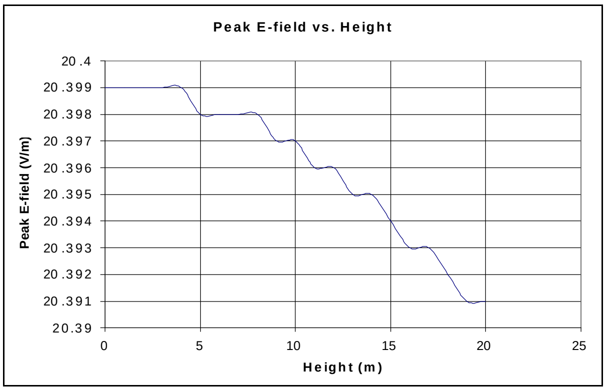

Figure 11: Peak electric field computed at different heights at distance 5000m

3.7 *Effect of longer conductors on the radiation pattern*

In the previous results, the line conductors are modelled as 3 km lengths. It is desirable to see the effect of longer conductor, although the increased number of segments, and thus computation time required, makes such an investigation very time-consuming. For this purpose, 3500 segments have been used and thus the conductor lengths are increased to 10.5 km. Figure 12 shows the radiation patterns, corresponding to Figure 6, generated by NEC with longer conductors.

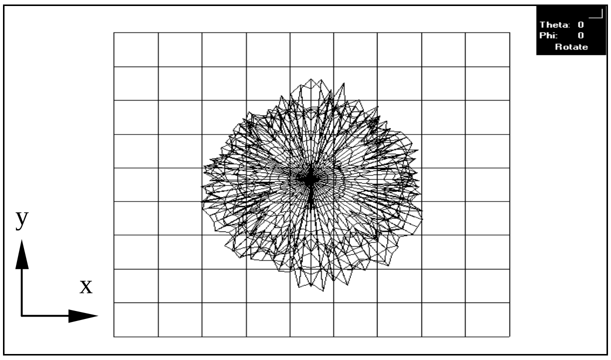

Figure 12: 10 MHz radiation pattern with longer conductor

Based on Figure 12, comparing to Figure 6, the pattern with longer conductors more closely resembles a circular pattern. This is a more desirable result than the one generated by the shorter conductor.

The polar gain plot of the gain with longer conductors is shown in Figure 13.

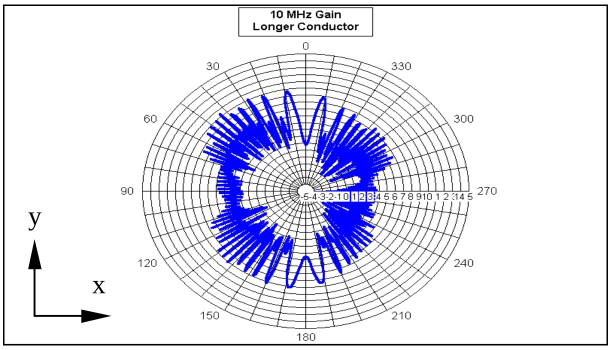

Figure 13: Polar plot for tower gain with longer conductor

Again comparing Figure 13 with Figure 7, one distinctive feature is the overall gain of the tower. The maximum gain for shorter conductor is about 8 dB, whereas for the longer conductor it is more than 10 dB. In general, the gain is higher with longer conductors and so the earlier results represent more stringent conditions than may be expected in practice.

3.8 Effects of different positions of the arc

So far the current source used to model the arc is positioned on the middle arm of the tower. The effects in the radiation pattern and electric field due to different arc positions were investigated.

Figure 14 shows the radiation pattern generated at 10 MHz where the current source is positioned on the upper cross arm of the tower. Similarly, Figure 15 shows the E-field at 5000 m from the tower as a function of bearing angle.

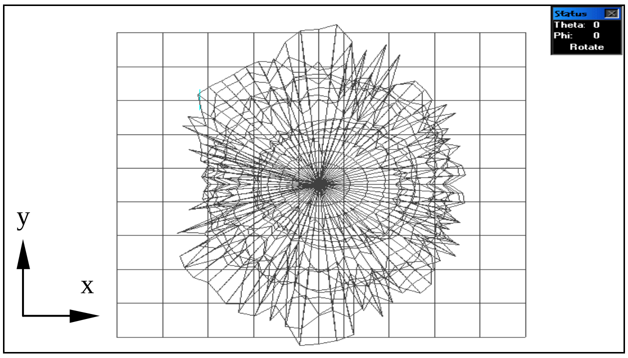

Figure 14: Radiation pattern at 10 MHz with current source at the upper arm

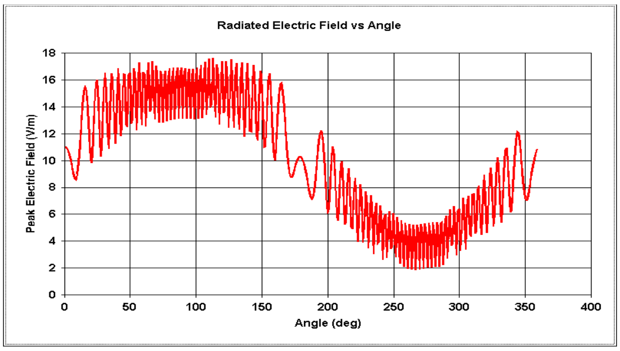

Figure 15: Graph of E_z versus bearing at 5000m with current source at the upper cross arm

From Figure 14, the radiation pattern is observed to remain approximately circular as previously shown in Figure 6. However by inspection, the E- field waveform in Figure 15 is not the same as the one generated by current source at the middle arm (Figure 9). The lowest point is at 2 V/m for current of 1000 A. Hence it can be seen that changing the position of the current source has a significant effect on the radiation pattern and electric field distribution around the tower.

4 MAXIMUM DISTANCE OF DETECTION

Arcing current is difficult to model; assumptions have been made in the calculation. The results show that the tower will produce a complicated radiation pattern. However, if it is assumed that the tower is an isotropic antenna – radiates equally in all directions - then standard radiocommunications theory can be applied. The carrier power available at the receiving antenna is given by

$$C\ (W) = P_T G_T \left(\frac{h_T h_R}{R^2}\right)^2 G_R \quad \text{(Watts)} \qquad (3)$$

where P_T is the transmitted power, G_T and G_R is the gain of the transmitting and receiving antenna respectively. R is the distance between the transmitting and receiving antenna.

It can also be expressed as the root mean square of the electric field, $E_{RMS,}$ which is given by

$$C\ (W) = \frac{E_{RMS}{}^{2}}{Z_{0}} \cdot \frac{\lambda^{2}}{4\pi}\ \ \text{(Watts)} \qquad (4)$$

Where Z_o is the plane wave impedance of free space, which has the value 377Ω. λ is the wavelength of electromagnetic wave at the frequency 10 MHz. The term $\frac{\lambda^2}{4\pi}$ corresponds to effective area of an antenna with gain 1(0 dB).

4.1 Minimum electric field needed for detection

The dominant frequency of radiation chose for this project is 10 MHz. For the reception, a receiver having a minimum sensitivity 1.25μV at frequency range 2 MHz to 10 MHz has been assumed; this is a typical figure from a standard communications receiver. From this sensitivity the minimum E-field required to drive the receiver at 10 MHz is E_{RMS} = 0.405 $\times 10^{-6}$ V/m or the peak value, E_{Peak}= 0.573 $\times 10^{-6}$ V/m. This is the value needed to just drive the receiver.

4.2 Maximum range of detection

From the NEC output files, the radiated power is calculated to be 74.5 Watts, which is the power radiated by a fault current of 1 Ampere at 10 MHz. As shown in Figure 7, there are 360 different values of gain at different angles. Gain G_T is sorted ascending. To obtain 100 percent probability of detection, the lowest gain value is –0.95 dB. The receiving gain is assumed to be 0 dB. The height, h_t of the current source is 29.6m above the ground. The height of receiving antenna is assumed to be 1 meter.

Using the equation (3), the value of R is 36 kilometre.

5 CONCLUSIONS

NEC has been applied to calculate the radiated electric field pattern from a 400 kV overhead transmission tower under single phase to earth arcing fault conditions. In order to maximise the distance at which the arcing may be detected, the highest frequency - 10 MHz - is concluded as the optimal choice. This decision is based on the radiation efficiency of the tower at this frequency, and also on the uniformity of the field pattern.

Investigations into the height of the receiving antenna showed that this parameter has little effect on the strength of the field sensed within the range 1 to 20 m. However, the position of the arc on the tower affected the far-field signal strength at various positions.

Using conventional radiocommunications theory, the furthest distance that an arcing event could be detected using standard receiver technology is 36 km.

This study has proved that NEC provides a viable method of predicting arcing induced transient radiation from power system plant. Future work will concentrate on overcoming the processing and memory limitations associated with its use in order that more accurate results from overhead towers and other plant items may be produced.

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