Numerical Calculation of Insulator Voltages in Transmitting Antennas
Comparison with Measurement

Peder Hansen, Wendy Massey
SPAWAR Systems Center Code 85, San Diego 92152

Introduction

High power transmitting antennas, especially in the lower frequency ranges (VLF, LF, MF, and the low end of the HF band) are often supported by insulated guyed masts. A significant part of the design problem is to specify the location and size (voltage) of the insulators in the antenna system. For antennas having many insulators, the cost of the insulators alone can be a large part of the total cost. The weight of the insulators must also be considered in the structural design and the added weight can significantly increase the cost of the structure. Standard design practice is to attempt to optimize the insulator locations and sizes to minimize the cost of the antenna.

The size of an insulator is primarily determined by the voltage that appears across the insulator in operation. Specification and selection of insulators in the past has been based on empirical methods including electrostatic model measurements. Numerical calculations using thin-wire method-of-moment codes provide a method for estimating insulator voltages but there is little data available to validate calculated voltages, consequently large safety factors are often used. It is desirable to have a validated method for estimating insulator voltages throughout an antenna system. Such a method will have application for the design of new transmitter antennas as well as in the determination of power limitations for existing antennas.

An experiment has been designed to provide measured data for comparison with calculations. A simple model antenna was constructed having several insulators in a single guy. Insulator voltages have been measured using a novel reciprocity-based technique to overcome problems associated with direct measurement of insulator voltages. The calculations were done using the Numerical Electromagnetic Code (NEC) [1] with the insulators modeled as point capacitance loads. The results show good agreement, mostly better than 10%, adequate for design. However, the presence of systematic differences suggests a technique for improving the numerical model.

Antenna Model

The antenna model selected was a 6-meter vertical above ground with the feed point at the base (Figure 1). A single guy cable connected the top of the vertical element to the ground screen at an angle of 45 degrees. The guy cable contained 14 small fixtures designed to hold capacitors that simulate insulators located at various locations.

Nine insulator-location configurations were tested, having between one and five capacitors. The insulator locations for these configurations were filled with 50-pF capacitors for one set of measurements and with 10-pF capacitors for a second set of measurements. These values of capacitance were selected to approximate the range of capacitance for insulators used in practice. A short was installed in the unused fixtures.
Measurement Technique

The measurement technique made use of reciprocity. A battery-operated device that could be suspended at the elevated insulator locations was used to inject current into the insulator port (Figure 2). The resulting voltage at the antenna feed point was measured using an RF voltmeter with a high impedance probe. This approach avoids problems associated with direct measurements of voltage on an elevated insulator. Reciprocity requires the mutual impedance be the same in both directions.

The current source operated on 2 MHz. At this frequency, the antenna is electrically small. The source had a series resistor ($R_s$) switched in and out at 5-second intervals. The value of $R_s$ was selected to ensure a significant difference in the high and low voltage measured at the feed point. Three values of $R_s$ were used: 1, 5.1, and 10 kilohms. The source voltage $V_s$ was measured before and after measurements and found to be stable over the measurement period of 2 to 3 minutes.

For each insulator position to be measured the source was suspended in place and two values of feed point voltage were recorded, $V_{high}$ and $V_{low}$ corresponding to the two conditions for $R_s$. The knowledge of $V_s$, $R_s$, $V_{high}$ and $V_{low}$ is sufficient to determine the magnitude of the mutual impedance from the insulator to the base.

\[
|Z_{21}| = \frac{V_h}{V_s} R_s \cdot \sqrt{\frac{V_i^2}{V_h^2 - V_i^2}}
\]

Calculations
NEC was used to calculate $Z_{11}$, the base input impedance and $Z_{ij}$ the mutual impedance between the base and the various insulator positions. The lead coming down from the antenna top was modeled as a continuous wire with the insulators simulated by point capacitance loads located in the segments corresponding to the insulator positions. The capacitance was equal to that placed in the model plus 1 pF to account for the fixture. Measurements were taken with both 10 pF and 50 pF capacitors used to simulate insulators. This model did not account for the extra capacitance of the shorted fixtures.

**Comparison of results**

The results for 50 pF capacitors are shown in Figure 3 in terms of the percent difference relative to the measured value. A positive percentage means the measured voltage was higher than calculated. The results for 10 pF are similar but have more variation.

![Figure 3. Measured versus calculated voltages for 50 pF capacitors](image)

Examination of the figure indicates there is a systematic tendency for the measured voltage to be higher farther down from the top of the wire. The majority of this is attributed to the effect of the stray capacitance from the fixtures and the source leads, especially as the source comes closer to ground. The source itself was shielded with tin foil (Figure 2), which helped to reduce this effect. An improved version of this test would have a smaller source with minimum connection lengths. In addition, the signal from the lower insulators was weaker and noise may be a factor there.

The largest errors occur in the first insulator of configuration 6. This configuration has three contiguous insulators at positions 2, 3, and 4. This configuration simulates the common practice of using contiguous insulators to withstand a higher voltage. In this case, the first insulator has much less voltage than calculated (-10% for 50 pF and –20% for 10 pF). However, the total voltage across the 3 insulators differs from the measured total by less than –5% for both cases. Thus, the total voltage across the insulator string is
close to the measured value but the distribution of voltage on the individual insulators is not. Again, this is mostly attributed to the stray capacitance from the fixture ends and source connection wires, which are not accounted for in the NEC model. This suggests an modified method for calculating insulator voltages by using thin wires to model the capacitance of the insulator ends and measuring the voltage between the ends using a resistor with a value greater than the capacitive reactance between the insulator ends.

NEC was also used to calculate the input impedance of the various configurations for comparison. Table 1 gives statistical parameters of the comparison of both the transfer impedance and the input impedance. Note that the magnitude of the calculated input impedance ($Z_a$) is very close to measured values with a standard deviation of 2%.

<p>| Table 1. Percent difference between measured parameters and calculated parameters over all configurations |
|---------------------------------------------------------------|---------------------------------|
| 50 pF set | 10 pF set |</p>
<table>
<thead>
<tr>
<th>$Z_{21}$</th>
<th>$Z_a$</th>
<th>$Z_{21}$</th>
<th>$Z_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-.012</td>
<td>2.83</td>
<td>4.69</td>
</tr>
<tr>
<td>Std Dev ($\sigma$)</td>
<td>4.33</td>
<td>1.42</td>
<td>8.81</td>
</tr>
<tr>
<td>Extrema</td>
<td>-9.93</td>
<td>-0.75</td>
<td>-21.39</td>
</tr>
<tr>
<td></td>
<td>+8.2</td>
<td>+5.09</td>
<td>+15.09</td>
</tr>
</tbody>
</table>

The mean difference in $Z_{21}$ for the 50-pF set is strikingly small, while the extrema and standard deviation indicate the data is spread. Some of this spread is systematic with the calculations giving voltages that are too low for the insulators farther away from ground (with higher voltages on them) and too high for insulators closer to ground. Unaccounted for stray capacitance would cause the difference to vary in this manner. The fact that the variation is greater when the smaller 10 pF capacitors were used supports this conjecture.

The extreme negative variations for both 10 pF and 50 pF were due to configuration number 3 with the 3 contiguous insulators. The largest difference occurs on the first insulator, however, the total voltage across the 3 insulators was close to that calculated. The extreme positive variations were from the insulators near ground. This is attributed to the increased stray capacitance from the fixtures and proximity of the hanging source to the ground. These insulators have less voltage so the error has less impact on the cost.

**Conclusions:**

Numerical techniques can be used to calculate transmitting insulator voltages to engineering accuracy. However, using point capacitor loads to model insulators leads to a systematic error resulting in too little voltage predicted for insulators with higher voltages and too much voltage predicted for insulators with lower voltages. The difference is especially significant when insulators are not separated. Refinement of the numerical technique to model the extra capacitance due to the insulator ends is likely to help alleviate this systematic error and provide increased accuracy.

**References:**