

# A Beginner's Guide to Modeling With *NEC*

## Part 4: Loads, transmission lines, tests and limitations

**In** this fourth and final installment of our series designed to get you started in modeling with *NEC*, we'll look at two disparate areas of modeling. The first arena involves a pair of auxiliary facilities built into *NEC*: the ability to model reactive (capacitive and/or inductive) loads and the ability to model transmission lines—both within limits. The second area is composed of model testing and some of the limits within which successful modeling occurs. Some words of caution will be a good way to conclude our preliminary survey. As we have done in the first three parts, we'll focus on *NEC-2* and two commercial implementations: *EZNEC 3.0* and *NEC-Win Plus*.

### Currents and Current Sources

In the very first episode of this series, we noted that using a voltage source is the most normal procedure for simple models with a single feedpoint. We can leave the source values at a magnitude of 1.0 and a phase of 0.0 degrees (the default values) for most models, since the criti-

cal output data in which the beginning modeler is interested does not depend on the source values. Gain, front-to-back ratio and the source impedance will come out the same for a single-feed antenna no matter what source values we use.

Sometimes it is convenient to use a current source. Should you wish to model phased arrays, you'll need to use current sources to establish the relative magnitudes and phases of currents for the feedpoint of each driven element. Our beginning project, however, will be much simpler: we want to look at the current levels along a simple dipole. We can do this by using a voltage source, but the typically low current values tend to be hard to interpret without some further arithmetic. If we only had a way to set the source current at a value of 1.0, then all of the other values along the dipole would be relative to 1 for easier comprehension.

Commercial versions of *NEC-2* provide a current source capability. The network used to transform the natural voltage source of *NEC* into a current

source at the antenna feedpoint is invisible to the user. However, by selecting a current source and using the default value of 1.0 for the magnitude, we can perform our survey with ease.<sup>1</sup> Our one caution is to note that while the *NEC* core and *NEC-Win Plus* use peak values of voltage and current, *EZNEC* translates these values into their corresponding RMS values. For our work here, the difference will not have significance, but for translating voltage, currents and impedances into power levels and back again, peak values must be transformed into RMS values.

Now let's build a simple free-space (no ground) model, a 20-meter (14.175 MHz) dipole using 1-inch diameter aluminum, 21 segments, and a modeling length along

<sup>1</sup>Notes appear on page 35.

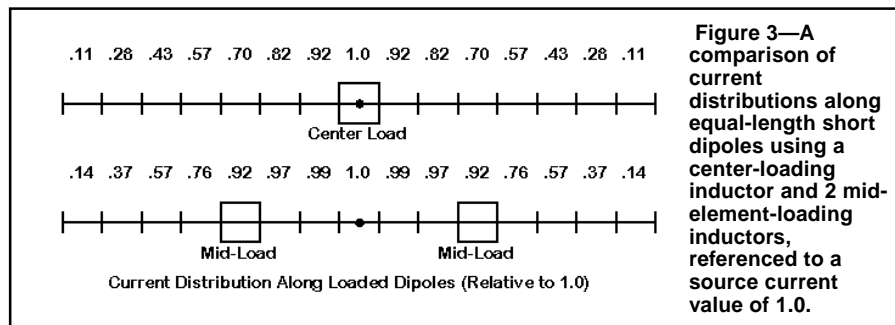
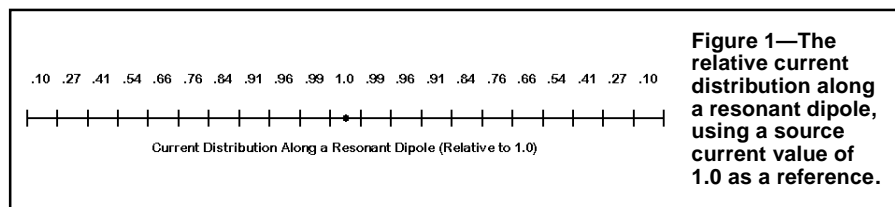


Figure 2—The *NEC-Win Plus* basic entry screen for a load consisting of a resistance and a reactance in series (called a “complex load”).



Figure 4—The *NEC-Win Plus* basic entry screen for loads consisting of a resistance and an inductance in series. A series capacitor, not used in this example, could be added to the mixed load. Note that parallel combinations of resistance, inductance and capacitance are also possible.

the Y-axis of  $\pm 198.75$  inches. We should find a source impedance at the design frequency of about  $72 \Omega$  with only a fraction of an ohm of reactance.

Our interest lies in Figure 1, a summary of the current magnitude on each segment of the model. *NEC* provides these values, and commercial implementations make them available as one of the tabular outputs. Figure 1 will be a standard for the next phase of our work, but for the moment, we can note two key items. First, the progression of values is almost, but not quite, a sinusoidal curve. Second, the lowest value is not zero because the calculation is for roughly the center of the outermost segment, not the very end.

## Loads

Next, let's shorten the dipole to  $\pm 144$  inches, or 24 feet overall. Reduce the number of segments to 15 so that each segment will be about the same length as in the original longer dipole. The shortened antenna, of course, will not be resonant. In fact, it will report a source impedance of about  $27 - j275 \Omega$ . If we want to resonate the antenna, we shall have to compensate for the high capacitive reactance with loading coils somewhere in the antenna structure.

*NEC* lets us model reactive loads. The loads can have a resistive as well as a reactive component, as shown by the *NEC-Win Plus* load screen in Figure 2. Adding a series resistance to the reactance lets us account for the Q of the loading coil. Note the reactance value:  $276 \Omega$ , just enough to compensate for the capacitive reactance. The resistance value ( $0.9 \Omega$ ) reflects a coil Q of 300. The upper left corner of the figure shows that the load has been placed at the center of the antenna, on the same segment as the source. Loads are always in series with a source on the same segment.

All loads that we introduce are mathematical models, not physical models. The difference is this: a physical model, such as the antenna wire, contributes to the radiation pattern. The mathematical loads do not. So any variations (normally insignificant) in radiation patterns that result from using large or small coils will not show up in the output of *NEC*.

If we run our model with its load, we'll find a source impedance of about  $31 \Omega$  and a fractional value for reactance. Remember that the inductive reactance of the load cancelled out the capacitive reactance at the source by simple addition. In series circuits, we add resistances and add reactances. The added resistance of the coil shows up in the resistive part of the source impedance.

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We need not always use a center loading coil. Instead, we can place coils in the middle of each antenna leg away from the feedpoint. If we remove the center loading coil, we can replace it with a coil 30% from the left end (segment 5) and another matching coil 70% from the right end (segment 11). Experimentally, we can adjust the reactance of the two coils until the antenna is once more resonant. For the 24-foot 20-meter model, values of  $j 212 \Omega$  (reactance) will do the job, and for a Q of 300, we can assign the resistance box a value of  $0.7 \Omega$ . Running our new mid-element loaded dipole will yield



Figure 5—The *EZNEC* screen for introducing a mathematical transmission line into a model.



Figure 6—The *NEC-Win Plus* screen for introducing a mathematical transmission line into a model.

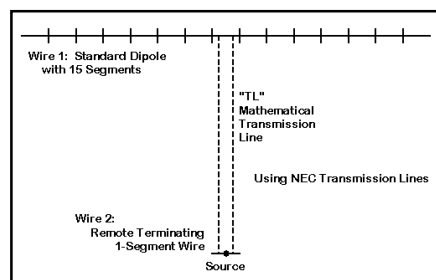


Figure 7—A standard use of a transmission line between the antenna wire and a short, 1-segment terminating wire that becomes the location of the antenna system source.

a resonant impedance of about  $45 \Omega$ . The impedance value is higher than with center-loading, but lower than the impedance of a self-resonant dipole.

Before we leave the loaded dipoles, let's look at the current tables (since we used a current source for our runs). Refer also to Figure 1 for comparison. The current level on the antenna wire past the loads suddenly decreases relative to the current distribution on an unloaded dipole. Hence, we would expect either loaded dipole to show somewhat less gain than the unloaded standard.

There are some cautions to observe for loads. First, the mathematical load assumes equal currents on both ends of a coil. As Figure 3 shows, this condition only exists for the center loading coil, but not for the mid-element coils. Hence, the calculations you make for mid-element loading coils will be slightly less precise relative to building the coil. Second, using the coil's reactance is good only for a single frequency. If you wish to perform a frequency sweep of the antenna, re-enter the coil values, an inductance and a resistance in the series RLC option for entry, as shown in Figure 4, a *NEC-Win Plus* load box for the center loading coil. Standard handbook equations for transforming reactance to inductance (or capacitance) apply here.<sup>2</sup> Some implementations of *NEC* call for  $\mu\text{H}$  and  $\text{pF}$ , while others may call for basic units. With inductive, capacitive, and resistive units, loads will show the correct reactance at each checkpoint of a frequency sweep, and the resulting source impedance values (and SWR values, if needed) will be much closer to the reality of the antenna's performance.

## Transmission Lines

A second mathematical convenience offered by *NEC* is the use of transmission lines in a model. Like loads, these lines do not enter into the calculation of radiation patterns. If the pattern influence of a transmission line is significant to a model, the modeler must physically model the line, which is possible for parallel lines, but not generally feasible for coaxial cables.

Figure 5 shows the *EZNEC* transmission line entry screen, while Figure 6 shows the *NEC-Win Plus* equivalent. Both show the same line: a shorted stub of  $600\text{-}\Omega$  line having a length of 11.02 inches or 0.2799 meters. *EZNEC* provides an invisible structure for open and shorted stubs, while *NEC-Win* shows the actual construction. Every transmission line must run from one wire to another. In *NEC-Win Plus* or raw *NEC*, we create a new short (1 segment) thin wire that is

far away from the antenna. Its position is not critical, since the line length entered into the proper box on the transmission line screen controls the calculation. A shorted stub requires a high shunt admittance. The long numerical entry for  $1^{10}$  (1 to the tenth power) is used to assure a true short circuit at the far end. Note in passing that we can reverse the line between the two terminating wires, essentially giving it a half twist—a useful feature for modeling phased arrays.

The transmission line entry boxes illustrate the critical elements of a *NEC* transmission line. Figure 7 shows the layout of such a standard sort of model using a transmission line used with a dipole. The dipole wire is one end of the line, while a new short 1-segment line terminates the transmission line. For this kind of application, we move the source from its usual position at the center of the dipole and place it on the new wire. We might wish to see what impedance we might obtain at the end of the line using various line lengths. We need only change the line length, perhaps in quarter-wavelength increments, to explore the effects of line length on the system source impedance. Note that some programs have a velocity factor entry box, which lets you enter the physical line length. Other programs do not have a velocity factor box, so you must precalculate the electrical length of the line and use that figure.<sup>3</sup>

There are cautions to observe in the use of *NEC* transmission lines. First, they do not account for line losses. For short line runs, the source impedance error will likely not be significant, but the error will grow with very long transmission line runs. Second, transmission lines are in parallel with sources (in contrast to loads, which are in series with sources). Third, transmission lines are accurate only where the antenna element current on each side of the line is equal. Hence, they are most accurate at element centers and other low impedance points along an antenna and become quite inaccurate at low current, high voltage positions.

Transmission line runs to a remote source are only one use of this *NEC* facility. Stubs are also useful for modeling some kinds of matching networks for antennas. For example, consider the 20-meter 3-element Yagi in free space, as shown in Figure 8. Before adjustment with a matching network, it has a source impedance of about  $24 - j25 \Omega$ . The resistance and capacitive reactance are exactly suited to the use of a beta match. We can implement the match with a small coil across the feedpoint or with a shorted transmission line stub (often called a “hairpin”). In fact, the stub that we used

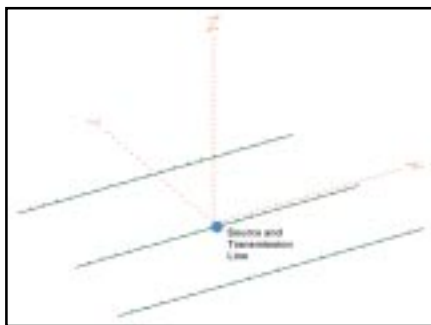


Figure 8—An *EZNEC* view of the 3-element Yagi with a beta-match shorted transmission-line stub (hairpin) at the driven element terminals.



Figure 10—The *NEC-Win Plus* report on the results of the average gain test for the 3-element Yagi used for the beta-match illustration.

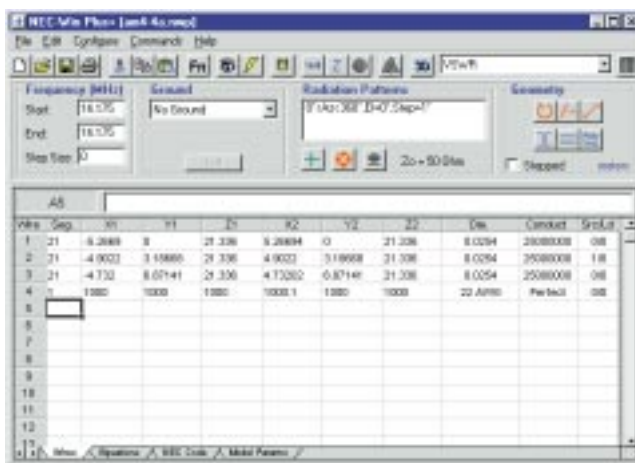


Figure 9—The *NEC-Win Plus* wires page for the 3-element Yagi and beta-match stub, showing the remote terminating wire for the transmission-line stub.

to illustrate the basic transmission-line setup in Figure 5 and Figure 6 is exactly what we need to introduce an inductive reactance of about  $50 \Omega$  across the antenna terminals. Because transmission lines are mathematical and use remote terminating wires for stubs, Figure 8 does not show the stub, but indicates its presence with a dot. (If the view tried to show the terminating wire for the stub, the antenna structure itself would shrink almost to invisibility in the graphic.)

Figure 9 shows the *NEC-Win Plus* wires page that goes with Figure 6, the corresponding transmission line screen. Wire 4 is the remote 1-segment thin wire that terminates the shorted stub. The units of measure are meters, which coincides with the stub length in Figure 6. If we run the model, we should get a source impedance at 14.175 MHz of about  $51 - j3 \Omega$ . You may wish to run a frequency sweep of the antenna across the entire 20-meter band to check the 50- $\Omega$  VSWR at the band edges.

Besides their use as standard transmission lines and as stubs in matching networks, transmission lines have other uses in advanced modeling. For example, the phase-line needed in a log periodic dipole

array (LPDA) runs from one element to the next with a half twist between each element. Such structures are extremely difficult to model physically, but the transmission line facility in *NEC* not only simplifies the process, but as well increases the accuracy of the array analysis. Used with care and with their mathematical (non-physical) nature always in mind, transmission lines in *NEC* can be a valuable design tool for many types of antennas.

## Testing Models

I have stressed that both loads and transmission lines must be used with care and within their limitations if we are to achieve accurate model results that coincide closely with the physical antennas the models represent. This same caution applies to the physical structure of models. There are two general tests that we can apply in order to increase our confidence in a given model.

The first analysis is called the convergence test. In Part 1 of the series, we noted the minimum number of segments to be used on open-ended linear elements. However, as the antenna geometry becomes more complex, we may need more than the minimum number of segments

to assure an accurate model. Moreover, segment length should ideally be about the same throughout a model. Whether we have enough segments of the right lengths is subject to a simple test.

Start by running the original model and recording the gain and source impedance. Then increase the number of segments for each wire by about 50%. Again, record the gain and source impedance. You may wish to give the test a third trial with another 50% increase in the number of segments per wire and record the results.

The level of segmentation at which the output figures for the model do not change significantly is the minimum level of segmentation for the model. The models are said to converge at this segmentation level. In some cases, minimum segmentation is satisfactory. In others, especially for antennas having a closed geometry (like angular loops), the required segmentation level may be higher. A few antennas, such as those with angular elements of different lengths extending from the feed point, may not converge until very high levels of segmentation. And some models will not converge at all because they exceed the limitations of the *NEC* core or have other construction errors. There is no absolute standard of what counts as the borderline between converged and non-converged models. However, if two successive levels of segmentation produce results that indicate differences in antenna performance or structure that go beyond normal tune-up adjustments, the models are likely not sufficiently converged.

A second test is called the average gain test. If we place a horizontal antenna model in free space or a vertical antenna over perfect ground, we can then perform a 3-dimensional radiation pattern test, using equally spaced checkpoints. To perform the test, we omit wire losses and resistive loads. The reason for these moves is that the average gain of a lossless antenna, taking into account a fair sampling of all possible directions of radiation, is 1. Resistive losses would interfere with this result.

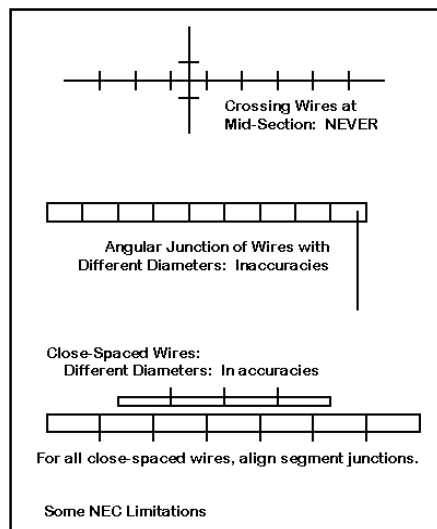
For the 3-element Yagi that we used to illustrate the beta matching stub, we receive the *NEC-Win Plus* report shown in Figure 10. Equal in quality to the 0.999 average gain value would have been 1.001, since the test is run with a large but not exhaustive sample of directions for the radiation pattern checkpoints. Again, there is no absolute standard for what counts as “highly accurate.” The level may depend on whether we are preparing to home brew an antenna or whether we are deriving some detailed

performance trends. For most uses, values of 0.95 to 1.05 for the average gain test indicate a very usable model for virtually any purpose.

However, both the convergence and average gain tests are necessary conditions of model adequacy. They are not sufficient conditions. There are at least a few types of models that can pass both tests and still yield inaccurate results. However, passing both tests should increase our confidence that we have a good model.

### NEC Limitations

A bad model (one which fails either



**Figure 11—Some *NEC* limitations, including the prohibition against wires crossing at mid-segment locations, and accuracy difficulties with angular junctions of wire having different diameters and close-spaced wires of different lengths or diameters.**

*Most of the NEC core rejection messages occur due to simple mistakes in creating or revising the geometry of an antenna model. The solution is to find and correct the error.*

or both tests) does not necessarily mean that the modeler is at fault. *NEC* has limitations. We saw some of those limitations in Part 1, when we noted certain guidelines for the minimum segment length to diameter ratio, segments per half wavelength of wire, etc. There are others, a few of which are illustrated in Figure 11. For example, letting two wires touch at mid-segment points (in contrast to junctions) will trigger the *NEC* core to reject the model. Most of the *NEC* core rejection messages occur due to simple mistakes in creating or revising the geometry of an antenna model. The solution is to find and correct the error. By using the paper planning techniques shown in Part 2, we minimize the chances of receiving a core rejection notice.

More subtle are *NEC* limitations that the core does not signal with a rejection message. For example, *NEC* will normally yield inaccurate results when two wires of different diameters meet at an angular junction. The difficulty grows more pronounced as we add more segments to each wire. Consider a folded X-beam composed of 1-inch aluminum elements in the facing V sections with thin wire tails pointing toward each other in each side of the structure. This antenna will not converge at any level of segmentation in *NEC*.<sup>4</sup>

Likewise, *NEC* can grow inaccurate when two wires of different diameters are brought close together. Wires of the same diameter should have their segment junctions well aligned when in proximity for highest accuracy, for example, with a folded dipole. However, even if the segment junctions are aligned, wires of different diameters and lengths will show errors of both gain and source impedance as they approach too closely. The degree of error depends on many factors, including the wire diameter, the spacing, the frequency, and the relative element lengths. The average gain test will normally catch this overstep of the limitations inherent in *NEC*.<sup>5</sup>

The *NEC* core also has a limitation in handling tapered-diameter elements, that

Wires											
No.	U (ft)	V (ft)	W (ft)	Gain	U (ft)	V (ft)	W (ft)	Gain	Int.	Segs.	
1	0	4	36	0.000	0	4	36	0.000	0.000	3	
2	0	4	36	0.000	0	4	36	0.000	0.000	3	
3	0	4	36	0.000	0	4	36	0.000	0.000	3	

Stepped Element Correction											
No.	U (ft)	V (ft)	W (ft)	Gain	U (ft)	V (ft)	W (ft)	Gain	Int.	Segs.	
1	0	1.000	36	0.000	0	1.000	36	0.000	0.000	3	
2	0	1.000	36	0.000	0	1.000	36	0.000	0.000	3	
3	0	1.000	36	0.000	0	1.000	36	0.000	0.000	3	

**Figure 12—A sample, from *EZNEC*, of the original tapered-diameter element and its uniform-diameter Leeson substitute.**

is, elements composed of ever-smaller diameters of tubing as we move outward from the element center. However, commercial implementations of *NEC*, including both *EZNEC* and *NEC-Win Plus*, offer the modeler a system of carefully calculated substitute elements having a uniform diameter. The corrective elements are based on the work of Dave Leeson, W6QHS (now W6NL).<sup>6</sup> Using a complex set of equations, the program precalculates substitute elements. However, the equations only work within about 15% of the design frequency and on symmetrical open-ended linear elements with no mid-element loads or transmission lines. Despite these limitations, the correction factor has been a boon to designers of directional arrays for the upper HF and lower VHF region.

Figure 12 provides a small sample of the Leeson corrections in action, using *EZNEC* as the source. The upper part of the figure shows the 3-wire dipole used as an example in Part 2 of this series. The lower portion of the figure shows the substitute elements that replace the tapered diameter model in *NEC* calculations. Note that the uniform-diameter element is not simply the average of the two diameters in the tapered-diameter version. As well, the uniform-diameter version is shorter than the physical dimensions being modeled. Elements that taper toward thinner diameters as we move away from the center feedpoint require longer physical element lengths for resonance than do uniform-diameter elements. Finally, note that the length dimension affects not only the outer ends of the element, but the length of the inner element piece as well.

The Leeson corrections have made the design of Yagis and similar directional arrays routine. Of course, the corrections must be used within the limitations that we noted above. The upshot is that there are arrays which are difficult (if not impossible) to model within *NEC*. Nonetheless, despite the limitations, *NEC* is capable of accurately modeling an almost endless variety of antennas for frequencies ranging from below the AM broadcast band into the upper UHF region.

## Conclusion

We have explored *NEC-2* modeling with the eyes of a beginning modeler, starting from the basic language of the modeling enterprise and ending with some fairly advanced cautionary notes about the limits of *NEC-2*. We have not exhausted all of the possibilities for combining the features of the *NEC* core and its commercial interfaces to improve the precision of our analyses or to ease the work involved in creating models. For

*Elements that taper toward thinner diameters as we move away from the center feedpoint require longer physical element lengths for resonance than do uniform-diameter elements.*

example, we have not mentioned trap antennas, which can be modeled with good results. We have not delved into modeling by equation, which can simplify the construction and revision of models and so speed up the design process. And we have not touched upon the modeling or complex structures, such as typical tower sections, or the use of substitute models.<sup>7</sup>

What we have attempted to do in this 4-part series is to acquaint you sufficiently with the fundamentals of *NEC* modeling so that you can embark on your own exploration of the antennas in which you have the most interest. Hopefully, there is enough information in these notes to make your initial efforts successful and make the next steps confident ones on your own.

Think of *NEC* as a precision tool. Even as I write, various improvements to the modeling process—some general, some for specific applications—continue to develop. However, even though *NEC-2* is nearly two decades old, it remains far more precise than older calculation methods. It is superior by far to those rules of thumb by which we measure dipoles and quads, and it is a distinct advance in antenna pattern and gain analysis compared to aperture-area calculations that were popular in the middle of the 20th century. In short, *NEC* is a good tool for the student of antennas to master as we move into the 21st century.

However, like every precision tool, *NEC* requires care, practice, patience, and focus to master well. What we learn about antennas along the way will be the reward for our efforts.

## Notes

<sup>1</sup>Users of raw *NEC* can achieve a source current of 1.0 in the following way. For a resonant antenna, use the voltage source at its default values to obtain the source impedance. Then use the source impedance as a revised voltage magnitude and phase-values, and rerun the model. The source current should be 1.0, since current equals the voltage divided by the impedance. Likewise, one can explore the actual current for a given power level by using the initial run source impedance and the desired power level. Select a voltage equal to the square root of the power times the impedance. See the main text for cautions concerning *NEC*'s use of peak voltage and current.

<sup>2</sup>As a reminder, here are the transformation

equations for inductance and capacitance and their respective reactance values:

$$X_L = 2\pi fL \quad L = \frac{X_L}{2\pi f} \quad (\text{Eq 1})$$

where  $X_L$  is the inductive reactance in Ohms,  $L$  is the inductance in Henries, and  $f$  is the frequency in Hz.

$$X = \frac{1}{2\pi fC} \quad C = \frac{1}{2\pi fX_C} \quad (\text{Eq 2})$$

where  $X_C$  is the capacitive reactance in Ohms,  $C$  is the capacitance in Farads, and  $f$  is the frequency in Hz. In addition, when using either the series or parallel RLC option, place a zero in the box for a missing value, for example, the capacitance box of Figure 4. *NEC* interprets the zero as a missing value and not as 0 pF capacitance.

<sup>3</sup>For reference,

$$L_p = VF \cdot L_e \quad L_e = \frac{L_p}{VF} \quad (\text{Eq 3})$$

where  $L_p$  is the physical length of the line,  $L_e$  is the electrical length of the line (in the same units), and  $VF$  is the velocity factor, ordinarily 1.0 or less.

<sup>4</sup>Interestingly, *MININEC* has no difficulty in modeling the angular junctions of dissimilar wires, although length tapering may be needed at the acute angle corners. *NEC-4* improves on the performance of *NEC-2* for such structures, but remains shy of perfection.

<sup>5</sup>Once more, *MININEC* has no problem with close spaced wires of different diameters and lengths. Hence, it yields quite accurate results for folded dipoles that use wires of different diameters. For further details of *NEC* limitations, especially as they appear in *NEC-4*, see L. B. Cebik, "NEC-4.1: Limitations of Importance to Hams," *QEX* (May/June, 1998, pp 3-16). The limitations of *NEC-4* also apply to *NEC-2*.

<sup>6</sup>David B. Leeson, W6QHS, *Physical Design of Yagi Antennas* (Newington: ARRL, 1992), Chapter 8. Once more, *MININEC* does not have difficulties in dealing with tapered-diameter elements and is used as a comparative standard by Leeson. (However, *MININEC* 3.13—the public domain version—does have numerous limitations of its own, such as a very slow-running core, limitations on the total number of available segments, no transmission line facility, a relatively poor system for calculating ground effects, source impedance calculated only over perfect ground, etc. These limitations have made *NEC-2* the more preferred modeling core among radio amateurs, although *MININEC* still has important uses. *NEC-4* requires a license and advanced software, both of which have placed this improved *NEC* core beyond the economic reach of most hams.)

<sup>7</sup>Those whose interests in antenna modeling grow deeper are invited to look at the series of *AntenneX* columns that I do monthly, all of which are at my Web site ([www.cebik.com](http://www.cebik.com)) under the "Antenna Modeling" heading, or to the text *Basic Antenna Modeling: A Hands-On Tutorial*, available from Nittany Scientific, Inc ([www.nittany-scientific.com](http://www.nittany-scientific.com)). The original *NEC-2* manuals remain the most authoritative references for understanding the operation of the core. The on-line or paper manuals accompanying commercial implementations of *NEC-2* are also authoritative for the respective software packages.

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