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Using the LC-Lumped Element Model for Transmission Line Experiments

F. Jalali
Electronic Engineering Technology Department
Fort Valley State University

Introduction

An array of cascaded lumped-element LC sections is an effective substitute for a real transmission line to carry out experiments on the basic characteristics of wave propagation along lines. The advantage of such a model over an actual line is the low cost of the test setups, since the operational frequencies, instead of being in GHz range, can be in kHz, for which the measurement equipment are readily available, even in small EET programs. The details of construction and how to determine the number of sections and values of the components were given earlier.[1] The model is based on the traditional analysis of wave

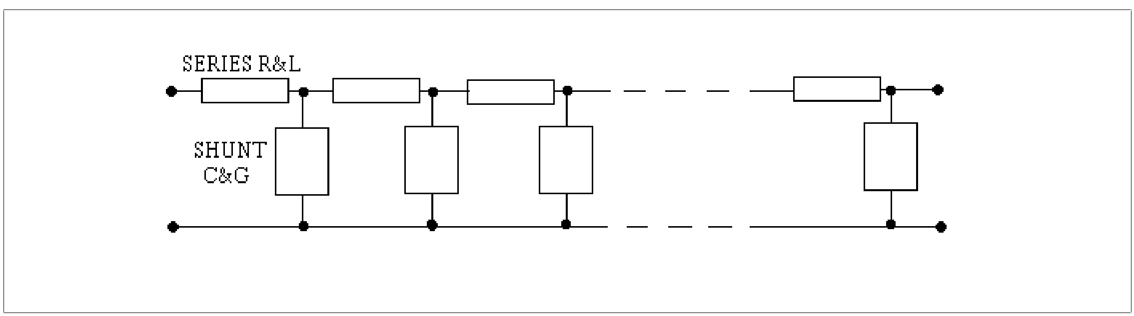

Figure 1. Lumped-Element Transmission Line Circuit

propagation along uniform lines, which considers the line as a large number of differential-valued RLGC components, connected in a cascade, as shown in Figure 1.

The analysis leads to the solution of voltage and current as functions of time and distance, as well to the relations for the characteristic impedance and the propagation constant. If R and G are omitted (R=G=0), the model represents a loss-less line in which the frequency, wavelength, and the distributed parameters L and C are related by $\lambda f = [LC]^{1/2}$. The distributed parameters in these lines are given in per section rather than per-unit length, and therefore the wavelength will have units of sections.

With appropriate values of L and C, the model can be operated in kHz frequencies and at the same time have wavelengths that are smaller than the total number of sections. This condition is necessary, since many of the basic experiments require standing wave data over at least a few quarter-wavelengths. Table 1 shows the specification of three of the lines used by the author. Each line has 18 sections, therefore 19 nodes at which voltage on the line may be measured. The operational frequency listed for each line produces travelling waves that have a wavelength of 14 sections.

T-Line	Series L (mH)	Shunt C (μf)	Frequency (kHz)
A	1.2	. 050	9.22
B	3.9	.022	7.71
E	2.7	.050	6.15

Table 1 – Component values for a few of the lines

The use of these lines for several basic experiments, such as finding the phase shift vs distance, the VSWR for different loads, and the experimental value of the wavelength from the Standing Wave plot, was outlined before.[1] In this paper, the procedure for an experiment on matching a line by use of a capacitive shunt is described, and typical results are given.

Designing a Load Matching Experiment

Most RF and microwave systems or circuits consist of components that are connected by sections of transmission line. For optimum operation, it is desirable that the transmission lines have matched loads. If the load is not already matched to a line, a reactive component may be connected to the line near the load to create matching. This can be a discrete component or a short piece of the transmission line (single-stub tuning).[2]

Matching a line by adding a shunt component involves determination of the location where the component is added and the type and value of the component. For some transmission lines, such as the two-wire open line, connection to the line is theoretically possible at any point. In the case of the lumped-element model, however, access is limited to the nodes connecting the adjacent lumped-element sections. Hence for an experiment on matching to give acceptable results, the distance from the load where the compensating shunt will be added must turn out to be whole multiples of sections. This outcome can be built into the experiment by proper selection of the value of the mismatched load.

To illustrate how to specify a mismatch load, the example of the lines in Table 1 is used. Let us assume that the given load will be purely resistive and that we would like for matching to be possible by connecting a capacitor at the node one section from the load. Since the specified frequency for each line results in a wavelength of 14 sections, the above distance is equivalent to (1/14) x 360 x 2 = 51.4 electrical degrees. At this position the normalized admittance of the line must be 1 – jB, for a capacitance to match the line. Therefore, the normalized load admittance must lie in the G > 1 region, as shown in Figure 2. This corresponds to a normalized admittance of 4.2 + j0, or a load impedance of

$$Z_L = 1/(Y_L) = 1/(Y_{Ln}Yo) = (1/Y_{Ln})\ Zo = (1/4.2)Zo = 0.23Zo.$$

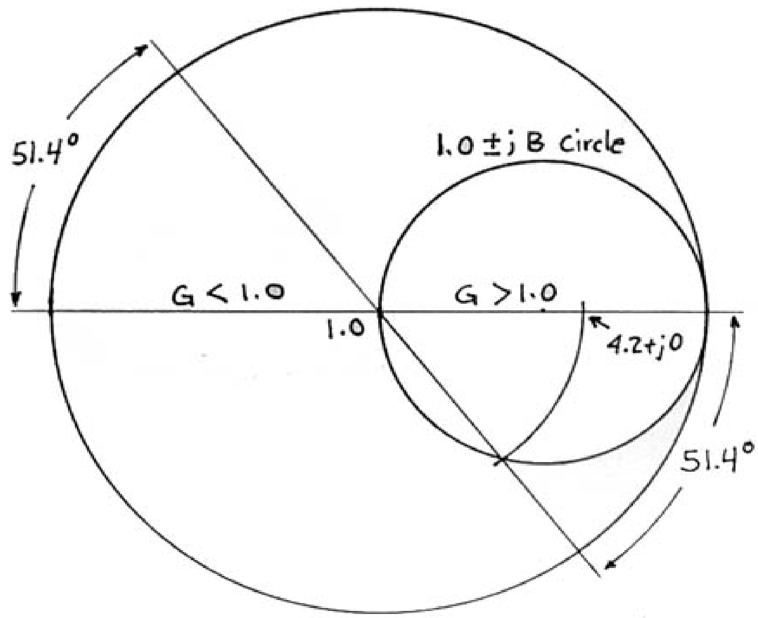

Figure 2. Determining the required mismatched load.

Therefore, for a load-matching experiment with these models, if the results stated above are to be obtained, the load impedance must be specified at a value equal to 0.23Zo.

Procedure for a Load Matching Experiment

A matched load on a transmission line absorbs all the transmitted energy. The parameter directly describing the degree of matching is the reflection coefficient, which by definition is the ratio of the reflected to the incident wave or voltage. Voltage Standing Wave Ratio (VSWR) is defined as the ratio of the magnitudes of the maximum to minimum voltage, or the E-field intensity, on the line. The VSWR and the reflection coefficient are related by $VSWR = (1+ |\Gamma|) / (1 - |\Gamma|)$.

For a matched line, the reflection coefficient is zero, or VSWR=1.0. On a totally mismatched line, the magnitude of the reflection coefficient is 1.0, resulting in a VSWR that approaches infinity. Thus, the degree of mismatch on a line can be described by the VSWR, which is experimentally easier to measure than the reflection coefficient.

The steps for carrying out the experiment may be given as follows:

a. Choose a transmission line and use the nominal values of its LC components to compute the characteristic impedance, Z_o. Select a resistive load (can use a potentiometer) equal to $0.23Z_o$, and connect as the load .

b. Energize your line with a sinusoidal voltage of frequency recommended for your line, and measure and record the rms (or p-p) value of the voltage at each node. Plot the resulting standing wave. (Note: distance is expressed in number of sections).

c. Using a Smith Chart and a procedure similar to single-stub tuning, determine the nearest point to the load where a capacitor may be connected to match the load. Compute the value of the needed capacitance. Connect a capacitor of this value across the line at the node identified by your matching procedure.

d. Retake the voltage data for plotting a second standing wave plot on the same graph sheet for comparison. Compare the two Standing Waves and compute the VSWR from each plot to show how well the matching effort succeeded.

Typical Results

If line B from Table 1 is used in a matching experiment, the following results are obtained:

a. $Z_o = [L/C]^{1/2} = 421$ Ohms. Therefore a $Z_L = 0.23Z_o = 97$ Ohms is used for load.
b. The voltage standing wave plot for the unmatched line is shown in Figure 4.
c. The single-stub matching technique applied here for determining the closest point where a capacitance may be connected is illustrated in the Smith Chart of Figure 3. From the Chart, we find the distance to the load where the capacitor is to be connected:
   $.0723\ \lambda \times (14 \text{ section}/\lambda) = .996$ section, rounded to 1.0 section.

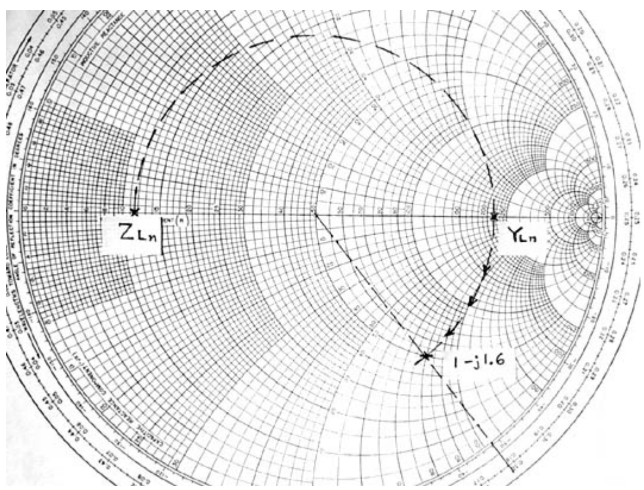

Figure 3. Using Single-Stub matching routine on a Smith Chart

Since the normalized admittance at this point is 1-j1.6, a compensating capacitor of normalized admittance +j1.6 must be used to match the line. Since the actual admittance of the capacitor, Yc, is $1.6Y_o$, where $Y_o=1/Z_o$, the value of capacitance can be found from $Yc=j\omega C$ and operational frequency. Using the above values of $Z_o=421$ Ohms and f=7.71kHz, C is found to be equal to .079 μF.

d. With the above capacitance installed, voltage data is taken again to plot the Standing Wave pattern for the matched line (see Fig. 4). The VSWR values computed from the two plots are 3.35 and 1.12 for the mismatched and matched cases respectively.

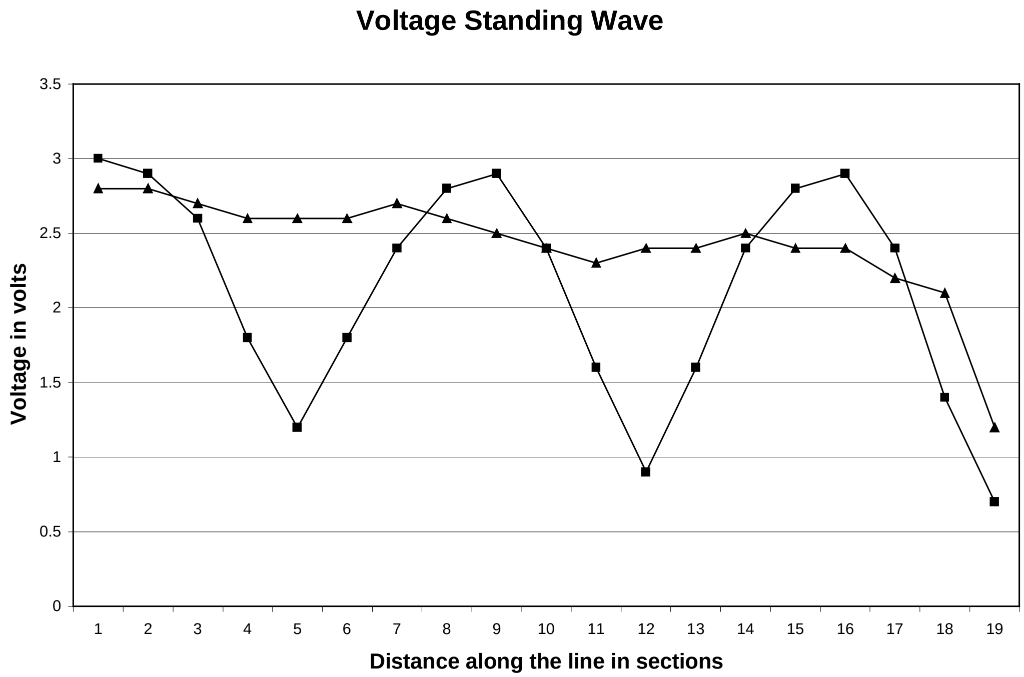

Figure 4. Voltage Standing Wave Plot of un-matched and matched line

As can be seen from the Standing Wave plots and the VSWR values, the model works well in producing the matched condition with the capacitive shunt.

Summary

The LC-lumped element model can be used as an economical means for performing experiments to study the basic characteristics of transmission lines as well as for more challenging experiments such as load matching. The advantage of the model is its economy, in contrast to real lines which must be operated above or near GHz frequencies for laboratory experiments, therefore require expensive instrumentation. The disadvantage of the model is in the limited number the points at which voltage data along the line can be taken.

Bibliography

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2. Sinnema, W. "Electronic Transmission Technology", Prentice-Hall, Inc. New Jersey, 1988

FEREYDOUN JALALI is a professor and head of the Electronic Engineering Technology department at Fort Valley State University in Fort Valley, Georgia. He received his BS, MEE, and PhD in Electrical Engineering from North Carolina State University at Raleigh, North Carolina. He has taught a variety of courses in digital and linear systems and in electromagnetic-related topics in both EE and EET programs, with a present interest in the application of innovative approaches to teaching "difficult" topics and to laboratory and project activities.