SOFTWARE TOOL FOR TRANSMISSION LINE ANALYSIS

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Abstract *¾ A brief description of a software tool developed to analyze transmission lines with arbitrary losses is presented in this paper. This tool* ***summarizes a complete methodology*** *for the analysis of arbitrary transmission lines by means of complex parametrizations of the different quantities which characterize the line, and their mutual relationship. This kind of methodology brings up new types of representations and, in particular, new ways to visualize and predict the complete behavior of a particular system, avoiding the complexity associated to the usual mathematical representations. From the educational point of view, this approach facilitates a more intuitive and broad understanding of the problem, and the software tool lets the students to graphically visualize the physical behavior of the system.*

Index Terms ¾ Arbitrary losses, Complex Analysis, Generalized Smith Chart, Generalized Z_n- and Y_n-planes.

INTRODUCTION

The transmission line analysis (TLA) has been for many years and continues being nowadays a very important part in the general background of electrical engineers and scientists. This is due to the fact that a good number of real systems such as waveguides, optical fibers and, in general, many electromagnetic problems and devices may be schematized by different tranmission line models which characterize the main aspects in the behavior of the original system. The usual presentation of the transmission line theory normally reduces to the ideal lossless and the low-loss approximation cases under time harmonic regime. Even in those cases, some important aspects are usually lost in their analysis, reducing their study to the application of certain practical formulas to different configurations but losing the physical interpretation under those results. Besides, the interpretation of these formulas is not easy when trying to predict and generalize the transmission line behavior when arbitrary losses are taken into account.

The software presented in the present paper is the result of a set of studies performed by our research group in order to establish a **complete methodology** which might be summarized as follows:

- Description of the general behavior of the *basic parameters* (*characteristic impedance* and *propagation constant*) associated to a general transmission line model with arbitrary losses under time harmonic regime.
- Description of the propagation phenomena along the arbitrary transmission line in time harmonic regime, with special emphasis in the *visualization* of the time- and space- variation of the incident, reflected and total waves as well as energy propagation associated to each wave. The interpretation of phase and energy velocities is fundamental in the process. Also, the time-space visualizations provide a better understanding of the physical meaning associated to the typical magnitudes such as phasor quantities and operators, Stationary Wave Patterns (SWP), phase velocities, etc.
- **Complex analysis** of the *descriptive parameters* of the line, *impedance* (*Z*), *admitance* (*Y*) and *reflection coefficient* (ρ) , by performing a complete parametrization of these operators in their respective complex planes and the mappings associated to them. This study provides a more complete and intuitive parametrization of the problem than the usual complex analysis in the ρ-plane (Smith chart parametrization). In fact, nowadays, and due to computer capabilities, the Smith chart is not importat as a computational tool but to visualize, describe and predict the behavior of a specific problem. From this point of view, new complex analysis such as those in the impedance- and admitance-complex planes become even more intuituve and useful than the usual one in the ρ-plane. In particular, these complex parametrizations provide a very powerful and intuitive tool to understand lines with *arbitrary losses*.
- Complex analysis and parametrization of the incident, reflected and total complex waves under time harmonic regime. This procedure provides the visual description of the *voltages* and *currents* along the line over their respective *v* - and *i* -planes. This leads to a better understanding of the physical processes appearing in time- and space- domains. Again these parametrizations become very useful when representing more complex systems such as those with arbitrary losses.
- Finally, all these representations and parametrizations may be extended to other time regimes, providing a very powerful tool to understand and visualize the line behavior from the *signal theory* point of view: Fourier analysis, harmonic analysis, properties of the system, etc.

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As a summary of this scheme, the final aim of this work is to present a powerful tool that may be able to visualize, predict and facilitate the analysis of more complex systems than the usual lossless tranmission line. In fact, the analysis of the arbitrary losses case allows a better understanding of the low-loss regime, which is not easy to justify rigurously from the usual point of view. Also, more complicated models such as frequency-dependent losses may be incorporated into the present analysis by following the same methodology.

In the following sections, the mathematical analysis related to the different time-, space- and complex-parametrizations will be summarized only for simplicity and we will concentrate on the general description of the final software tool. Finally, a particular illustrative example will be presented in detail to show some of the capabilities of the TLA software.

MATHEMATICAL MODEL

The analysis implemented in the software is based on the usual model shown in Figure 1 which is characterized under time harmonic variation *exp*(*-j*ω*t*) by the following well known expressions:

$$\begin{aligned} v(z) &= v^{+}(z) + v^{-}(z), \\ i(z) &= i^{+}(z) - i^{-}(z). \end{aligned} \qquad (1)$$

$$\begin{aligned} v^{+}(z) &= v_0^{+}(z)\exp(-\gamma z)\ ,\ v^{-}(L) = v_L^{-}(l)\exp(-\gamma l), \\ i^{+}(z) &= i_0^{+}(z)\exp(-\gamma z)\ ,\ i^{-}(L) = i_L^{-}(l)\exp(-\gamma l), \end{aligned} \qquad (2)$$

with

$$Z_0 = v^{+}/i^{+} = v^{-}/i^{-} = \sqrt{(R + j\omega L)/(G + j\omega C)} \qquad (3)$$

denoting the characteristic impedance, and

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)/(G + j\omega C)} \qquad (4)$$

the propagation constant.

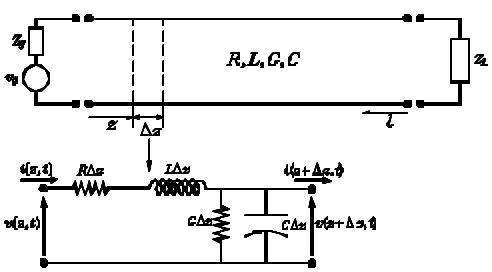

FIGURE 1
TRANSMISSION LINE BASIC MODEL

In addition, the usual *impedance*, *admitance* and *reflection coefficient* should be kept in mind as the main parameters described by the complex analysis,

$$Z(z) = \frac{v(z)}{i(z)} \qquad \rho(z) = \frac{v^{-}(z)}{v^{+}(z)} = \frac{i^{-}(z)}{i^{+}(z)} \qquad (5)$$

with

$$Z(z) = \frac{1}{Y(z)} = Z_0\,\frac{1+\rho(z)}{1-\rho(z)} \qquad (6)$$

or their corresponding expressions in terms of l. Notice that the present parametrization of the losses assumes that the elements R and G are not frequency dependent. This approach is only valid within specific frequency ranges, but becomes a valid representation to introduce the general methodology involved in the analysis. By following a similar scheme, more realistc models of $R(\omega)$ and $G(\omega)$ may be incorporated into this methodology. This set of well known quantities are recalled only for convenience and should be complemented with the usual expressions which take into account the movements along the transmission line in their different versions which may be recalled, for instance, from [1]. Once the line is fed by an arbitrary voltage generator (v_g,Z_g) and terminated by an arbitrary load impedance Z_L, the system may be completely analyzed in detail. The basis of the complex analysis (see *Complex Analysis* in the *Software Description* section) arises when studying all these quantities in their respective complex planes and by establishing their mutual relationships. The easiest example of this kind of analysis is the usual Smith chart for lossless transmission lines, which corresponds to a specific mapping from Z-plane into ρ-plane with Z_0 being a real magnitude. The complete mathematical development and summary of the different parametrizations and graphs in all the complex planes is not the objective of the present paper and may be found in [2]-[3] for both lossless and arbitrary losses transmission lines. It is important to recall that all the complex transformations which are possible to visualize with the software tool have been **analytically obtained**, and can be described by clean explicit mathematical expressions.

Finally, all the complex analysis may be complemented by direct interpretation of the complex magnitudes into the real time- and space-domains (see *V&C* in the *Software Description* section). These insterpretations may be graphically depicted, providing a powerful tool to visualize the physical processes represented by the original equations in the frequency-domain.

SOFTWARE DESCRIPTION

The complete methodology cited in previous sections may be summarized through the following scheme which provides a general overview of the TLA software tool.

The main window allows to input the data corresponding to the problem under analysis and gives place to the next analysis windows. The data which is necessary to provide may be summarized as follows:

- Harmonic voltage generator: frequency, voltage amplitude v_g, and internal impedance Z_g.

- Transmission line: basic parameters per unit length, R, L, G and C, line length, and a specific position on the line for time analysis z_{pos}.
- Load: terminal impedance Z_L.
- Other: number of samples along the line, and number of samples in time.

TABLE I
GENERAL OVERVIEW OF THE TLA SOFTWARE TOOL

V&C	Reference Values		
	SWP		
	Signals in Time	Normalization Values	
		Phase	
		Phase Velocity	
Complex Analysis	Z_0-γ	$Z_0(\omega)$	
		$\gamma(\omega)$	
	Z-ρ	$Z(z)$	Amplitude
			Phase
		$\rho(z)$	Amplitude
			Phase
		Z-3D	Curves along the surface
			2D Projections
		ρ-3D	Curves along the surface
			2D Projections
	V&C		

After all data have been introduced, the general overview follows the scheme presented in Table I which may be summarized as follows.

V&C (Voltages and Currents)

A detailed analysis of voltages and currents in space and time is performed in this section of the program. A first window with *Reference Values* provides a set of interesting data for the analysis of the line, such as wavelength, different parameters of the line, important values of the reflection coefficient, voltages and currents at the end of the line, etc. All this values let to predict the future behavior of the system which will be observed in the following sections. The second window shows the usual *SWP* along the line, specifying all the interesting values on it and also the values at the specific position z_{pos} under analysis. Finally, the third window (*Signals in Time*) provides a complete visual description of voltages and currents in time and space. The various graphical representations show the variation of voltages and currents in time at the specific position z_{pos}, and the incident, reflected and total waves along the line together with the SWP which modulates the total magnitudes for different values in time. Each time step is user-selected by pressing a specific button, allowing to visualize how the signals move along the line. The presentations show all the important values at every specific instant in time so all the interpretations may be done interactively as the signals progress in time. Also, it is possible to visualize the phase and the associated phase velocity in different windows for every signal involved in the process. This visualization makes possible to perfectly understand the relationship between phase, phase velocity and the propagation process along the line. This is particularly important when trying to understand the behavior of the total magnitudes v and i.

Complex Analysis

The second and very important section of the software is that devoted to visualize the different complex parametrizations performed in our theorethical studies, [2].

The first subsection *(Characteristic Impedance and Propagation Constant*) corresponds to the complex analysis of the basic parameters $Z_0=|Z_0|exp(\phi_{Zo})$ and $\gamma=\alpha+j\beta$, analysis which becomes really important for lines with arbitrary losses, that is R and G with nonzero values. In the present analysis it is assumed that both R and G are not frequency dependent. Some reference curves in the corresponding complex planes can be visualized and the concrete values for the problem can be overlapped on those curves. Also it is possible to visualize reference curves for $Z_0(\omega)$ and $\gamma(\omega)$ and their concrete values in the problem under analysis over them. These representations are really important because they show the possible values that these parameters may take for any arbitrary values of R, L, G and C.

TABLE II
COMPLEX IMPEDANCE AND REFLECTION COEFFICIENT TRANSFORMATIONS SUMMARY

Lossless Transmission Lines		
$Z_n=Z/Z_0=R_n+jX_n$	$R_n=cte$; $X_n=cte$	Smith chart (ρ-plane)
	$Z_n=cte$; $\phi_{Zn}=cte$	
$\rho=(Z_n-1)/(Z_n+1)$ $=\rho'+j\rho''$	$\rho'=cte$; $\rho''=cte$	
	$\lvert\rho\rvert=cte$; $\phi_\rho=cte$	Geometrical location of $Z(z)$ and $Y(z)$ along the line
Transmission Lines With Arbitrary Losses (parametric curves with ϕ_{Zo})		
$Z_n=Z/\lvert Z_0\rvert=R_n+jX_n$	$R_n=cte$; $X_n=cte$	Generalized Smith chart (ρ-plane)
	$Z_n=cte$; $\phi_{Zn}=cte$	
$\rho=(Z_n-1)/(Z_n+1)$ $=\rho'+j\rho''$	$\rho'=cte$; $\rho''=cte$	
	$\lvert\rho\rvert=cte$; $\phi_\rho=cte$	
	$\rho=\rho_L\exp(\alpha(\phi_\rho-\phi_{\rho L})/\beta)$	Geometrical location of $Z(z)$ and $Y(z)$ along the line

The second subsection (*Impedances and Reflection Coefficient*) has the ability to represent in the same window both the impedance and the reflection coefficient complex planes. In the lossless case, this fact provides the usual representation of the Smith chart together with its dual representation in the Z_n-plane. By the way, this is only one of the possible visualizations; another important parametrizations have been included, as shown in Table II. Over these reference curves it is possible to represent all the actual values of the problem, such as the load impedance, the impedance at any point in the line (geometrical location of $Z_n(z)$ along the line), etc. Also, it is possible to visualize in 2D and 3D the amplitude and phase of both quantities along the line and to compare directly with the representations in the respective dual complex planes (Z_n vs. ρ and ρ vs. Z_n). The transformations in the alternative Y_n-plane are also included. Another time, the representations for the arbitrary losses case become very important, leading to generalized impedance and reflection coefficient graphs (i.e., a generalized Smith chart on the ρ-plane).

Finally, the third subsection (*Voltages and Currents*) is able to show different complex representations in both voltage- and current-complex planes, which may be interpreted together with the different results in time and space described in section *V&C*. Another time, it is possible to overlap the reference curves with the actual data of the problem under analysis.

In the following sections we will try to show some of the graphical capabilities previously summarized by choosing a specific example with a transmission line with losses out of the low-loss regime.

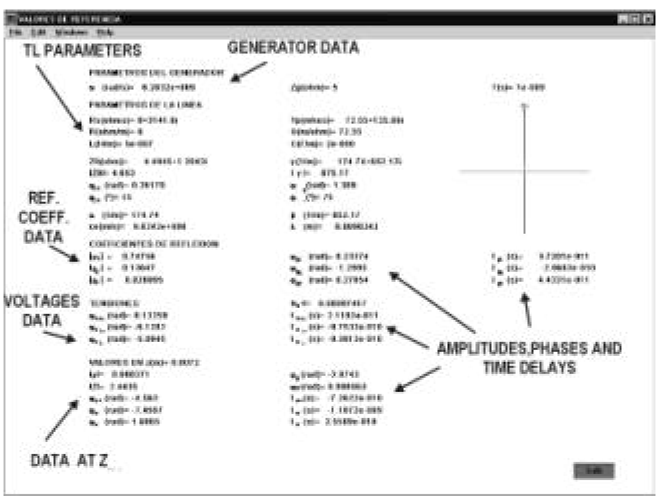

FIGURE 2
REFERENCE VALUES WINDOW

AN EXAMPLE BASED ON A TRANSMISSION LINE WITH LOSSES

Let us consider a specific example described by the following data: f =1 GHz, v_g=2 mV, Z_g=5 Ω, R=0 Ω/m, L=0.5 μH/m, G=72.55 $(\Omega\text{m})^{-1}$, C=20 nF/m and Z_L=15+j20 Ω. The length of the line is 0.96 cm and the specific position under analysis z_{pos}=0.72 cm from z=0. In this case, the basic parameters Z_0 and γ are both complex magnitudes.

V&C (Voltages and Currents)

As we proceed through the different options, it is possible to visualize the different windows cited in the previous section. The *Reference Values* window in Figure 2 shows a set of important data related to the problem, such as generator parameters, line parameters, reflection coefficients ρ_L, ρ_g and ρ_0 and their associated time delays, incident and reflected voltages at Z_L and their associate time delays, and different values at z_{pos}.

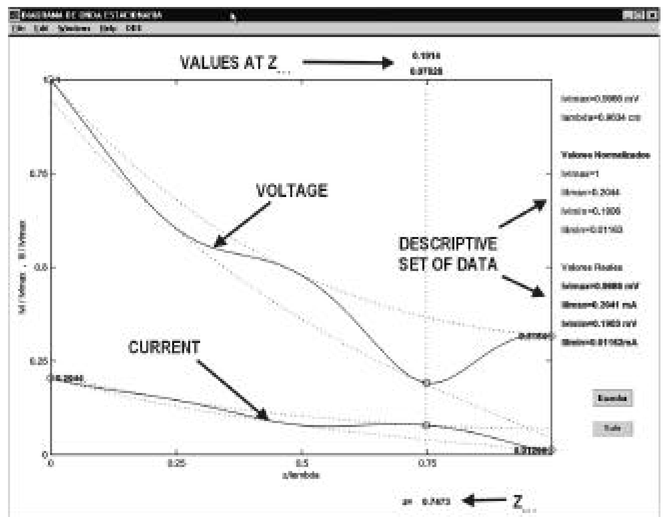

FIGURE 3
SWP WINDOW SHOWING ITS TYPICAL BEHAVIOR ALONG A TL WITH LOSSES

From this set of data it may be noticed that the wavelength in this specific problem (λ_{cp}≈0.96 cm) becomes smaller than the one corresponding to the lossless case (λ_{sp}=1 cm in the present example). Notice that the length of the line has been chosen to be equal to the actual wavelength. In fact, it may be recalled that the phase velocity associated to the line parameters is smaller than the corresponding one in the lossless case (c_{ecp}≈9.63 10^6 m/s vs. c_{esp}=10^7 m/s). Also, the value reported for the characteristic impedance is a complex magnitud with amplitude and phase equal to $|Z_0|$≈4.65 Ω and ϕ_{Zo}=15°. This value may be found to be a valid solution in the *Complex Analysis* section (see Figure 5). Also, the value of the phase will determine the complete behavior of the analysis in the complex Z_n- and ρ-planes (generalized impedance and Smith charts). Finally, another important fact may be recalled from the data corresponding to the magnitudes $R+j\omega L$≈0+j3142 Ω/m and $G+j\omega C$ ≈72.55+j126 $(\Omega\text{m})^{-1}$. Clearly, the behavior of the line cannot be described under low-loss approximation since R<<ωL but G≈ωC; this fact will determine the behavior observed in time-, space- and complex-planes analysis. This may also be corroborated from the value of the attenuation constant α=174.74 m^{-1} which gives place to a ratio of α/β.

The *SWP* window in Figure 3 provides all the necessary information related to this representation, including the specific data associated to z_{pos}. It may be seen how the losses affect the SPW which will later modulate the total voltage and current.

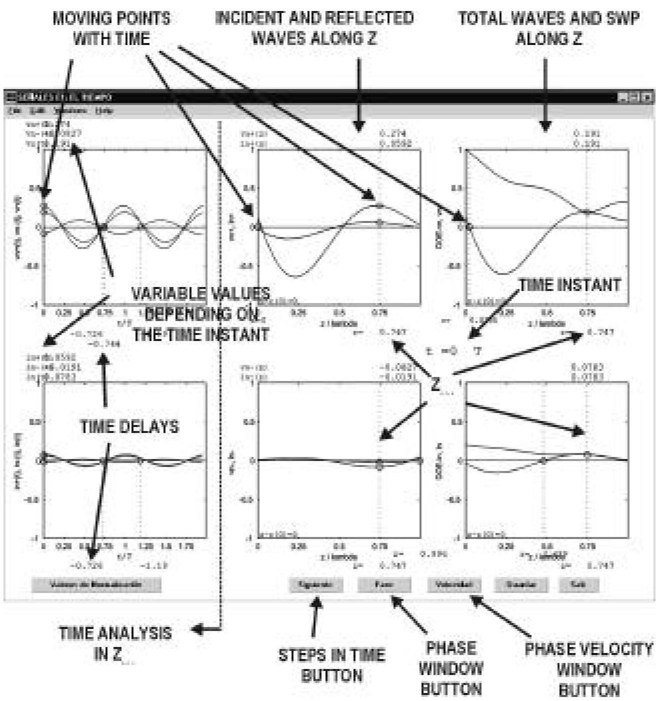

FIGURE 4
SIGNALS IN TIME WINDOW

The *Signals in Time* window looks as shown in Figure 4. By using the STEPS IN TIME BUTTON it is possible to visualize all the voltages and currents involved in the process in fractions of the period fixed by the generator. At any instant, the values are refresh and all pictures are characterized by the corresponding set of data. The left hand side representation corresponds to the analysis in time of the different waves at the specific location z_{pos}. The center and right hand sides pictures correspond to the waves along the line for each time value. This makes possible to visualize the propagation process all along the line. Many important data are associated to these pictures, such as distances, amplitudes of the signals, time delays, etc.

Finally, the phase and phase velocity buttons open two independent windows which provide all the necessary information (graphs and data) related to the phase and phase velocity of the different waves along the line. These windows are not included here because of space requirements.

Complex Analysis

The second section of the TLA software tool gives place to the complex analysis of the system under study. Figure 5 shows an example of the possible representations that may be performed into this window.

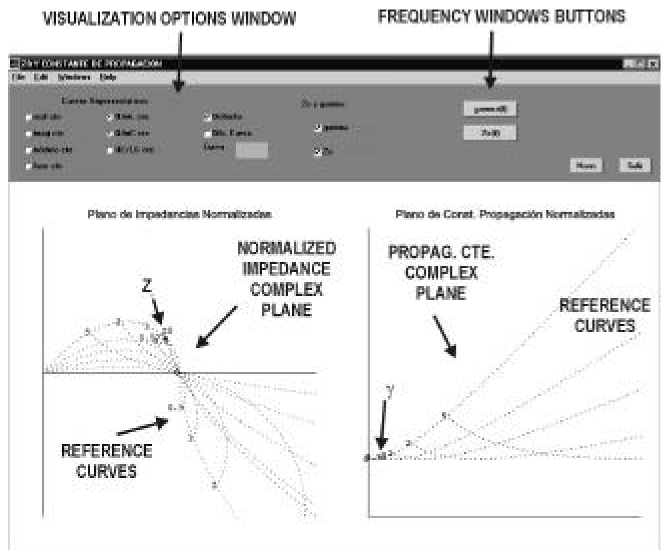

FIGURE 5
CHARACTERISTIC IMPEDANCE AND PROPAGATION CONSTANT COMPLEX ANALYSIS WINDOW

The visualization options let to determine which data will be depicted in both planes, such as some reference curves with constant $R/\omega L$ or $G/\omega C$, particular values of Z_0 and γ, etc. Also, the analysis of $Z_0(\omega)$ and $\gamma(\omega)$ may be visualized in separated windows by using the FREQUENCY WINDOWS BUTTONS. Figure 6 shows an example of the window corresponding to the analysis of $Z_0(\omega)$.

The second section of the complex analysis corresponds to the complete parametrization into the normalized impedance- and reflection coefficient-complex planes. Figure 7 shows an example of one possible visualization, with the generalized impedance and Smith charts as reference curves.

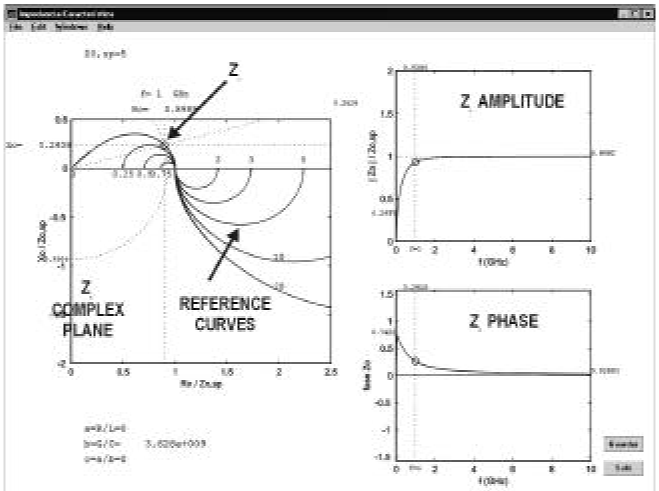

FIGURE 6
FREQUENCY ANALYSIS OF THE CHARACTERISTIC IMPEDANCE

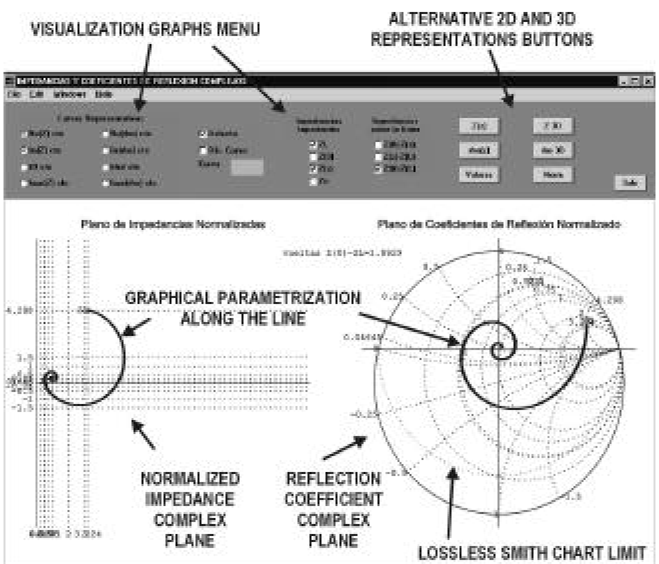

FIGURE 7
NORMALIZED IMPEDANCE AND REFLECTION COEFFICIENT WINDOW

Depending on the selections made by the user, it is possible to represent specific values of impedances and reflection coefficients overlaping the reference curves at both planes, as well as changing these reference curves as summarized in Table 2. Also, the geometrical location of impedances and reflection coefficients along the line may be visualized over the reference curves. Figure 8 shows an example of the visualization when $|\rho|$=cte. and ϕ_ρ=cte. are selected as reference curves in the analysis.

Also, the alternative 2D and 3D buttons provide different representations of both magnitudes along the line.

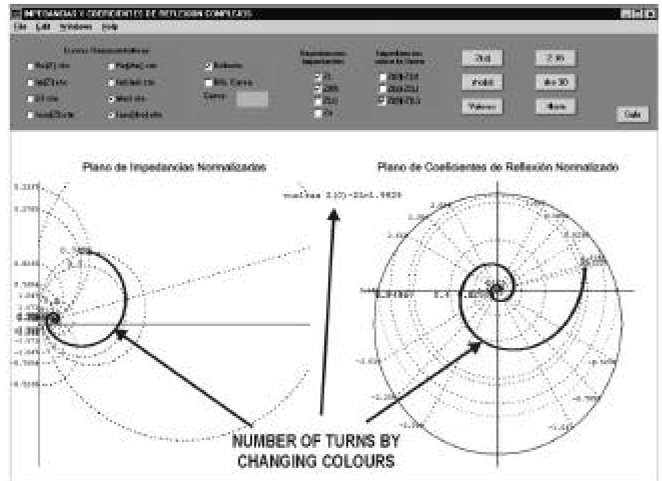

FIGURE 8
ALTERNATIVE VISUALIZATION OF THE NORMALIZED IMPEDANCE- AND REFLECTION COEFFICIENT-PLANES

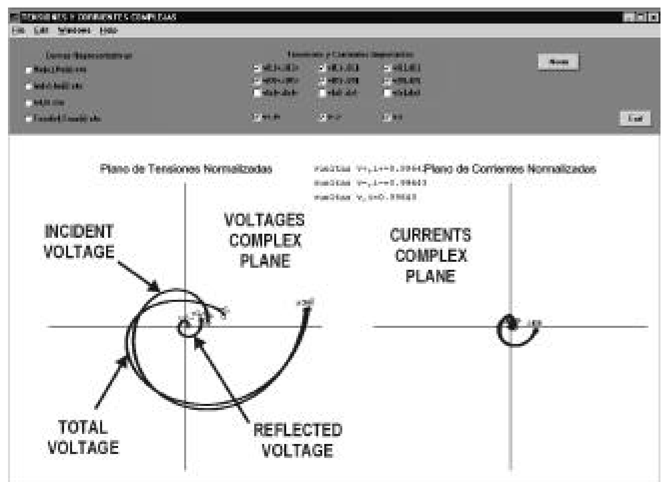

FIGURE 9
VOLTAGES AND CURRENTS COMPLEX PLANES WINDOW

Finally, Figure 9 shows an example of the visualization of voltages and currents in their complex planes. The kind of options are completely similar and the important relevance becomes when performing its interpretation together with the time-space signals shown in Figure 5.

SUMMARY

In the present paper, the description of a TLA software tool has been summarized and exemplified though a transmission line with relevant losses. Only the main windows have been presented and the mathematical analysis has been only referenced but the important point under this presentation is the complete methodology which gave place to the development of this tools, in particular, the generalized complex analysis and parametrization of the magnitudes involved in the description of the line and their relationship with the physical behavior and how all of them may be visualized and discussed together. The actual software has been developed with MATLAB codes, but JAVA improved versions with extended features (arbitrary time signals, spectral complex analysis, frequency dependent losses, etc.) are currently under development.

Acknowledgment. This work has been supported by the Spanish CICYT under grant PB97-0487.

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