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RESEARCH ARTICLE

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Design and implementation of an open source transmission line impedance matching educational framework

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Abstract

Determining input impedance, assigning reflection coefficient, and matching load impedance are important transmission line problems those involve complex calculation steps because of complex connection architectures in transmission lines. Efficient understanding of such problems in undergraduate and graduate courses should be supported by rich visualization tools. The Smith chart is a convenient tool for transmission line calculations especially for wave propagation and maximum power theory that discusses impedance matching problems. In this context, we can say that Java is a widely used open source educational tool having strong computational environment for research and development aims. In this study, an open source transmission line impedance matching educational framework (TLIME) has been designed to teach efficiently wave propagation and maximum power theory that discusses the impedance matching problems. The success of developed educational framework has been measured by a questionnaire held in courses in the third and fourth years of the electrical and electronics engineering undergraduate program at Sakarya University of Applied Sciences, Turkey. The visual preparation of the problem solutions with rich graphical user interface and simulations of the mathematical representations has been evaluated to contribute to a better understanding of the wave propagation and impedance matching transmission line subjects. The functionality and simplicity of the developed framework scored by over 82% among course enrolled students. The rest of the paper is organized as follows. Section 2 explains transmission line impedance matching problem in the context of maximum power theory. Section 3 discusses transmission line planning and problem solving with Smith chart. Section 4 discusses explanation and usage of developed TLIME framework and last section discusses results.

KEYWORDS
educational framework, impedance matching problems, java programming, Smith chart, transmission line, wave propagation theory

1 | INTRODUCTION

Active and efficient teaching methodologies that will provide a better understanding of complex engineering problems have been diversified thanks to technological developments taking place in recent years. Besides gaining the ability to use computers as a tool for complex calculations in engineering education, it has become widespread to use it in the preparation of instructional materials to teach complex engineering problems more effectively [15]. Both for undergraduate and graduate students, embodiment of complex problems involved with related engineering program will help them to conceptualize these subjects permanently [14]. The existence of complex problems mentioned in the discipline of electrical and electronics engineering has a very important place. Many of the most complex and important problems are in the discipline of the transmission lines theory which is established between circuit theory and electromagnetic theory [20]. Within the discipline of transmission lines, there are two essential disciplines of electrical engineering and they are communication theory and power systems theory. Solutions of Kirchhoff voltage and current laws explain wave propagation, formation of standing waves, and maximum power theory [3]. Determining input impedance, assigning reflection coefficient, and matching load impedance are important transmission line problems those involve complex calculation steps because of complex connection architectures in transmission lines (TL) [5,7,9,11,16,23]. A reliable transmission line not to be affected by adverse conditions even in the case of steadily changing transmission line expansions should be built [10]. In this context, transmission line system planning that involves determining and scheduling the additional unpredictable conditions plays a crucial role for enhancing reliability of the transmission system. This situation forces using efficient transmission line planning tools for easy and extent vision of overall transmission network.

Efficient understanding of such problems in undergraduate and graduate courses also should be supported by rich visualization tools that support active teaching methods for efficient solution of impedance matching problems with distributed components in transmission line [10]. By this context, the Smith chart is a convenient graphical tool for transmission line calculations especially for wave propagation and maximum power theory that discusses impedance matching problems. Developing functional and effective visual engineering tools, Java is a widely used open source educational tool having strong computational environment for research and development aims. In this study, an open source transmission line impedance matching educational framework (TLIME) has been designed to teach efficiently wave propagation and maximum power theory that discusses impedance matching problems. The framework can also be implemented into complex calculation of wireless transmission line modeling. Without having to use a licensed utility software, education based on the designing of simple programs, which will be prepared by students themselves and which can be used as web based from any place they want freely, about various problems related to the engineering fields is the main target of this paper.

The main goal of this article is to provide an easier and more effective understanding of complex transmission line problems. For strengthening this goal, we make it clear that the advanced computation and planning calculation abilities should be continuously open for updates that can solve much more complex problems of transmission lines.

For this purpose, the proposed framework has been written in an open source style, and it is designed with a flexible framework architecture for the aim of continuous development and distribution. The success of developed framework has been measured by a questionnaire held in courses in the third and fourth years of the electrical and electronics engineering undergraduate program at Sakarya University of Applied Sciences, Turkey. The visual preparation of the problem solutions with rich graphical user interface and simulating the mathematical representations has been evaluated to contribute to a better understanding of the wave propagation and impedance matching transmission line subjects. The functionality and simplicity of developed framework scored by over 82% among course enrolled students.

The rest of the paper is organized as follows. Section 2 explains transmission line impedance matching problem in the context of maximum power theory. Section 3 discusses transmission line planning and problem solving with Smith chart. Section 4 discusses explanation and usage of developed TLIME framework and last section discusses results.

2 | TRANSMISSION LINE IMPEDANCE MATCHING PROBLEM

All environments that capable of propagating electromagnetic waves exhibit characteristic impedance. If the wave passes through medium with different characteristic impedances while moving on the transmission line, a part of this transmitted wave is reflected. This is an undesired situation. The impedance of the reflected waveguide during transmission should be minimum and this is because need for an impedance matching technique. This technique guarantees lossless and non-reflective transmission through the line [2].

The impedance matching technique is based on the maximum power theory. The theory says that transferring between generator and load should be via conjugate impedance or same resistance. The transferred power to the load is given below as Equation1 [8]

$$W = \frac{V^2}{2} \frac{R_L}{(R_L + R_G)^2} \tag{1}$$

In Equation1 W, V, R_L, and R_G indicate that

W = Transferred power

V = Voltage

R_L = Load with resistance

R_G = Generator with resistance

While differentiating (Equation1) with respect to RL to find the value that maximizes the load power, we have

$$\frac{dW}{dR_L} = \frac{V^2}{2}\left[\frac{1}{(R_L + R_G)^2} - \frac{2R_L}{(R_L + R_G)^3}\right] = 0 \tag{2}$$

Arranging Eq.2 gives maximum power equality condition between load and generation side.

$$\frac{R_L}{(R_L + R_G)} = \frac{1}{2} or R_L = R_G \tag{3}$$

The impedance matching technique matches impedance either between the main line and load or between the main line and sideline. The match is applied with inductor or capacitor elements by creating the appropriate connection type. These elements may be parts of serial or parallel connected components of the transmission circuit, or may be part of a circuit or equipment [13].

The role of the matching line (network) can be expressed as fitting the source impedance ZS to the load impedance ZL. In Figure 1, a general impedance matching block diagram is given.

The analytical solutions of the transmission line impedances involve complex calculation steps because of complex connection architectures in transmission lines. In practice, the impedance calculation of line has been handled by using computer-aided and graph-based calculation tools. By this context, a commonly used method is used to graphically solve the transmission line impedance matching problems.

There are various impedance matching techniques in the literature [1,12,17,24].

(1) Two element matching (L shape)
(2) Three element matching
  - Pi-shape matching
  - T shape matchin
(3) Stub tuning matching
  - Single stub matching
  - Double stub matching
(4) Quarter wave transformer matching
(5) Conjugate matching

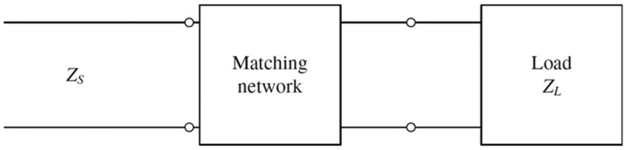


FIGURE 1 A Lossless Impedance-Matching Network

There are eight possible combinations of inductors and capacitors in the L network. In L shape matching technique, impedance transformation depends on the value of the original inductors or capacitors in the L-configuration. Two basic topologies of L-section matching networks are shown in Figure 2.

Achievement of wide bandwidth matching is more difficult than single frequency matching especially with changing load conditions. So that L shape matching network needs simplicity in design.

Another technique, single-stud tuner (SST) is shown in Figure 3. The SST uses a shorted or open section of TL that is attached at some position along another TL. The shorted or open section of TL can easily be made adjustable and little to no power is dissipated in the stub.

The shunt-connected section is called the stub. All sections of TL will be assumed to have the same Z_0 and β. The transformed load impedance at the stub position $z = -d$ is

$$Z = Z_0 \frac{Z_L + jZ_0 \tan(\beta d)}{Z_0 + jZ_L \tan(\beta d)} = Z_0 \frac{Z_L + jZ_0 t}{Z_0 + jZ_L t} \tag{4}$$

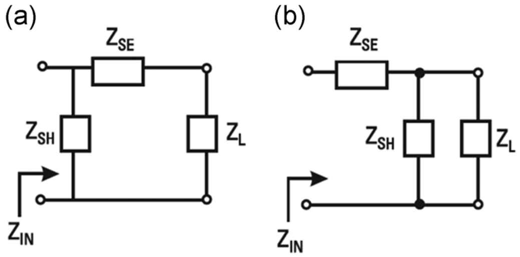


FIGURE 2 Two basic configurations of L-shaped lumped-element matching networks

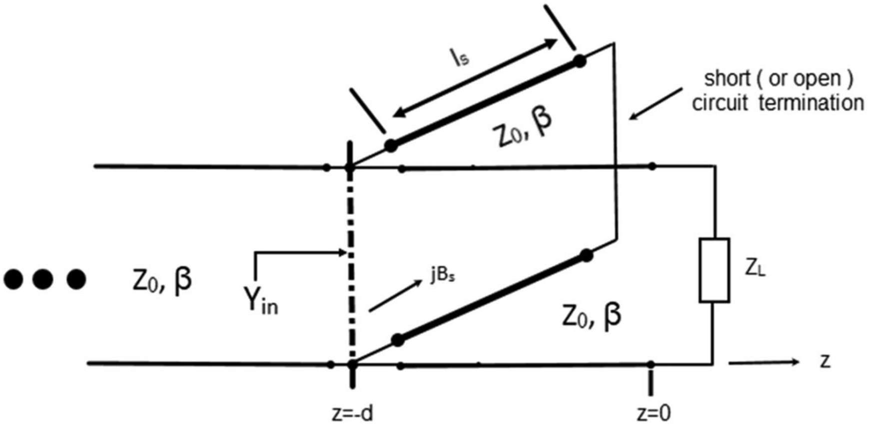


FIGURE 3 Short or open circuit of single-stub tuner [25]

Here, $t \equiv \beta$. Calculation with admittances is much simpler than impedances in shunt connection. So, transformed load admittance is defined as $Y = 1/Z = G + jB$. Here, the distance is chosen so that $G = Y_0 = (1/Z0)$ condition leads to the solutions of

$$\frac{d}{\lambda} = \begin{Bmatrix} \frac{1}{2\pi}\tan{-1t}, & t > 0 \\ \frac{1}{2\pi}(\pi + \tan{-1t}), & t < 0 \end{Bmatrix} \tag{5}$$

Here

$$T = \begin{Bmatrix} \frac{X_L \pm \sqrt{\left(\frac{R_L}{Z_0}\right)[(Z_0 - R_L)^2 + X_L{}^2]}}{R_L - Z_0}, & R_L \neq Z_0 \\ -\frac{X_L}{2Z_0}, & R_L = Z_0 \end{Bmatrix} \tag{6}$$

and $Z_L = R_L + jX_L$.

By the location of stub, real part of transformed load admittance is Y0 which is almost matched. Imaginary part of B is YL. Finally, the parallel combination of the transformed load admittance and stub input susceptance becomes Yin = Y0 and seen from the source end of the TL.

The quarter wave transformer matching is another impedance matching technique shown in Figure 4. As already known, a transmission line behaves like a transformer and the input impedance of the transmission line varies from maximum to minimum and from minimum to maximum with quarter wavelength intervals. The quarter wave transformer also uses this feature of the transmission line. It acts like a quarter wave section of the transmission line [21,25]. With a quarter-wavelength transformer, it is possible to match the fully ohmic loads or non-ohmic loads to the source. The impedance transitions of the quarter-wavelength transmission line are as follows:

$R_L = Z_0$: The quarter-wave line, acts as a transformer with a 1: 1 winding ratio.
$R_L > Z_0$: The quarter wave line, acts as a step-down transformer.
$R_L < Z_0$: The quarter-wave line, acts as a step-up transformer.

The characteristic impedance of the quarter wave section is mathematically calculated with following formula:

$$Z'_o = \sqrt{Z_o Z_L} \tag{7}$$

Here,
Z'_o = Characteristic impedance of a quarter-wave transformer
Z_o = Characteristic impedance of the matched transmission line
Z_L = Load impedance

In this paper, we'll solve and analyze transmission line problems by using the L-shape matching, stub tuning, and quarter wave transformer impedance matching techniques.

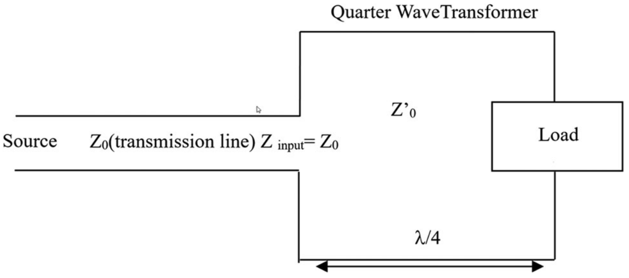


FIGURE 4 One-line diagram of quarter wave transformer matching technique [22]

3 | TRANSMISSION LINE PLANNING AND PROBLEM SOLVING WITH SMITH CHART

Determining input impedance, assigning reflection coefficient, and matching load impedance are important aspects for transmission line planning. These calculations bring about the difficulty of working with complex numbers. Difficulties at complex calculations can be made easier by using the Smith chart, which provides a graphical solution method. By this context, the Smith chart is best known and the most widely used graphical representation tool used for visualizing both normalized resistance and reactance functions in the complex reflection-coefficient plane. This visualization method makes transmission line calculations easier than analytical methods [22]. The Smith chart is also a convenient tool for general circuit calculations especially for impedance matching circuit design.

In generally, the Smith chart is made of many interlaced circles [4]. The construction of Smith chart for a lossless transmission line is examined by voltage reflection coefficient of the load impedance which is given below:

$$\Gamma_{\mathrm{L}} = \frac{V_{\mathrm{refl}}}{V_{\mathrm{inc}}} = \frac{Z_{\mathrm{L}} - Z_0}{Z_{\mathrm{L}} + Z_0} = \Gamma_{\mathrm{re}} + j\Gamma_{\mathrm{im}} \tag{8}$$

Γ_{re} and Γ_{im} are real and complex parts of reflection coefficient Γ_L, respectively. The Z_0 is characteristic impedance which basically selected as a constant value. The formation of normalized load impedance can be given as follows:

$$z_L = \frac{Z_L}{Z_0} = \frac{R + jX}{Z_0} = r + jx \tag{9}$$

While substituting Equation (9) into (8) voltage reflection coefficient of the load impedance can be written as follows [18]:

$$\Gamma_{\mathrm{L}} = \Gamma_{\mathrm{re}} + j\Gamma_{\mathrm{im}} = \frac{(Z_{\mathrm{L}} - Z_0)/Z_0}{(Z_{\mathrm{L}} + Z_0)/Z_0} = \frac{z_{\mathrm{L}} - 1}{z_{\mathrm{L}} + 1} \tag{10}$$

Equation (10) is rearranged for getting normalized load impedance as below:

$$r + jx = \frac{\left(1 + \Gamma_{\mathrm{re}}\right) + j\Gamma_{\mathrm{im}}}{\left(1 - \Gamma_{\mathrm{re}}\right) - j\Gamma_{\mathrm{im}}} \tag{11}$$

Then, removing complex denominator, Equation (11) is written as follows:

$$r = \frac{(1 - \Gamma_{\mathrm{re}}^2) - \Gamma_{\mathrm{im}}^2}{(1 - \Gamma_{\mathrm{re}}^2) + \Gamma_{\mathrm{im}}^2}(5), x = \frac{2\Gamma_{\mathrm{im}}^2}{\left(1 - \Gamma_{\mathrm{re}}\right)^2 + \Gamma_{\mathrm{im}}^2} \tag{12}$$

Finally, the rearrangement of Equation (12) can be made as

$$\left(\Gamma_{\mathrm{re}} - \frac{r}{1 + r}\right)^2 + \Gamma_{\mathrm{im}}^2 = \left(\frac{1}{1 + r}\right)^2 \tag{13}$$

The final equation resembles a parametric equation $(x\text{–}a)^2 + (y\text{–}b)^2 = R^2$ in the complex plane $((\Gamma_{\mathrm{re}}, \Gamma_{\mathrm{im}})$ of a circle centered at coordinates $(\frac{r}{r+1}, 0)$ and radius of $\frac{r}{r+1}$. Diverse r values produce unlikely radius circles with centers at varied locations on the Γ_{re} -axis.

As shown in Figure 5, properties of r circles have three basic rules. The first rule highlights that all r-circles' center lie on Γ_{re} -axis. The second rule constitutes the largest radii circle at r=0 short. The third rule explains that during r increases from 0 (short) to ∞ (open), r-circles becomes smaller.

In the same way, the rearrangement of Equation (11) can be made as

$$(\Gamma_{\mathrm{re}} - 1)^2 + \left(\Gamma_{\mathrm{im}} - \frac{1}{\mathrm{x}}\right)^2 = \left(\frac{1}{x}\right)^2 \tag{14}$$

The final equation resembles a parametric equation $(\mathrm{x}\text{–}\mathrm{a})^2 + (\mathrm{y}\text{–}\mathrm{b})^2 = \mathrm{R}^2$ in the complex plane $(\Gamma_{\mathrm{re}}, \Gamma_{\mathrm{im}})$ of a circle centered at coordinates $(1, \frac{1}{x})$ and radius of $\frac{1}{|x|}$). Diverse x values produce unlikely radius circles with centers at varied locations on the Γ_{re} –axis.

As shown in Figure 6, properties of x circles have three basic rules. First rule highlights that all x-circles' centers lie on Γ_{re} -axis for x>0 case known as inductive reactance above Γ_{re}-axis and $x < 0$ case known as capacitive reactance below Γ_{re} -axis. The second rule constitutes that during |x|, increases from 0 (short)

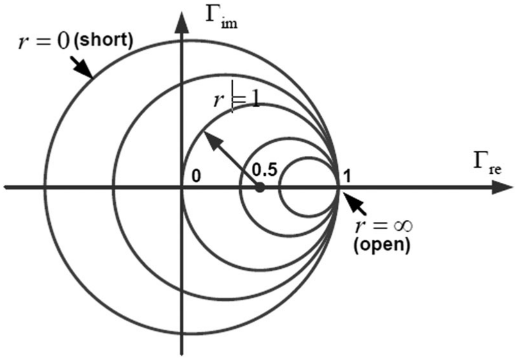


FIGURE 5 The r-circles in the complex plane (Γre, Γim)

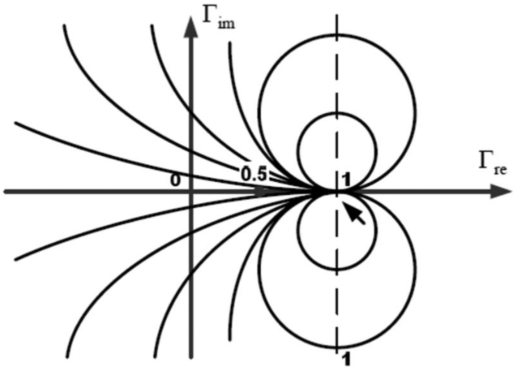


FIGURE 6 The x-circles in the complex plane (Γ_{re}, Γ_{im})

to ∞ (open), x-circles becomes smaller. The third explains that all x-circles pass through ($\Gamma_{\text{re}} = 1, \Gamma_{\text{im}} = 0$) [19].

As a result, Smith chart is constituted by the chart of r and x circles for $|\Gamma| \leq 1$. The intersection point of r-circle and x-circle defines normalized load impedance $z_L = r + jx$.

As shown in Figure 7, a point in the Smith chart gives the values of the normalized impedance z and the complex reflection coefficient Γ at the same point on a transmission line. In condition of $\Gamma = 0$, $\Gamma = |\Gamma|$. Therefore,

$$\frac{(1+\Gamma)}{(1-\Gamma)} = S \tag{15}$$

If the angle of Γ is zero

$$\frac{(1+\Gamma)}{(1-\Gamma)} = z = r \tag{16}$$

Bold dotted circle on Smith chart explains the same Γ and known as the constant VSWR circle [6]. When used correctly, impedance matching can be performed without any computation. The only effort required is the reading and following of values along the circles.

4 | OPEN SOURCE TRANSMISSION LINE IMPEDANCE MATCHING EDUCATIONAL (TLIME) FRAMEWORK

In the TLIME framework, an interface design has been designed to make transmission line calculations easier and more efficient through using the Smith chart. In the Smith chart interface, the reflected wavelength information of the load and the line is visually shown from the source to the load. The magnitude of wavelength and distance can also be changed through the slider tool for better understandings of their effects on transmission line planning. As shown in Figure 8, the graphical user interface of TLIME framework consists of 10 functional blocks.

Blocks of TLIME are described as follows in terms of numbers on figure:

1. This block is used to adjust wavelength from load to source or vice versa for the purpose of impedance calculation of any desired point on transmission line.
2. This graphical block is Smith Chart representations of TLIME module and is used to visualize the SWR circles and phasor representations of impedance of any desired point on transmission line in terms of degree and λ.
3. This block is used to activate or deactivate SWR tangent circle and maximum–minimum voltage points on Smith Chart.
4. This block is used to visualize the main parts of all charts in terms of impedance or admittance. The characteristic impedance value Z_0 is parametrically adjustable so that the effect of the characteristic impedance change on the transmission calculations at the TLIME interface is more clearly shown.
5. This block is used to show some mathematical values such as unit impedance of load, reflection coefficient, and angle which changes according to load position on TL.
6. This block is used to update transmission line impedance.
7. This block is used to adjust load impedance in terms of impedance, admittance, or reflection coefficient. For all transmission line calculation, the values of the

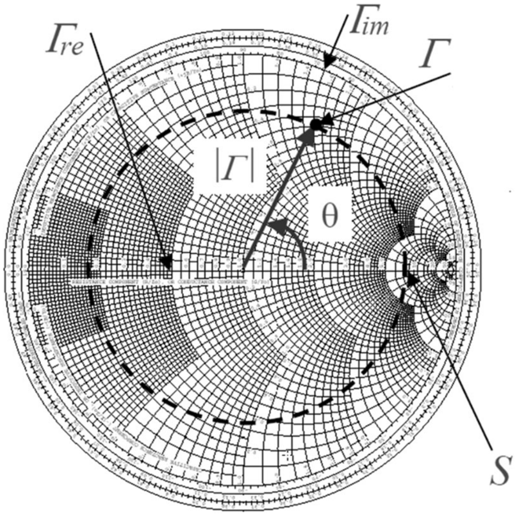


FIGURE 7 The representations of (S, 〚Γ,Γ〛 _re,Γ_im) in Smith Chart

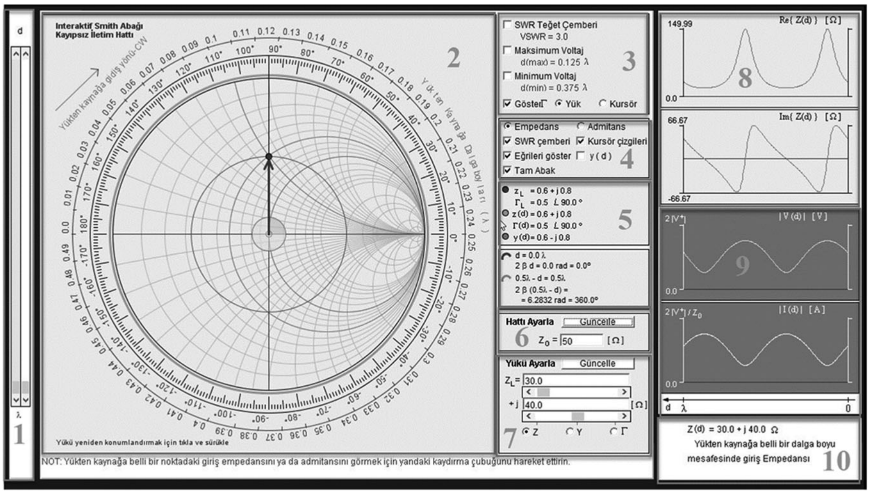


FIGURE 8 Graphical user Interface of TLIME framework. TLIME, transmission line impedance matching educational framework

Interaktif Smith Abağı
Kayıpsız İletim Hattı

Yükü yeniden konumlandırmak için tıkla ve sürükle

NOT: Yükten kaynağa belli bir noktadaki giriş empedansını ya da admitansını görmek için yandaki kaydırma çubuğunu hareket ettirin.

☐ SWR Teğet Çemberi
VSWR = 3.0
☐ Maksimum Voltaj
d(max) = 0.125 λ
☐ Minimum Voltaj
d(min) = 0.375 λ
☑ Göster ☐ ● Yük ○ Kursör

● Empedans ○ Admitans
☑ SWR çemberi ☑ Kursör çizgileri
☑ Eğrileri göster ☐ y (d)
☑ Tam Abak

z_L = 0.6 + j 0.8
Γ_L = 0.5 ∠ 90.0 °
z(d) = 0.6 + j 0.8
Γ(d) = 0.5 ∠ 90.0 °
y(d) = 0.6 - j 0.8

d = 0.0 λ
2 β d = 0.0 rad = 0.0°
0.5λ - d = 0.5λ
2 β (0.5λ - d) =
= 6.2832 rad = 360.0°

Hattı Ayarla Güncelle
Z_0 = 50 [Ω]

Yükü Ayarla Güncelle
Z_L = 30.0
+ j 40.0 [Ω]
● Z ○ Y ○ Γ

Z(d) = 30.0 + j 40.0 Ω
Yükten kaynağa belli bir dalga boyu mesafesinde giriş Empedansı

load and transmission line impedances both in terms of its ohmic and reactive sides are parametrically adjustable by using a slider tool.

8. This block is used to visualize the standing waves on transmission line at any desired point from load to source or vice versa.
9. This block is used to visualize voltage and current wave patterns of designed TL. Designer can trace angle differences between voltage and current on transmission line.
10. This block is used to visualize the input impedance from load to source or vice versa at a certain wavelength distance.

UML diagram of 'TLIME Framework' is sketched in Figure 9. As shown in UML diagram, "Chart Class" constitutes the backbone of the TLIME framework and the methods, fields and nested classes of Smith Panel, Smith Control and Smith Probe superclasses are inherited by subclasses in Chart class. It also runs Input Panel superclasses and Java Object Events. In addition, the constructors of all these superclasses are invoked from the subclasses in Chart class.

Thanks to the designed TLIME framework, transmission line impedance matching case problems are modeled for education purposes. One of case problem is determination of any desired point on the transmission line input impedance from fully ohmic (resistive) load and complex load to the source. Calculations have been driven by the use of TLIME framework.

Using the TLIME framework, we can calculate the input impedance and SWR of a transmission line with a characteristic impedance of 50 Ω and a load impedance of ZL = 30 + j40 Ω as follows.

As shown in Figure 10a, the load-phasor is positioned over the SWR ring at 90° angle. The normalized impedance is obtained as zL = 0.6 + j0.8 Ω. There are two half-wave distances within a 1.25 wavelength distance,

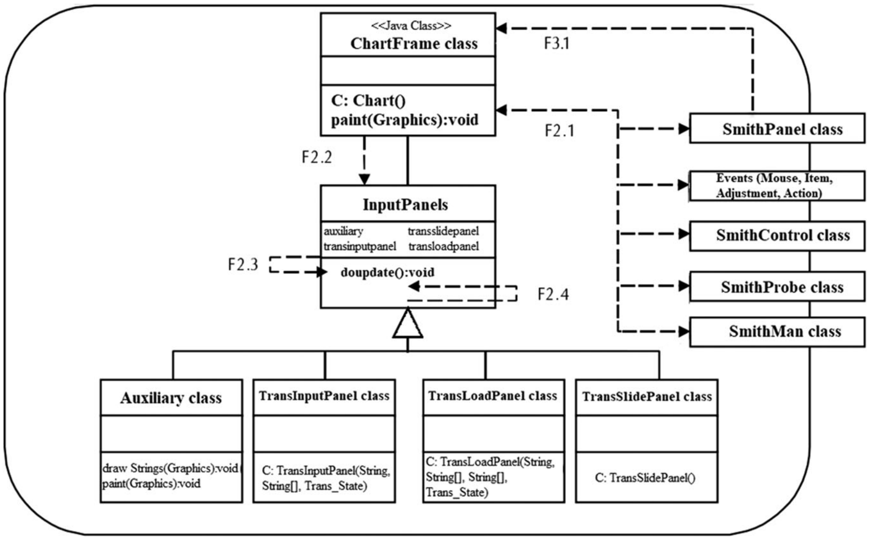
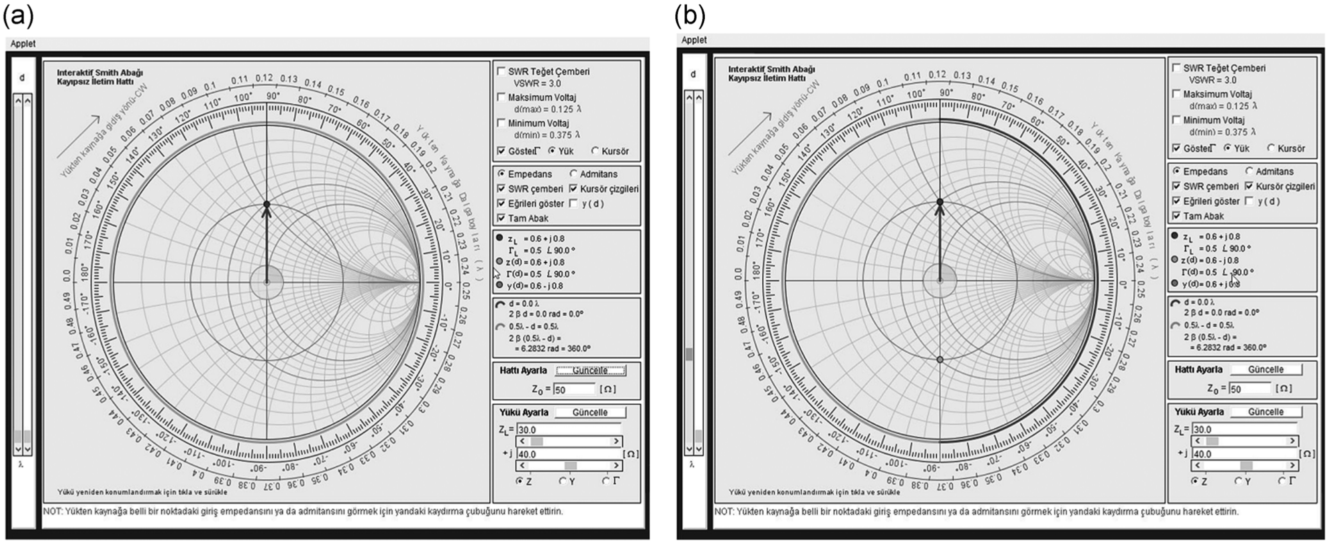


FIGURE 9 UML diagram of TLIME framework


(a)

☐ SWR Teğet Çemberi
VSWR = 3.0
☐ Maksimum Voltaj
d(max) = 0.125 λ
☐ Minimum Voltaj
d(min) = 0.375 λ
☑ Göster Γ ● Yük ○ Kursör

● Empedans ○ Admitans
☑ SWR çemberi ☑ Kursör çizgileri
☑ Eğrileri göster ☐ y (d)
☑ Tam Abak

z_L = 0.6 + j 0.8
Γ_L = 0.5 ∠ 90.0°
z(d) = 0.6 + j 0.8
Γ(d) = 0.5 ∠ 90.0°
y(d) = 0.6 - j 0.8

d = 0.0 λ
2 β d = 0.0 rad = 0.0°
0.5λ - d = 0.5λ
2 β (0.5λ - d) =
= 6.2832 rad = 360.0°

Hattı Ayarla Güncelle
Z_0 = 50 [Ω]

Yükü Ayarla Güncelle
Z_L = 30.0
+ j 40.0 [Ω]
● Z ○ Y ○ Γ

Yükü yeniden konumlandırmak için tıkla ve sürükle

NOT: Yükten kaynağa belli bir noktadaki giriş empedansını ya da admitansını görmek için yandaki kaydırma çubuğunu hareket ettirin.

(b)

☐ SWR Teğet Çemberi
VSWR = 3.0
☐ Maksimum Voltaj
d(max) = 0.125 λ
☐ Minimum Voltaj
d(min) = 0.375 λ
☑ Göster Γ ● Yük ○ Kursör

● Empedans ○ Admitans
☑ SWR çemberi ☑ Kursör çizgileri
☑ Eğrileri göster ☐ y (d)
☑ Tam Abak

z_L = 0.6 + j 0.8
Γ_L = 0.5 ∠ 90.0°
z(d) = 0.6 - j 0.8
Γ(d) = 0.5 ∠ 90.0°
y(d) = 0.6 + j 0.8

d = 0.0 λ
2 β d = 0.0 rad = 0.0°
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Yükü yeniden konumlandırmak için tıkla ve sürükle

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FIGURE 10 The screenshot of (a)- 30 + j40 Ω load connected to a 50 Ω line (b)- input impedance at the point of 0.25λ far away from the 30 + j40 Ω load

and the line repeats itself on each half-wave, so the part of 0.25 is taken. For this reason, 0.25 λ is added from the phasor point (0.125 λ distance) obtained in the framework.

This is done by moving the scrolling toolbar by a quarter wavelengths in the simulator. The new point is shown in grey color which is mirror direction of row sketched in Figure 10b. As shown in Figure 10b, the normalized impedance of the new point is obtained as z (d) = 60–j0.8 Ω. The real input impedance is obtained as Z (d) = 30–j40 Ω. As noted, the new input impedance obtained at the end of the quarter wavelength is conjugate of the load impedance.

Another case is based on the use of the TLIME framework in transmission line impedance matching problems. Two commonly used methods of matching transmission lines to load are quarter-wave transformer matching and stub tuning methods as discussed previous section.

For quarter-wave transformer case, it is used for matching 50 Ω characteristic impedance portion of the RG-8A/U with a 150 Ω ohmic load at the 150 MHz operating frequency. The question is the determination of physical size and frequency for a portion of the RG-8A/U.

$$\lambda = \frac{c}{F} = \frac{3x10^8\,\mathrm{m/s}}{150\,\mathrm{MHz}} = 2\,\mathrm{m} \tag{16}$$

$$\frac{\lambda}{4} = \frac{2}{4} = 0.5\,\mathrm{m} \tag{17}$$

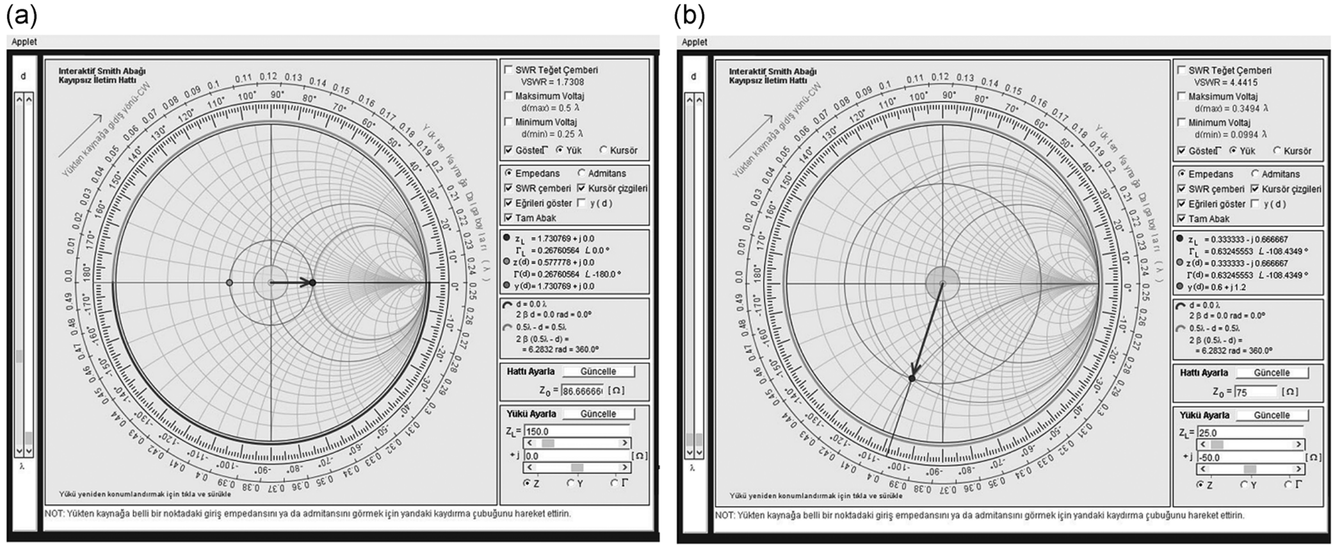
$$Z_0' = \sqrt{Z_o Z_L} = \sqrt{50 \times 150} = 86.6\,\Omega. \tag{18}$$

As the load is fully ohmic, the quarter-wave transformer is connected to its own point where the first ohmic load becomes visible. For this reason, there is no need to use smith chart to calculate for the location of the quarter-wave transformer in the ohmic loads. However, we can use the designed TLIME framework to simulate how impedance matching works. As shown in Figure 11a, the calculated value of the quarter-wave transformer (86.666 Ω) is entered in the part of the Z0 line impedance in the simulator. The screen update is performed from the framework menu, and when a quarter wave distance from the phasor is advanced, the input impedance Z (d) is obtained as 50 Ω.

As another example, we can use the framework to determine the exact location of the quarter-wave line transformer to be placed to match a 75 Ω transmission line to ZL = 25–j50 Ω a complex load with a capacitive component. As shown in Figure 11b, when the impedance values of line and load are entered, framework p.u impedance of the load is calculated as z_L = 0.333–j0.667 Ω.

In Smith Chart, the point where z (d) is fully formed is the 180 o point of the axis. The distance indicated by the load phasor is about 0.4λ. In this case, the distance of the quarter-wave transformer to the load is calculated as $D = 0.5\lambda - 0.4\lambda = 0.1\lambda$. The impedance value at this point is determined as $Z(\mathrm{d}) = 16.89$ Ω. The characteristic impedance of the quarter-wave transformer is calculated as below:

$$Z_o' = \sqrt{Z_o Z_d} = \sqrt{75 \times 16.89} = 35.59\Omega \tag{19}$$



(a)

☐ SWR Teğet Çemberi
VSWR = 1.7308
☐ Maksimum Voltaj
d(max) = 0.5 λ
☐ Minimum Voltaj
d(min) = 0.25 λ
☑ GösterΓ ● Yük ○ Kursör
● Empedans ○ Admitans
☑ SWR çemberi ☑ Kursör çizgileri
☑ Eğrileri göster ☐ y(d)
☑ Tam Abak
z_L = 1.730769 + j 0.0
Γ_L = 0.26760564 ∠ 0.0°
z(d) = 0.577778 + j 0.0
Γ(d) = 0.26760564 ∠ -180.0°
y(d) = 1.730769 + j 0.0
d = 0.0 λ
2 β d = 0.0 rad = 0.0°
0.5λ - d = 0.5λ
2 β (0.5λ - d) =
= 6.2832 rad = 360.0°
Z_0 = 86.66666 [Ω]
Z_L = 150.0
+j 0.0 [Ω]
● Z ○ Y ○ Γ

(b)

☐ SWR Teğet Çemberi
VSWR = 4.4415
☐ Maksimum Voltaj
d(max) = 0.3494 λ
☐ Minimum Voltaj
d(min) = 0.0994 λ
☑ GösterΓ ● Yük ○ Kursör
● Empedans ○ Admitans
☑ SWR çemberi ☑ Kursör çizgileri
☑ Eğrileri göster ☐ y(d)
☑ Tam Abak
z_L = 0.333333 - j 0.666667
Γ_L = 0.63245553 ∠ -108.4349°
z(d) = 0.333333 - j 0.666667
Γ(d) = 0.63245553 ∠ -108.4349°
y(d) = 0.6 + j 1.2
d = 0.0 λ
2 β d = 0.0 rad = 0.0°
0.5λ - d = 0.5λ
2 β (0.5λ - d) =
= 6.2832 rad = 360.0°
Z_0 = 75 [Ω]
Z_L = 25.0
+j -50.0 [Ω]
● Z ○ Y ○ Γ

NOT: Yükten kaynağa belli bir noktadaki giriş empedansını ya da admitansını görmek için yandaki kaydırma çubuğunu hareket ettirin.

FIGURE 11 The screenshot of (a)- quarter wave transformer matching technique in ohmic load, (b)- complex load

If Z (d) is set as the load impedance and Z'0 is set as the line impedance at the framework, it will be seen that the impedance at the quarter wave distance becomes 75 Ω.

For the case of stub tuning, the TLIME framework is used for easy matching a complex load with $Z_L = 50–j100$ Ω with a 75 Ω transmission line.

Steps are given below:

First, the normalized input impedance Z_L is calculated:

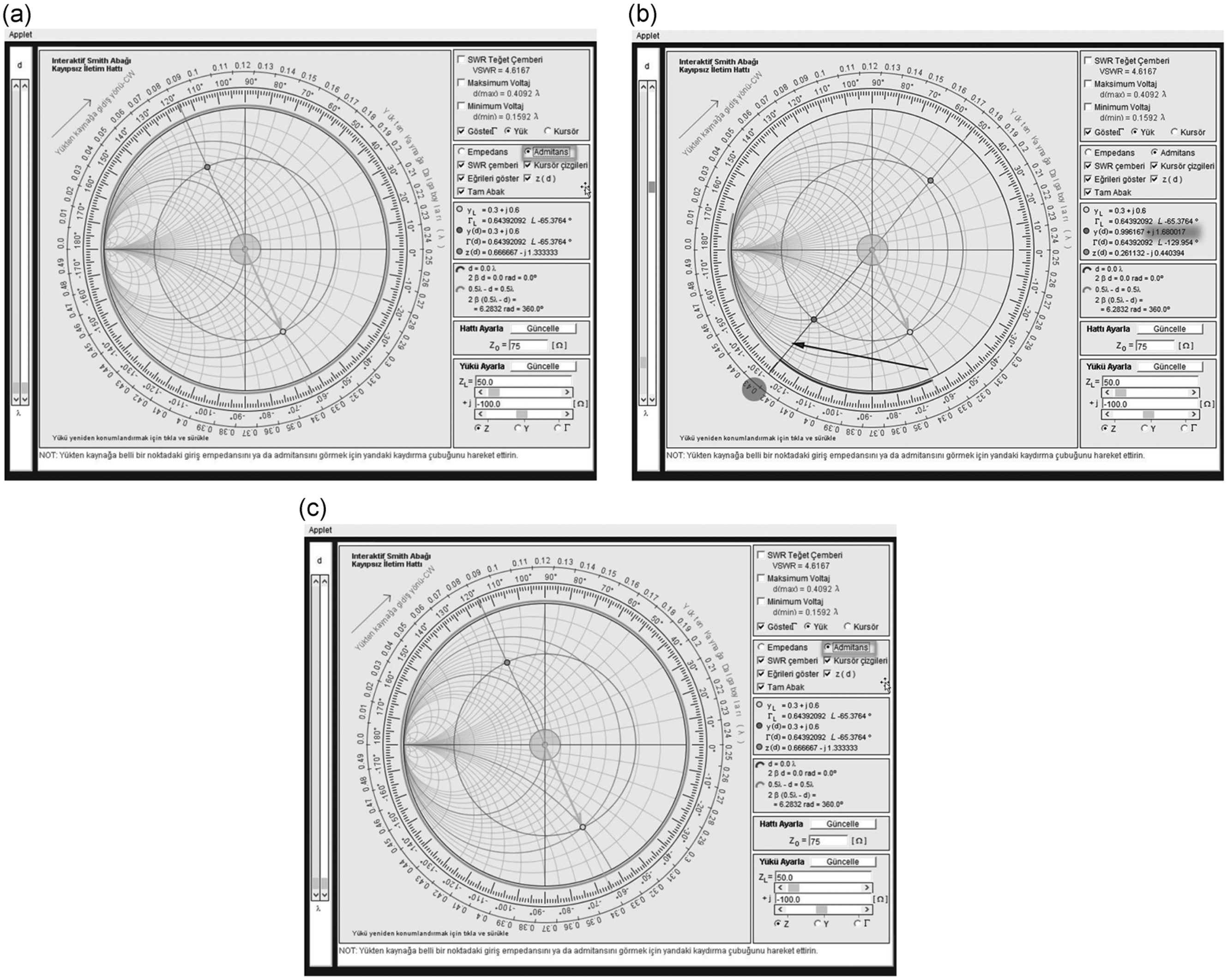
$$z_L = \frac{50 - j100}{75} = 0.67 - j1.33\Omega \tag{20}$$

As shown in Figure 12a, the admittance checkbox that highlighted in the grey rectangular frame is checked on the TLIME framework, and then, the framework display switches the admittance mode. Using the TLIME framework, the stub tuning matching technique utilizes admittance instead of impedance. The grey admittance phasor is obtained as follows: $y(L) = 0.3 + j0.6$

1. Then, as shown in Figure 12b, the admittance is scrolled clockwise from the load phasor, the wavelength slider is moved until it intersects with the $R = 1$ circle, and, when intersection is satisfied, the admittance value is obtained as $y\,(d) = 1\ + j1.68$.
2. The distance between the admittance phasor obtained in the previous step and newly calculated point is also the distance that the stub should be placed relative to the load. Therefore, the distance of the stub is calculated as: $0.43\lambda - 0.34\lambda = 0.09\lambda$.
3. The ohmic component of the stub admittance should be zero and the susceptance should be opposite polarity (so that $y = 0–j1.68$). As shown in Figure 12c, to find the length of the stub which has $y = 0–j1.68$ admittances, wavelength slider is continued to be moved clockwise direction until conjugate point of previous point (j1.68 point) is reached. The distance from the zero wavelengths to the distance of the conjugate point gives the length of the stub to be used. The length of the stub is calculated as $= 0.07\lambda - 0.0\lambda = 0.07\lambda$.

5 | OPEN SOURCE TRANSMISSION LINE IMPEDANCE MATCHING EDUCATIONAL (TLIME) FRAMEWORK

The TLIME framework has been used as an educational tool in courses in the 3 and 4 years of the electrical engineering undergraduate program at Sakarya University of Applied Sciences, Turkey. Students were selected among those who enrolled in power system analysis (88), electric circuits II (25), and communication theory (24) courses. After the several lectures about transmission line impedance matching methods with analytical solution and smith chart solution, "quarter-wave transformer matching and stub tuning matching methods" were asked to the students in a short exam. In the evaluation of the short exam, the full accuracy of the impedance matching problem solving steps was found in 65% of the attendant



(a)

Interaktif Smith Abağı
Kayıpsız İletim Hattı

☐ SWR Teğet Çemberi
VSWR = 4.6167
☐ Maksimum Voltaj
d(max) = 0.4092 λ
☐ Minimum Voltaj
d(min) = 0.1592 λ
☑ Göster Γ ● Yük ○ Kursör

○ Empedans ● Admitans
☑ SWR çemberi ☑ Kursör çizgileri
☑ Eğrileri göster ☑ z (d)
☑ Tam Abak

○ y_L = 0.3 + j 0.6
Γ_L = 0.64392092 ∠ -65.3764 °
● y(d) = 0.3 + j 0.6
Γ(d) = 0.64392092 ∠ -65.3764 °
● z(d) = 0.666667 - j 1.333333

d = 0.0 λ
2 β d = 0.0 rad = 0.0°
0.5λ - d = 0.5λ
2 β (0.5λ - d) =
= 6.2832 rad = 360.0°

Hattı Ayarla Güncelle
Z_0 = 75 [Ω]

Yükü Ayarla Güncelle
Z_L = 50.0
+ j -100.0 [Ω]
● Z ○ Y ○ Γ

Yükü yeniden konumlandırmak için tıkla ve sürükle

NOT: Yükten kaynağa belli bir noktadaki giriş empedansını ya da admitansını görmek için yandaki kaydırma çubuğunu hareket ettirin.

(b)

Interaktif Smith Abağı
Kayıpsız İletim Hattı

☐ SWR Teğet Çemberi
VSWR = 4.6167
☐ Maksimum Voltaj
d(max) = 0.4092 λ
☐ Minimum Voltaj
d(min) = 0.1592 λ
☑ Göster Γ ● Yük ○ Kursör

○ Empedans ● Admitans
☑ SWR çemberi ☑ Kursör çizgileri
☑ Eğrileri göster ☑ z (d)
☑ Tam Abak

○ y_L = 0.3 + j 0.6
Γ_L = 0.64392092 ∠ -65.3764 °
● y(d) = 0.996167 + j 1.680017
Γ(d) = 0.64392092 ∠ -129.954 °
● z(d) = 0.261132 - j 0.440394

d = 0.0 λ
2 β d = 0.0 rad = 0.0°
0.5λ - d = 0.5λ
2 β (0.5λ - d) =
= 6.2832 rad = 360.0°

Hattı Ayarla Güncelle
Z_0 = 75 [Ω]

Yükü Ayarla Güncelle
Z_L = 50.0
+ j -100.0 [Ω]
● Z ○ Y ○ Γ

Yükü yeniden konumlandırmak için tıkla ve sürükle

NOT: Yükten kaynağa belli bir noktadaki giriş empedansını ya da admitansını görmek için yandaki kaydırma çubuğunu hareket ettirin.

(c)

Interaktif Smith Abağı
Kayıpsız İletim Hattı

☐ SWR Teğet Çemberi
VSWR = 4.6167
☐ Maksimum Voltaj
d(max) = 0.4092 λ
☐ Minimum Voltaj
d(min) = 0.1592 λ
☑ Göster Γ ● Yük ○ Kursör

○ Empedans ● Admitans
☑ SWR çemberi ☑ Kursör çizgileri
☑ Eğrileri göster ☑ z (d)
☑ Tam Abak

○ y_L = 0.3 + j 0.6
Γ_L = 0.64392092 ∠ -65.3764 °
● y(d) = 0.3 + j 0.6
Γ(d) = 0.64392092 ∠ -65.3764 °
● z(d) = 0.666667 - j 1.333333

d = 0.0 λ
2 β d = 0.0 rad = 0.0°
0.5λ - d = 0.5λ
2 β (0.5λ - d) =
= 6.2832 rad = 360.0°

Hattı Ayarla Güncelle
Z_0 = 75 [Ω]

Yükü Ayarla Güncelle
Z_L = 50.0
+ j -100.0 [Ω]
● Z ○ Y ○ Γ

Yükü yeniden konumlandırmak için tıkla ve sürükle

NOT: Yükten kaynağa belli bir noktadaki giriş empedansını ya da admitansını görmek için yandaki kaydırma çubuğunu hareket ettirin.

FIGURE 12 The screenshot of stub tuning matching technique in (a)- complex load - step1, (b)- complex load–step2, (c)- complex load–step3

students. The remaining students were found to have matching method step errors or calculation errors in their solutions. In addition, it was seen that only 30% of the students, whose short exam evaluations, were able to correctly place matchings on the smith chart and commentate matching parameters. In the next lesson, thanks to the dialogues with students after the exam, it was determined that the students could not fully understand the advantage of the method applied for impedance matching.

Before using the framework, a brief presentation was given by a lecturer about main functions and usability of developed framework. To see the abilities, usefulness, positive, and negative aspects of the developed framework, at first, the lecturer kept solving exam problems with the traditional calculation method and handwritten Smith charts as has been before.

Then after, the solutions of the exam questions were demonstrated to the students via the developed TLIME framework, and the advantage of the method applied for both visual matching was demonstrated with the dynamic smith chart applet built into the TLIME framework. At the same time, the advantage of the both methods explained within variable load cases based on a number of different transmission parameters value is explained via the developed TLIME framework. A survey or questionnaire is very simple, direct, and important way to evaluate for this kind of new tool for education purposes and it uses in common. Therefore, the success of developed educational framework has been measured by also a questionnaire held in courses.

A questionnaire was applied to the students to evaluate the developed framework, and Table 1 summarizes the observed data from the questionnaires of the 137 students that completed the survey and results were obtained.

TABLE 1 Questionnaire about the functionality of developed Smith Chart framework

Question	CA	A	SA	NAND	SD	D	CD
The framework is helpful for transmission line related subjects	88	25	13	4	1	2	4
It is helpful for learning impedance matching method	111	7	8	2	2	2	5
It is easy to use	101	12	7	9	4	1	3
It is not enough flexible	11	23	20	12	45	24	2
It is too simple	21	95	12	5	2	2	0
It is too complex to understand and usage	5	12	15	38	23	36	8
Smith chart is already too complex to explain impedance matching	13	12	17	28	16	33	18

Abbreviations: A, agree; CA, completely agree; CD, completely disagree; D, disagree; NAND, neither agree nor disagree; SA, somewhat agree; SD, somewhat disagree.

Results show that functionality of TLIME framework for transmission-line-related subjects and impedance matching subjects have been scored over 83%. Nearly, the same percentage of students (82%) also were chosen with simplicity and easiness for the use of framework. 25% students answered with a bit complexity about usage, this result is nearly the same (33%) for theory of using smith chart for impedance matching problem.

The visual preparation of the problem solutions with graphical interface and simulating the mathematical representations has been evaluated to contribute to a better understanding of the transmission-line-related subjects and impedance matching subjects. By using the TLIME framework without falling into calculation complexity, it is possible to easily teach the students about the importance of load change and fault occurrence on any section of transmission line more precisely.

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