ELECTRICAL ENGINEERING EDUCATION USING MAPLE

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Abstract— *Many electrical engineering (EE) students have difficulty in learning technical subjects because they lack sufficient competence in mathematical modeling and in algebra. Maple is a powerful program for doing symbolic algebra, numerical calculation, and plotting of graphs, so using this program allows students to spend more time on modeling and interpreting results. Maple also has a text editor, which makes it feasible to require students to explain their results in writing. The design of Maple documents suitable for EE teaching is discussed; a standard format, including bibliographical information, is recommended for easier use.*

Index Terms — *CAS, Engineering Education, Maple, Writing Across Curriculum*

INTRODUCTION

This author's experience and the literature show a problem in electrical engineering (EE) education, namely that students do not master the mathematical tools that are prerequisite for studying EE. Lack of mathematical knowledge makes it difficult for them to analyze signals and circuits, a task that is heavily dependent on mathematical modeling and manipulation. Problem solving in electrical engineering often starts with a verbal statement of the physical problem, and the solution can be regarded as a four-step process. The first task is to state the problem in mathematical terms, i.e. to formulate the equations representing the physical situation. The second step is to symbolically solve those equations for the desired terms. The third step is the easy part: plugging in the values and doing the numerical calculations. The fourth step, frequently overlooked by many students, is to judge the correctness of the initial equations, the analytical solutions, and the final numerical results.

Students frequently have difficulties stating a physical problem in mathematical terms. In addition, they often lack the ability to do the symbolic manipulations necessary for solving the equations. They avoid solving problems from first principles, preferring rather to choose a similar looking (but often incorrect) formula from a textbook, put in numerical values, and get some numbers. Unintentionally, I'm sure, textbooks and lectures aggravate this problem by deriving general formulas for use in numerical calculations. Students then believe that the important thing is to memorize formulas and plug in numbers.

The third step, numerical calculation, for decades has been performed by calculators and computers. The second step, symbolic manipulation, often turns out to be the main focusing point in engineering subjects. EE classes have a tendency to become remedial classes in algebra. Although students must have the means of doing the second and third steps in problem solving, this is not the essential part of studying EE. To fully comprehend EE, students must work on the first and last steps in problem solving and this should be the focus of our teaching effort.

One problem we face as teachers is therefore how to handle the situation that many students have limited ability to do symbolic manipulations. The literature is full of good suggestions, one of which is to have students use Computer Algebra Systems (CAS). CAS, such as Derive, Mathematica and Maple have been used in college education for several decades [1] with good pedagogical results [2]. Early use of CAS in teaching focused on mathematics education, but in recent years CAS have also been used in teaching other subjects including physics [3], chemistry [4] and EE [5], [6].

Maple, as one of several advanced CAS systems, is well suited for analysis of electronic circuits. In addition to performing symbolic algebra, it can plot graphs and provide solutions to numerical calculations. Thus, Maple promises to remove the drudgery of the second and third steps of problem solving, giving more time to the first and last steps. Maple combines these mathematical capabilities with a text editor that enhances the usefulness of Maple as a teaching tool. Text can be included with calculations and be saved in an electronic document referred to as a worksheet. The possibility for teachers and students to write extensive worksheets including both advanced mathematical modeling and textual explanations should be exploited. This means employing another educational technique that will benefit the students, namely writing as a way of learning [7].

A MODEL WORKSHEET AND ITS USE

At Gjøvik College, Maple has been used for several years in teaching of mathematics, physics and EE, and many Maple worksheets have been written. We use essentially three different kinds of worksheets. Supplementary lecture notes, similar to the one presented in this paper, have been distributed to the students. Students have been required to submit a number of homework assignments in the form of Maple worksheets. Solutions to homework problems completed by both teachers and students have been distributed by posting them on the course web page. Worksheets written by people at other institutions have also been used.

The result is a set of worksheets numbering in the hundreds. Experience gained has shown the importance of paying attention to details in Maple worksheet design. To sum

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up our experience, a worksheet is presented in the appendix. It serves as a model for worksheets distributed to our students and provides the required format for student homework submissions.

Creating quality worksheets is time-consuming and use of Maple would become even more appealing if such documents could be shared among teachers and students at different institutions. Distribution of Maple documents among institutions is another reason to pay careful attention to the details in worksheet design.

The layout of a good worksheet will vary according to personal preference. However, a sensible division of the worksheet into different sections is necessary. What follows is the presentation of a worksheet written according to a standard that I have found useful in my own teaching and that I have encouraged the students to follow.

Bibliographical Information

Any worksheet that will be used by more than one person must have a section containing some bibliographical information. Experience tells us that students and teachers forget orally provided information about a worksheet, so information needs to be included in the document.

Each document must have a descriptive title so that the user can refer to it easily. If it contains the solution of a problem given in a textbook, make the title of the worksheet some combination of the author's name, the title of the book, and the problem number. Finding descriptive titles is more difficult than it may first appear, especially in a set of connected worksheets. Often it is useful to have a subtitle that identifies the worksheet as one in a series of several. I have had to change titles on a set of worksheets more than once in order to get a coherent system. The reason for including the name of the author of the worksheet below the title should be obvious.

Students may have questions about the contents of a worksheet and may wish to contact the author. Postal and/or E-mail addresses are therefore necessary information in a worksheet. I once distributed a borrowed worksheet that did not contain an address; the next day a student asked for the office address of the author who was a continent away.

The date and version number of a worksheet are also important information. If the worksheet is to be used in teaching, it will probably need to be modified, and it will be very easy to lose track of the latest version of the document.

Another mundane and irritating problem is that both teachers and students often lose track of the number of their Maple release. At our school we use MapleV Releases 2, 4, 5 and 6. All releases remain available because many worksheets were written for the different releases and it is a huge task to upgrade all these worksheets. As other CAS programs may also be used, worksheets should contain both the name of the program and the release number.

It is easier to find the right worksheet by leafing through paper copies than to find it among computer files. The name of the file must therefore be included in the document. As soon as I get more than 10 worksheets, I lose track of the contents and the corresponding file no matter how carefully I choose the file name. Choice of filenames requires some thought, and to make informative filenames out of a limited number of characters becomes difficult when there are many files (Long_File_Names_Are_Not_Very_Convenient). The obvious possibilities are to use a name related to the subject or to the course where the worksheet is used. I prefer the former because a worksheet often is used in more than one course.

It may be necessary to use one or more external library functions in a worksheet. I regularly use a plotting package that is placed in a private library. In order for others to use such worksheets, it is important to inform them that the document uses one or more routines in a particular library package and where this package is available on the Internet. In my sample worksheet this is done with a reference to the external library *EEplot4* at the web address: **http://www.hig.no/avdeling/ea/maple/lib/EEplot/**

For pedagogical reasons worksheets designed for education should encourage students to make modifications. One may assign additional problems, or the students may want to add notes to clarify a point. This will result in many different versions of the same original worksheet, and it becomes important to know who has made each modification. I always encourage my students to modify the worksheets and strongly urge them to write their name in the "modified by" space.

The above information should be kept in a single region in the beginning of the worksheet so that it can be collapsed and thus largely hidden while the students work on the main part of the document. However, it is important that the region be expanded when a printed copy of the worksheet is made so that the information becomes visible.

Pedagogical Considerations

Worksheets should have an introduction. The content of this introductory section may differ according to the purpose of the worksheet. For supplementary class notes, some theoretical presentation of the subject at hand is appropriate. Use adequate references to keep this introduction to a short review of the theory. If the worksheet is an answer key for a homework assignment, then the problem to be solved should be stated in the introduction. To merely refer to a problem number in a textbook is not sufficient. In addition, the homework that students submit should have the problem accurately stated in the introductory section. To save students the time of copying the problem, a worksheet containing only the problem may be provided.

The main part of the worksheet may be divided into two sections. The first section would be for the theoretical analysis, which should be kept symbolic where possible. The second section is then reserved for numerical calculations, presenting and discussing the results, and checking the correctness of the answers.

Symbolic calculation should start from first principles. In EE, that often means Ohm's and Kirchhoff's laws. This is important - students don't get enough experience in applying these laws to different physical situations. The additional work that would result if these calculations were to be done by hand is largely eliminated by the use of Maple. Although it is tempting to start with a well-known formula for a given class of circuits, it should not be done. Well-known formulas are useful as intermediate checks of the results, but not as a starting point for analysis.

Pedagogical considerations make it important to keep calculations symbolic as long as possible. For instance, symbolic expressions show the relationship between components in a circuit, whereas a numerical value gives no indication of any such dependencies. Symbolic results of a calculation, for example a transfer function, are therefore important for students to better judge and evaluate the validity of the analysis. Students have a tendency to do numerical calculations using calculators and to resist doing symbolic manipulations. If numerical answers to a problem are required, as is often the case, they should be obtained and checked at the end. A worksheet written by a teacher should therefore stress the importance of doing the symbolic analysis before obtaining the numeric results. As teachers, we should require the same of our students.

Another important point: students should always be required to judge the correctness of the obtained results. It can be done in different ways depending on the particular subject, but limit estimates are very suitable for many circuits where transfer functions are involved; and Maple will happily do limits. Such checks have a dual purpose in education. First, the symbolic solution and the estimates provide a deeper insight into the behavior of a circuit and are therefore important learning experiences. Second, checking results is important in any workplace, and it should be practiced with regularity.

Worksheets need to encourage students to do further work on a subject. Thus, a worksheet might contain a series of questions and problems for students to solve. I have used two ways of posing questions in a worksheet. First, the worksheet should have short questions to help students focus on important aspects of the problem; this should result in students modifying and adding to the document. Questions could require students to elaborate further on a point of understanding in writing, or could require them to do calculations on similar problems or other aspects of the same problem. I have found that such questions require a standard form that students will recognize immediately from one worksheet to the next, so I have used a double question mark and a bold italic type.

Second, a set of elaborate problems relating to the topic could be posted at the end of the worksheet. These should be designed so that students are required to work on a problem in several ways, theoretical, numerical and practical. To encourage this I have in the example included problems that further focus on the topic of impedance matching. These problems require the student to do further work in Maple, to do simulations on a numerical tool like PSpice, and finally to test the actual circuit in the lab.

In EE, it is important to represent circuits by drawings or schematics (Fig. 1 in appendix). Maple is not a graphics package, and suitable drawings cannot be made in Maple. However, schematics can be generated in a circuit program like *MicroSim Schematics*, and then cut and pasted into Maple. *MicroSim* (Fig. 2 in appendix) is usually more convenient than regular drawing programs, such as *Paintbrush*. It gives a circuit representation that is familiar to students and is much easier to use.

Well-designed instructional materials contain references to other literature so that the reader can examine a subject from other points of view. It is important that a worksheet also contains such a list of references to relevant literature. Although the courses where our worksheets are used include textbooks, it is necessary to encourage students to use the library to get different perspectives and, hopefully, a better understanding of the topic.

Finally, it is not realistic to expect students to learn more than a limited number of Maple commands. Thus, it is important that the worksheets used by students contain only this limited number of commands. The specific commands will vary from subject to subject, but teachers should consider this problem before they use Maple for teaching. Unusual commands used in, or output from, a worksheet may be explained in the documentation for the benefit of the students. In the appendix, the expression *RootOf* is briefly explained.

Writing Across Curriculum

A pedagogical method that has recently gone through a revival and become popular is to have the students write about the subject they are studying [8]. This method is often referred to as WAC (writing across curriculum) and has been combined with Kolb's learning-style theory [9]. If students have to formulate in words what they are investigating, it helps them build cognitive structures. Obviously, students cannot write sensibly about a subject if they don't understand it well. Writing can therefore be an important way of learning a subject. Maple, with its reasonably good text editor, can combine mathematical work in engineering and WAC into one document. Students as well as teachers should use this for learning and teaching purposes.

When solving problems using Maple, students should be required to document their reasons for formulating their equations. They should also have to explain how to solve these equations manually. When checking the mathematical results obtained by Maple, students should explain why they believe the results are correct. In fact, anything that is relevant to solving a problem and interpreting the results should be documented.

Maple is an ideal tool for doing these tasks, and the problems in the sample worksheet are formulated so that students are required to write in addition to the mathematical work. Homework is a learning tool, and requiring written explanations forces students to think through the subject matter. Writing their own worksheets as an alternative or a supplement to taking class notes is also valuable. Apart from being a learning tool, writing is also a necessary skill for any engineer and should be practiced often. Any assignment given should be considered a small project; it therefore requires a small report written according to accepted standards.

All this work sounds like a lot to expect from a worksheet, especially one written by a student. However, it is better, I believe, for a student to do a few detailed problems rather than many problems superficially. Experience tells me that the majority of the students are willing to put more effort into making extensive worksheets than into regular handwritten reports. Maple documents look more professional and are more easily modified.

SUMMARY AND CONCLUSIONS

Use of CAS like Maple adds a new and powerful tool to EE education. It reduces the drudgery of symbolic manipulations that students find so tedious. Maple includes graphic and numeric capability that may be inferior to more specialized packages, but is more than adequate for most students. Maple contains a text editor, making it possible to include mathematical expressions, figures and text in a single document. However, if Maple worksheets are to be used successfully in education it is important that simple design guidelines be observed. Worksheets must have comprehensive bibliographic information such as a descriptive title, name of the author, address and E-mail address of the author, date, version number, file name of the worksheet, and Maple release number. If a worksheet makes use of procedures in special libraries or files, the location of these files or libraries needs to be included.

For pedagogical reasons, calculations in worksheets should start from first principles and be kept symbolic as far as possible. Students should be assigned problems that enlarge the worksheet. A key to effective learning, I believe, is that students should concentrate on modeling and testing results. To do this they should include both mathematics and written discussion in the worksheet. Having students write as a way to learn is strongly emphasized, and Maple is very well suited for this purpose.

Overall, I find Maple a most exciting tool to use in EE teaching, and I am sure that all the possibilities have not yet been exploited. Maple or other similar CAS could become a unifying program in EE education, replacing a string of other programs from word processors to numerical simulation tools. This replacement should be seriously considered, since one of the main complaints from students is that there are far too many different programs to be learned, sometimes two or three in one course, and that some of these programs are used in one course only.

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APPENDIX

IMPEDANCE MATCHING NETWORK

Supplementary Notes in Electronic Circuits #3.1
Ola Royrvik

• Information

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E-mail: OlaR@hig.no
Date: June-97 Version: 1
File: IMPMACH1.MWS Maple V Release 4
Extern. Lib.: EEplot4 at **http://www.hig.no/avdeling/ea/maple/lib/EEplot/**

Modified by: Nobody

• Introduction

This worksheet contains a brief introduction to the theory of a simple impedance matching network, along with some theoretical and practical student problems.

Assume a given signal source with a given impedance R2 and a load R1, both impedances being real. In order for the maximum power to be transferred from the source to the load, R1 must be equal to R2. If the two impedances are different, we may insert an impedance matching LC-network between the source and the load (Krauss et al., 1980; Franke, 1991). We will construct an impedance matching network starting with a circuit as outlined in Fig. 1.

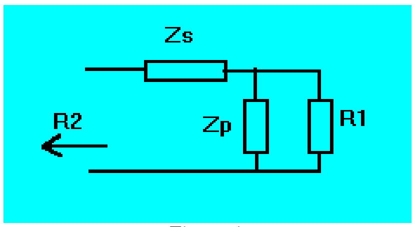


Figure 1

We make no assumptions about Zs and Zp except that they are imaginary, so Zs=jXs and Zp=jXp. For matching to occur, the impedance of the network as seen from the terminals must equal the source impedance R2. This will insure that the maximum energy will be transferred from the source to the load resistance R1, since Zs and Zp have purely imaginary impedances and thus can absorb no energy.

• Derivations and Calculations

• Derivations

The impedance of this network between the terminals is equal to the impedance of the source (Franke, 1991, Krauss et al., 1980); thus, we have the following equations:

```
> restart:
> E1:=R2=Zs+Zp*R1/(Zp+R1); Zs:=I*Xs;  Zp:=I*Xp;
```

$$E1 := R2 = Zs + \frac{Zp\,R1}{Zp + R1}$$

$$Zs := I\,Xs$$

$$Zp := I\,Xp$$

```
> E2:=evalc(E1);
```

$$E2 := R2 = \frac{Xp^2\,R1}{R1^2 + Xp^2} + I\left(Xs + \frac{Xp\,R1^2}{R1^2 + Xp^2}\right)$$

We have obtained an equation relating the unknowns Xs and Xp to the known resistances R1 and R2. Since this is a complex equation, the real and the imaginary parts must be equal, so we may rewrite equation E2 as follows.

```
> Eq1:=evalc(Im(lhs(E2)))=evalc(Im(rhs(E2)));
```

$$Eq1 := 0 = Xs + \frac{Xp\,R1^2}{R1^2 + Xp^2}$$

```
> Eq2:=evalc(Re(lhs(E2)))=evalc(Re(rhs(E2)));
```

$$Eq2 := R2 = \frac{Xp^2\,R1}{R1^2 + Xp^2}$$

We have obtained two purely real equations with unknowns Xp and Xs, and we shall solve these equations with respect to the two unknowns. Solving Eq1 and Eq2 gives.

```
> solve({Eq1,Eq2},{Xs,Xp});
```

$$\{Xs = \mathrm{RootOf}((R2 - R1)\,\_Z^2 + R2, label = \_L1)\,(R2 - R1), Xp = \mathrm{RootOf}((R2 - R1)\,\_Z^2 + R2, label = \_L1)\,R1\}$$

```
> assign(''):
```

((RootOf indicates that there is more than one solution to the equations. The individual solutions may be found by giving the command "allvalues".))

```
> Xs:=[allvalues(Xs)];  Xp:=[allvalues(Xp)];
```

$$Xs := [-\sqrt{(-R2 + R1)\,R2}, \sqrt{(-R2 + R1)\,R2}]$$

$$Xp := \left[\frac{\sqrt{(-R2 + R1)\,R2}\,R1}{-R2 + R1}, -\frac{\sqrt{(-R2 + R1)\,R2}\,R1}{-R2 + R1}\right]$$

From these expressions we see that R1>R2, otherwise Xp and Xs would be imaginary - contrary to our assumptions. Furthermore, we have two sets of solutions, where a positive Xs gives a negative Xp and vice versa. Note that it is the first root of Xp that is negative, since (R2-R1)<0.

We get two different circuits that fit our requirement, each with a coil (L) and a capacitor (C) as shown in Fig. 2. Remember that positive X means a coil and negative X means a capacitor.

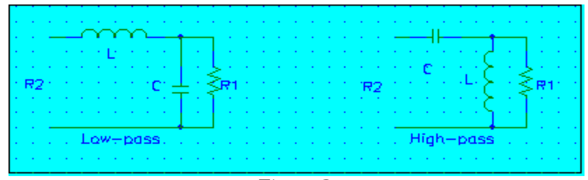


Figure 2

These circuits provide impedance matching between the source and the load, but at only one frequency. The reason for this is that X_L and X_C are frequency dependent. As a function of frequencies, these two circuits are filters, one LP and one HP.

?? Make sure you understand why these circuits are LP and HP filters, respectively, by performing limit estimations.

We proceed to find expressions for L and C for the HP circuit.

```
> E1:=-1/(wo*Chp)=-1*sqrt(R2*R1-R2^2);
```

$$E1 := -\frac{1}{wo\,Chp} = -\sqrt{R2\,R1 - R2^2}$$

```
> Chp:=solve(E1,Chp);
```

$$Chp := \frac{1}{\sqrt{R2\,R1 - R2^2}\,wo}$$

```
> E2:=wo*Lhp=-R1*sqrt(R2*R1-R2^2)/(R2-R1);
```

$$E2 := wo\,Lhp = -\frac{R1\sqrt{R2\,R1 - R2^2}}{R2 - R1}$$

```
> Lhp:=solve(E2,Lhp);
```

$$Lhp := -\frac{R1\sqrt{R2\,R1 - R2^2}}{wo\,(R2 - R1)}$$

?? Note that L and C are functions of R1, R2 and the frequency wo. Make sure you understand why this is so. Simplify these expressions somewhat by hand. Find similar expressions for the LP circuit.

• Calculations

Consider the HP circuit in Fig. 2, and choose values for the components so the impedance of the circuit as a function of frequency may be plotted.

```
> Zp:=1/(1/(s*L)+1/R1);  Zi:=1/(s*C)+Zp;
```

$$Zp := \frac{1}{\frac{1}{s\,L} + \frac{1}{R1}}$$

$$Zi := \frac{1}{s\,C} + \frac{1}{\frac{1}{s\,L} + \frac{1}{R1}}$$

Use the following values:

```
> R1:=200; R2:=150; wo:=evalf(2*10^6,3);
```

$$R1 := 200$$

$$R2 := 150$$

$$wo := .200\ 10^{7}$$

Numerical values for the capacitor (C) and the coil (L), are therefore:

> C:=evalf(Chp,3); L:=evalf(Lhp,3);

$$C := .576\ 10^{-8}$$
$$L := .000173$$

?? Given these values for C and L, analyze the circuit as seen from the load resistance R1. Show that this impedance is equal to R1 so that the circuit also acts as an impedance matching network from R2 to R1.

Plot the real and imaginary parts of the impedance as a function of frequency. If done correctly, we expect to get a purely real impedance (R2) at the designed frequency. We expect the imaginary part of the impedance to be equal to zero.

> s:=I*w;

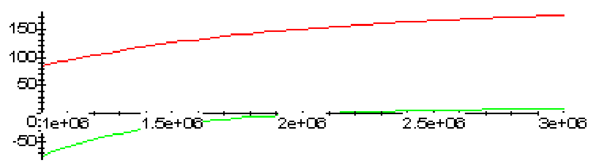
$$s := I\,w$$

> Zre:=evalc(Re(Zi)); Zim:=evalc(Im(Zi));

$$Zre := \frac{1}{200}\,\frac{1}{\dfrac{1}{40000} + \dfrac{.3341240937\ 10^{8}}{w^{2}}}$$

$$Zim := -.1736111111\ 10^{9}\,\frac{1}{w} + \frac{5780.346821}{w\left(\dfrac{1}{40000} + \dfrac{.3341240937\ 10^{8}}{w^{2}}\right)}$$

> plot({Zre,Zim},w=10^6..3*10^6);



Plot 1:

Plot 1 shows that the real and imaginary parts of the impedance behave as expected.

?? Explain the graphs in Plot 1. Why does the imaginary part of the impedance change sign at the design frequency?

Finally, let us find the Bode plot for the HP circuit (Fig. 2) in order to investigate the behavior of this filter. Plot 2 confirms that the circuit is an HP filter.

> s:='s';

$$s := s$$

> Z1:=R2+1/(s*C); Z2:=R1*s*L/(R1+s*L);

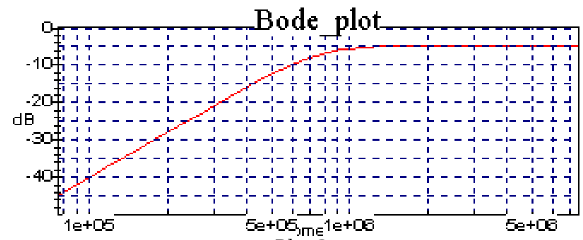
$$Z1 := R2 + \frac{1}{s\,C}$$

$$Z2 := \frac{R1\,s\,L}{R1 + s\,L}$$

> H:=simplify(Z2/(Z1+Z2));

$$H := 346000.\,\frac{s^{2}}{.6003472222\ 10^{12}\,s + 605500.\,s^{2} + .3472222222\ 10^{18}}$$

> with(EEplot4):
> Bodeplot(H);



Plot 2

• Problems

* Find the transfer function for the LP circuit (Fig. 2) with the output measured across R1. Plot the amplitude and phase of this function when R2=75 Ohm, R1=150 Ohm, and fo=500 kHz.

* Plot the impedance (real and imaginary or amplitude and phase) of the LP circuit as a function of frequency. Compare this to the impedance plots for the HP circuit already found.

* Do a similar analysis for the circuit in Fig. 3.

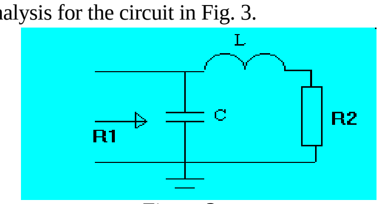


Figure 3

* Assume that one of the resistances R1 or R2 equals 75 Ohm, and the other 150 Ohm. Determine R1 and R2. The circuit should operate at 10 kHz. Determine L and C.

* Find the transfer function for the circuit as seen from R1 and plot the frequency response.

* Simulate the circuit using Spice and determine the frequency response and the input impedance of the circuit at the design frequency.

* Construct the circuit and measure the frequency response and impedance of the circuit at the design frequency. Measure the circuit seen from R2 when the input is terminated by R1.

* Compare the results obtained by the three different methods.

* Use the circuit in Fig. 3 but exchange the values of R1 and R2. What will the results be?

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