AUTOMATIC IMPEDANCE MATCHING CONTROL SYSTEM BETWEEN SOURCE AND LOAD

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

ELECTRONICS AND COMMUNICATION ENGINEERING
(With Specialization in Control and Guidance)

By

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Candidate Declaration

I hereby declare that the work being presented in the dissertation report titled **"Automatic Impedance Matching Control System Between Source and Load"** in partial fulfillment of the requirement for the award of the degree of Master of Technology in Control and Guidance, submitted in the Department of Electronics and Computer Engineering, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out under the guidance of Dr. Vijay Kumar, in the Department of Electronics and Computer Engineering, Indian Institute of Technology Roorkee. I have not submitted the matter embodied in this dissertation report for the award of any other degree.

Dated: 30|06|09
Place: IIT Roorkee

Hitesh Shukla

Certificate

This is to certify that above statements made by the candidate are correct to the best of my knowledge and belief.

Date: **30th June 2009**
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Last but the most I would like to dedicate this thesis to **My Parents** and I will pray to God that every child on this planet may get parents like them

Hitesh Shukla

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List of Abbreviations

RF: Radio Frequency

LINAC: Linear Accelerator

FM: Frequency Modulation

AM: Amplitude Modulation

HDTV: High Definition Plasma Television

BARC: Bhabha Atomic Research Centre

CERN: European Organization for Nuclear Resaearch

Cyclo: Cyclotron

Synchros: Synchrotrons

CCP: Capacitively Coupled Plasma Chamber

ICP: Inductively Coupled Plasma Chamber

HPPC: Heavy Particle Plasma Chambers

DoF: Degree of Freedom

IHVS: Intelligent Highways and Vehicle Systems

GPS: Geo-Positioning System

MMIC: Monolithic Microwave Integrated Circuits

TEM: Transverse Electromagnetic Mode

TM: Transverse Magnetic Mode

Q-factor: Quality Factor

BW: Bandwidth

Z_{IN}: Input Impedance

Z_0: Characteristic Impedance or Reference Impedance

MEMS: Micro Electro-Mechanical System

ML: Medium Low

Med: Medium

MH: Medium High

FKBC: Fuzzy Knowledge Base Controller

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Abstract

This dissertation mainly concerns about a basic problem in RF technology of Impedance matching between source and load. There are many applications of RF where continuously changing load increase reflected power towards source, thus transmitted power to load decreases, as a consequence source malfunctioning and losses increase. This topic basically provides knowledge about impedance matching between source and load, not only this but how automatic impedance matching control system can be designed for a varying load such as PLASMA chambers and Microwave ovens. Other applications of impedance matching control system are Acoustic systems where the impedance of diaphragm keeps on changing because the incident frequency on the same changes which again needs impedance matching between the reflector and the receptor diaphragm.

This topic encloses a basic knowledge about the impedance matching, how it can be achieved? How some of the soft computing techniques can be used for matching the impedances. Not only this but this dissertation discusses about some of the instruments that can help to find the RF characteristics of the network. The working frequency is considered to be 13.56 MHz (being a non-patented frequency for research). This being low frequency only lumped elements can be used for the matching purpose. A study for two and three element matching has been done and for simplicity and reduced complexity controller for two element matching network has been designed and results for the same are discussed. A fuzzy logic controller for the same has been designed and the comparison between the ideal controller and fuzzy controller has been established. Effects of delay in matching have been studied and the results for the same have been included in the report. The variations in the element values with respect to changes have been included in the report.

Chapter 1: Introduction

1.1 Introduction

RF and Microwave Engineering is one of the fastest growth areas of the past decade and will probably continue to be a very active area of research and application in a large variety of fields. Military, RADAR, Research, Wired and Wireless Communication, Home appliances etc. are some of the areas where RF technology is used most frequently. Various frequencies ranges are used for various purposes for example 9 KHz to 540 KHz band is used for Radio and Navigation purposes, 540 KHz to 1.63 MHz is used for AM Radio broadcasting, 88 MHz to 174 MHz is used for FM Broadcasting of signals etc. 8 GHz to 12GHz of frequency range is used widely for military purposes. Among all these bands some of the frequencies are allotted for personal communication purposes. And so as to use these frequencies one has to go for patenting that frequency, and then use it for further laboratory work. Among all these applications the main objective is to transfer maximum power to the required destination, so as to minimize the losses and to use power efficiently. Not only this but some of the power is reflected back to the source. Thus this reflected power towards the might harm the source and if not minimized may cause malfunctioning of the source. One more problem is of excessive heating, RF has a peculiar effect of heating, which is nowadays used in many microwave ovens. Besides all these problem of mismatch between source and load are very common.

The topic of this dissertation throws a spotlight over one of the problems that are faced in microwave applications the most i.e. problem of minimizing the reflections and maximizing the amount of power transmission. The destination may be considered as a load, this problem is basically considered as the problem of mismatch between the source and load. Also there are some applications where the load keeps on changing and because of this change in the load the reflections and the transmitted power keeps on changing. Thus, so as to achieve maximum transmission of power and to minimize the reflections the source should also be changed. But source has some intrinsic characteristics that can not be changed, which causes heavy reflections from source towards load. The source and the load would be considered as matched if and only if the reflections are zero and maximum power is transferred to the load.

1.2 Motivation

Now a days RF technology has become a part of our life. Home appliances like microwave ovens, High Definition Plasma Television (HDTV), mobiles, communication technology, etc. are some of places where the RF technology has hit the human life most.

Various organizations such as CERN, BARC, Plasma Research Institute are working in the field of Linear Accelerators. Linear accelerators are the devices in which the ions or the electronically charged particles are accelerated and bombarded on a heavy metal target for particle studies. Sometimes particles before entering Cyclos and Synchros require initial energy and after this they are allowed to revolve in a predefined circular part. This initial energy is provided by Linear accelerators. These linear accelerators are also given a name 'LINAC'. The particles that are used for this purpose are either electrons or heavy particles.

For generation of heavy particle Plasma Chambers (HPPC) are used. This plasma is generated with the help of RF energy supplied by an RF source. As energy is supplied to the chamber, gaseous material filled in the chamber gets ionized and the conduction starts. Initially due to absence of charged particles very low amount of conduction was there, which results in an increased resistance, while as avalanche takes place, due to availability of free charges, suddenly the conduction increases resulting in a low resistance. This results as a rapid change in impedance of the plasma chamber. The dependencies of plasma impedance are yet not found which makes it a field of research. It has been found that impedance depends on the composition of the gas used, temperature, amplitude, time for which energy is supplied to the chamber etc.

BARC, one research organizations in the country, is going to design a high energy heavy ion linear accelerator leading country one step ahead in field of RF and particle study, for which a Capacitively Coupled Plasma Chamber (CCP) is to be used for ion generation. For this project one of the basic problem reflections are to be solved so that efficient use of energy can be assured, as well as for preventing source from malfunctioning because of reflections.

1.3 Problem Statement

The problem states that an automatic impedance matching control system is required to match a capacitively coupled plasma chamber, such that the impedance of the chamber varies between 5 ohms to 50 ohms. It is given that the calculations regarding the impedance at a given instant of time is known. RF frequencies are to be patented before use; hence a working frequency of 13.56 MHz has been used. It is required that the reflections at the source side should be minimized. Assume that changes in the impedance are gradual; instruments used have no loading effect on the source.

1.4 Organization of Dissertation Report

The organization of the report is as follows:

Chapter 2: Covers a detailed explanation about impedance matching and different ways of impedance matching, previous defects in matching control systems, plasma chambers, study of fuzzy controllers, etc. Impedance measurement techniques at RF frequency.

Chapter 3: Covers briefly about PLASMA chambers.

Chapter 4: Explains about the background of work done in this dissertation. Algorithm for impedance matching, designing a fuzzy controller, deciding the rule base for controller, matching network with DoF 2 and 3, design of exact controller to minimize reflected power has been proposed.

Chapter 5: Analyses the results of the work concluding about the accuracy, speed and stability of the control system designed.

Chapter 6: Concludes the dissertation report and gives suggestion for future work.

Chapter 2: Impedance Matching

2.1 INTRODUCTION [1]

There has been a very fast growth in RF and microwave technology during the past decade. RF and Microwave is considered as the hottest and most emerging feild of engineering. Some of the expanding activities in these fields include wireless communications (mobile, cellular, and satellite), wireless sensors, local area networks, remote control and identification, global positioning systems (GPS), and intelligent highway and vehicle systems (IHVS).

Generally speaking, RF and microwave circuits and systems consist of multiple planar and/or nonplanar transmission-line sections (passive elements) and active devices (e.g., transistors, diodes) that are interconnected in an appropriate manner in order to achieve specific high frequency signal processing. In some cases, it is also possible to design a complete microwave system with only passive components. At lower frequencies (e.g., 300MHz–10 GHz), the circuits usually involve lumped elements such as resistor, inductor, and capacitor to keep circuit dimensions small.

At higher frequencies, the quality of lumped elements deteriorates rapidly, and mostly distributed elements are used. In any case, the transmission-line technique is the foundation for designing such microwave elements. In a typical microwave circuit or system, the passive part easily makes up 75% or more of the circuit real estate area. Because of different electromagnetic signal processing techniques involved in each component and also specific requirements for component-to-component signal transfer or transmission, impedance transformers, and/or matching networks are always needed.

The purpose of an impedance transformer is to transform given impedance to a specific value in view of microwave signal transmission. An impedance-matching network may consist of more than one impedance transformer. Its design goal is to match a given impedance to a prescribed value over a frequency range of interest to ensure maximum power transfer from one place to another (e.g., from a source to a load). Impedance transformers and matching networks are perhaps the most important and most widely used microwave circuit components, which are usually passive. There also exist in practice active and electronically tunable impedance transformers and matching networks for special applications such as broadband or multiband systems design. In this case, semiconductor-based monolithic microwave integrated circuits (MMICs) are a choice of preference. Electrical (active) and/or mechanical (passive) impedance tuners, for example, are widely used in RF and microwave measurement setups, such as load-pull nonlinear and noise characterization systems.

Nevertheless, most practical matching networks are fixed (passive) with respect to the center frequency, bandwidth of application, and impedance transformation (impedance ratio). The typical applications of this include optimizing the reflections from a load towards the source by inserting a matching network or matching transformer in between so that conjugate matching can be done, also very importantly the impedance matching between a laser diode and its driving circuitry.

The definition of impedance changes from transmission line to transmission line. Impedance also depends on the mode in which the waveguides are used, the impedance of waveguide is different in the TEM mode and is different in TM mode. For a single mode application the impedance for a device can be defined and can be used easily, but in multi mode transmission defining impedance becomes more complex and still a challenge today. Thus, it requires a basic definition of impedance to be given for a particular device at a particular instance.

A basic block diagram of impedance transformers and matching networks is shown in Figure 2.1. Various design techniques are available. Techniques based on the Smith chart are popular in connection with the lumped-element network approach. Matching networks may be built from lumped or distributed elements or a combination of both. In the figure 2.1 'Zs' is the impedance of the source while 'Z_L' is the load impedance.

Impedance matching networks are not just designed for the requirement of optimal flow of power from source and load. Many practical impedance matching networks are not only designed to achieve the optimal flow of power but also to meet additional constraints such as minimizing the noise influence, maximizing power handling capacity and linear zing the frequency response in the desired range of frequencies.

The impedance of the load and the source can not be changed as these are intrinsic properties. This can only be done by inserting a matching network in between source and load.

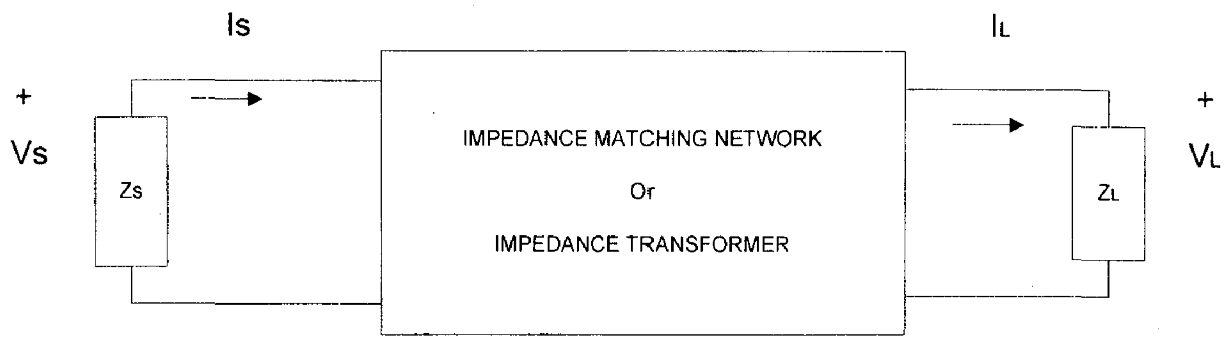


Figure 2.1: Basic block diagram of impedance transformer or impedance matching network.

2.2 IMPEDANCE MATCHING NETWORK

Impedance matching networks are used to transform an arbitrary load to a fixed load. In other words matching network transforms specific value impedance at one reference plane to impedance in another reference plane. Looking to the figure 2.1 it is evident that whole network can be considered to be made of three parts a load and a source which are connected by impedance matching network.

Impedance has different values at different frequency and non TEM mode or multiple modes. Hence the relationship given below can be considered for TEM mode only. The impedance matching process can be considered as the process of optimizing a phenomenon called as reflections of the transmitted signal. The relationship given below in equation 2.1 introduces a new parameter called reflection coefficient.

This equation says that the circuit is said to be matched if the value of Γ = zero, and they are said to perfectly mismatched condition, if the $\Gamma = 1$.minimizing reflection coefficient itself means to minimize the reflection losses and to maximize the forward power to be transmitted to the load. The reflection coefficient [2] can be defined as follows:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad \text{.......(2.1)}$$

where, Zs is the impedance of the source and the Z_L is the load impedance. The condition of matching is Γ = zero which results in $Z_L = Zs$. This condition is base for all impedance matching circuits. The table given below tells about different kinds of impedance matching networks along with there characteristics.

The primary criterion for selecting the matching network is flexibility, complexity, readily availability and easy designing of the network components. For matching basically two types of network topologies are used:

1. Lumped elements.
2. Distributed elements.

Ideally lossless lumped elements are designed with the help of inductors and capacitors. While distributed elements are designed with the help of open circuited and closed

Table 2.1. Comparison between various Matching networks and there characteristics. [1]

Matching Network	Element Type	Operating Bandwidth	Network Flexibility	Network Complexity	Load Impedance	Design Technique
L-network	Lumped	Narrow	Low	Low	Complex	Smith Chart or analytical method
T or Pi Network	Lumped	Medium	Medium	Medium	Complex	Smith Chart or analytical method
Ladder Network	Lumped	Large	High	High	Complex	Synthesis method
Single Stub	Distributed	Narrow	Low	Low	Complex	Smith Chart
Double Stub	Distributed	Medium	Medium	Medium	Complex	Smith Chart
Filter Theory	Distributed	Large	Large	High	Complex	Synthesis method
Quarter-Wave transformer	Distributed	Narrow	None	Low	Real	Analytical method
Multi-section Transformer	Distributed	Large	Medium	High	Real	Synthesis method
Tapered Line	Distributed	Large	Large	High	Real	Analytical method
Combination	Lumped and Distributed	Small to Large	Large	Low to High	Complex	Smith chart or Analytical method

circuit transmission lines. The restriction on the number of elements is only the complexity also as the number of elements increases the bandwidth increases to a maximal value after that the bandwidth becomes constant. Also some circuits are more flexible that the others but more flexibility have a trade off with the complexity. More complexity results in more flexibility, lesser complexity lesser would be flexibility. Impedance matching is done for two types of loads,

- Real loads
- Complex loads

In the first case transmission lines are terminated with a real load and matching is to be provided to real source impedance. While, in the later case a real source is terminated in a complex load. The way of designing both is a bit, different but for both we can use Smith charts.

2.2.1 LUMPED ELEMENTS MATCHING

Lumped elements are the elements for which value never changes with the frequency or direction. Capacitors and inductors are two lumped elements by which we can match any complex load can be matched to a real load. Except the condition of perfectly imaginary load i.e. a load with straight reactance graph can not be matched. Commercially lumped elements are used to the frequency of 3GHz. Still some of the lumped elements are designed for frequencies above 100GHz. Beyond that performance of lumped elements degrades and hence beyond this we start using distributed elements. In the next heading we would be discussing about lumped element matching networks. Still some of the lumped elements are designed for frequencies above 100GHz.

Basically the matching networks are classified on the basis of no. of elements that are used in the design of matching network;

- Two element matching also known as L-section matching.

- Three element matching networks also known by the name T and Pie network matching.
- More than three element matching also known as Ladder matching networks.

2.2.1.1 TWO COMPONENT MATCHING NETWORK

In designing any circuit there are basically two goals that are to be satisfied: first the system requirements should be met, and second to find a way by which this task can be accomplished in a cheap and reliable manner. The cheapest and the most reliable matching networks are the one which are designed using minimum number of components.

This topic contains the design criterion and analysis of the simplest possible type of matching networks containing two components, also known as L- sections [1], due to their arrangement. These components are alternatively connected in shunt and series with the load and source. These components are reactive and have opposite nature to each other. Based on the arrangement there may be eight different configurations shown in figure 2.1.

Matching networks can be designed in two ways:

1. To derive the values of the elements analytically.
2. To rely on graphical techniques such as Smith charts.

First method of designing is very precise and is used for computer aided designing and analysis. The second method of designing is easy and do not require complicated computations. The figure 2.1 suggests that every load can not be matched using a single matching network. The figure implies that all the loads falling in the shaded region cannot be matched by 50 ohm source. The same for all the matching configurations are provided in the figure. Thus forbidden regions can be defined as the region in which the load can not be matched with source. The regions are depicted for a source impedance of 50 ohms only. While forbidden regions change their shapes if the source impedance varies. Some of the calculations are done for L-section shown in figure 2.2(j). The calculations

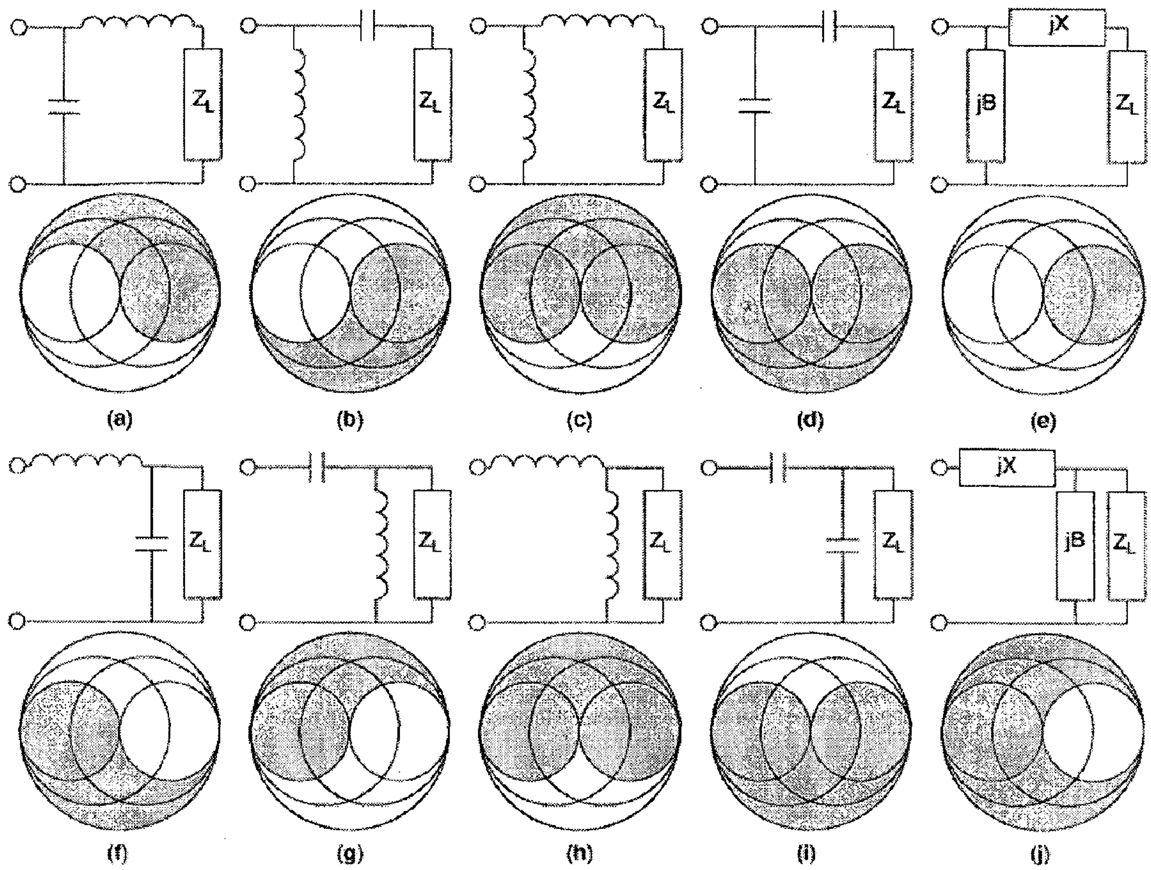


Figure 2.2: Shows eight different combinations and there forbidden region [1, 3, 4]

are done for impedance (0.5+jX) where X is the reactance of source impedance. The value of the reactance can be given as follows

$$B = \frac{X_L \pm \sqrt{R_L / R_0}\sqrt{R_L^2 + X_L^2 - Z_0 R_L}}{R_L^2 + X_L^2} \quad \text{...(2.2)}$$

$$X = \frac{1}{B} + \frac{X_L Z_0}{R_L} - \frac{Z_0}{BR_L} \quad \text{...(2.3)}$$

The plus and minus sign reveal the possibility that there are always two possible circuits available for matching the load of type (0.5+jX), and the possible choices are figure

2.2(g) and figure 2.2(f). If the figure 2.2(e) is used then value of the reactances can be calculated as follows,

$$X = \pm\sqrt{R_L(Z_0 - R_L)} - X_L \quad (2.4)$$

$$B = \pm\frac{\sqrt{(Z_0 - R_L)/R_L}}{Z_0} \quad (2.5)$$

Again the equation suggests that there are two possible configurations that can be inserted between source and load.

2.2.1.2 THREE COMPONENT MATCHING NETWORKS

Sometimes to increase bandwidth number of components is to be increased. Increasing no. of components increases the complexity but the bandwidth increases.

The T or Pi networks can be considered as cascaded form of two L sections. As shown in the figure 2.3.

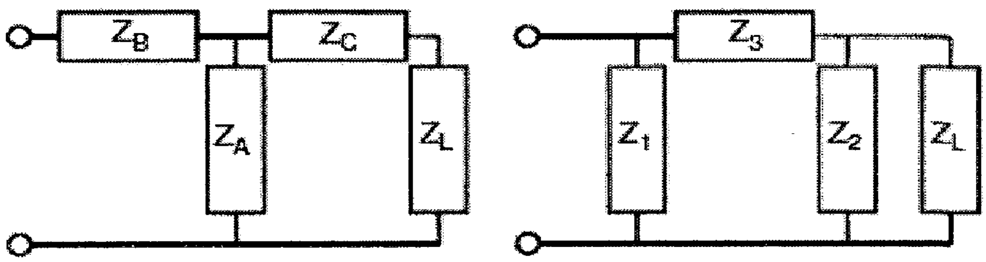


Figure 2.3: shows a T network and a Pi network in a load Z_L

Addition of one more component increases one variable that is required to be calculated, which requires one more circuit characteristics to be inserted. This characteristic is known as Quality Factor [1, 3, 4, 6], which is defined by the ratio of resonant frequency and 3dB bandwidth.

$$Q = \frac{fo}{BW} \quad (2.6)$$

where Q is the quality factor, fo is the resonant frequency and BW is the 3 dB bandwidth. Increase in one more network component increases possible combinations to 16, thus providing more flexibility as compared to L networks. From this one can easily derive the values of components. Also if someone wants to convert L-sections to T or Pie network then Kuroda's identity [2] can be used, also T and Pie networks are interconvertible and can be used in place of each other if impedances are known by following equations:

$$Z_A = \frac{Z_1 Z_2}{Z_1 + Z_2 + Z_3}, Z_B = \frac{Z_1 Z_3}{Z_1 + Z_2 + Z_3},$$

$$Z_C = \frac{Z_2 Z_3}{Z_1 + Z_2 + Z_3}, Z_1 = \frac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_C},$$

$$Z_2 = \frac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_B}, Z_3 = \frac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_A}$$

....(2.7)

analytical expressions can be found from [3].

2.2.1.3 LADDER NETWORKS

As we have seen, adding an element to the L network increases the degree of freedom in the design. This freedom can be used to improve the bandwidth. As more elements are added, the bandwidth can be increased, but there is a limitation on the bandwidth. To design a ladder network, synthesis methods should be applied. As in the design of filters, Butterworth or Chebyshev frequency responses can be synthesized for the ladder networks. The technique details are presented in detail in [4]. Ladder networks can again be considered as cascaded form of more than two L sections. One of the ladder networks is given in figure 2.4 below. These circuits are designed using Q-transformation techniques, any two arbitrary loads can be matched with the help of these circuits. These are hugjly complex circuits to be designed and hence, require CAD and other development softwares for analysis and design.

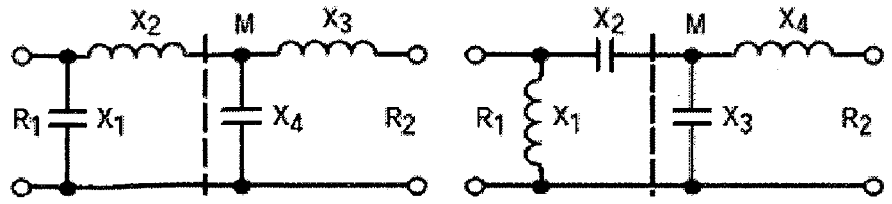


Figure 2.4: shows 2 ladder networks designed by cascading 2 L-sections increasing DoF from 2 to 4.

2.2.2 DISTRIBUTED ELEMENT MATCHING

Most of the matching networks working at higher RF frequencies are designed with distributed elements. Due to ease in fabrication, and flexibility and low loss characteristics transmission lines are used to design most of the RF circuits. Transmission lines are considered as back bone of distributed matching networks some of them are used as open circuited stubs and some of them are used short circuited stubs.

Quarter wavelength transmission line would transform an open circuited transmission line to a short circuited transmission line and vice versa. While in practice all the circuits are different from each other. With MLine technology it is easy to fabricate a circuit with open circuited transmission line, while a short circuited line is difficult to be designed. Thus MLine technology can not be used for rectangular waveguides because they require a short circuited transmission lines. If both lines are to be used then so as to minimize the losses, the delay and increase bandwidth, the one that requires shortest path should be considered.

2.2.2.1 SINGLE STUB MATCHING

Single stub matching is the simplest way of matching the impedance using transmission line as distributed element. The degree of freedom for this matching is two: first being the length at which the stub is to be placed, second being length of the stub. For this work Smith chart can be used as a basic tool for matching, which has been explained in [1, 2, 4]. With the parallel stubs, it is easier to work with admittance. The first segment, going from the load to the stub, has admittance equal to Yo and an electrical length equal to Y_1.

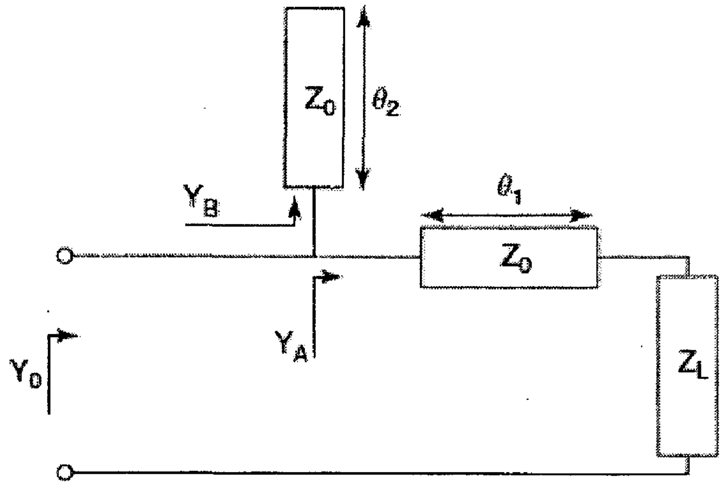


Figure 2.5: Single stub matching network

The admittance looking into the input of the transmission-line section is

$$Y_A = G_A + jB_A = Y_0 \frac{Y_L + jY_0 \tan\theta_1}{Y_0 + jY_L \tan\theta_1} \quad (2.8)$$

The electrical length y1 must be chosen so as to match the real part of the admittance: GA = Yo. Then, a parallel stub of admittance Yo and electrical length Y_2 is added to cancel out the reactive part. The admittance looking into the input of this stub, for the open/short-circuit case, is

Open circuit: $Y_B = jB_B = jY_o \tan(\theta_2)$ ....(2.9)

Short circuit: $Y_B = jB_B = -jY_o \cot(\theta_2)$ ....(2.10)

The electrical length θ2 must be selected to cancel out the reactive part; thus $B_B = -B_A$ and yields

$$Y_A + Y_B = 0 \quad (2.11)$$

an analytical solution for θ2 and θ1 can be found with the relation given in [2].

2.2.2.2. DOUBLE STUB NETWORKS

With a single-stub network, the length between the load and the stub is a variable related to the value of the load. In some cases it is better to have the stub at a fixed position, for example, in the case of designing a tunable matching network in which the stub length is easier to change than its position. This can be done by using two stubs. The double-stub matching network is widely used to design tuners. The circuit is shown in Fig. 2.6 with two parallel stubs. Serial stubs are also used in the same way. This type of network cannot match all the loads on the Smith chart. There is always a blind zone that is impossible to match

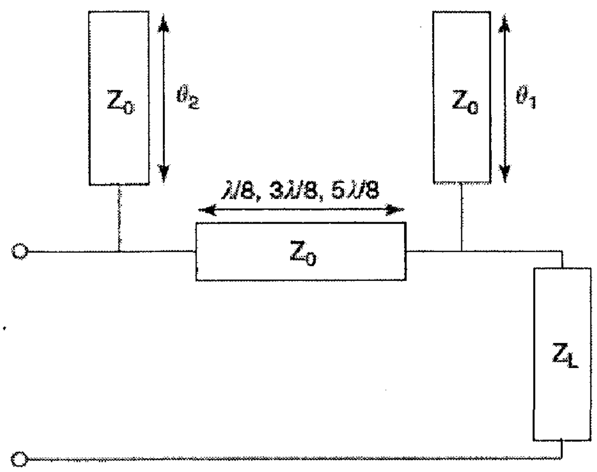


Figure 2.6: A double stub matching network.

To minimize this area, the distance between the two stubs must be kept as short as possible. This distance is, however, limited by the physical size of each stub. Furthermore, spacing close to 0, λ/2, and their multiples are too frequency-sensitive to be of interest. In practice, spacing equal to λ /8, 3λ/8, or 5λ/8 is usually chosen. The double stub matching technique makes use of the Smith chart or analytical equations in finding the length of each stub [2].

2.2.2.3 Filter Theory for Designing Matching Networks.

As can be seen in Section 2.1, increasing the number of elements makes it possible to design matching networks with a wider bandwidth. In the same way, multi-section distributed-element networks are usually used to improve the bandwidth. Filter synthesis techniques are also applied in the design of such circuits. The reader is referred to [3], for a complete explanation of the synthesis method.

2.2.2.4 Quarter-Wave Transformer.

All the matching networks presented in the preceding sections can be used to match a complex load. Another class of matching networks is used only to match real loads, presented below. Although those circuits seem limited, they are used largely to connect two transmission lines of different impedances and to design various transitions. The most common network applied to adapt two real impedances is the quarter-wave transformer, as shown in Fig. 2.7. The impedance looking into the input of the quarter-wave transformer is

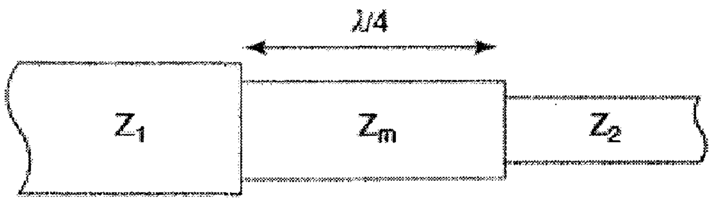


Figure 2.7: Shows a quarter wavelength transformer

$$Z_{IN} = \frac{Z_m^{\ 2}}{Z_2} \qquad (2.12)$$

To match both lines, one should have $Z_{IN}=Z_1$. The quarter wavelength line impedance must be

$$Z_m = \sqrt{Z_1 Z_2} \quad (2.13)$$

The bandwidth for this circuit is related to the line impedance at the input and at the output. The closer they are, the wider the bandwidth is. It becomes infinite when the impedances are equal.

2.2.2.5 Tapered-Line Transformer

If we increase the number of sections to the infinite, a tapered line is formed. However, it has an infinite length, which is not of practical value. The tapered line of finite length is still an excellent matching circuit. The simplest taper is the linear one, and it requires very little calculation, but does not provide a wide bandwidth. Exponential taper increases the bandwidth and is still easy to design. Many other tapers have been proposed, such as in the triangular [2], cosine squared, and parabolic configurations [5].

With all these tapers available for the design, one may wonder which one is the best. The taper proposed by Klopfenstein [6] is optimum in the sense that it provides the shortest length for a given reflection coefficient. However, the Klopfenstein taper presents a step at both ends. Sometimes, these steps are undesirable because they generate high-order modes and radiation loss. The taper proposed by Hecken then becomes optimum [7]. For a desired reflection coefficient, this profile provides the shortest length for a taper without steps. Although there are many different tapers, the design technique is fundamentally the same for all of them. Let us begin with a topology shown in Fig. 8. The tapered line design is always done at the lowest frequency of interest.

In the first step, the impedance variation as a function of the position Z(z) is formulated. The impedance variations, for the most common tapers, are listed in Table 3. Knowing the impedance, one can evaluate the reflection coefficient as a function of the taper length using the following equation:

$$\Gamma = \frac{1}{2}\int_{z=0}^{L} e^{-2j\beta z}\frac{d}{dz}\ln\left(\frac{Z(z)}{Z_1}\right)dz \quad \text{.......(2.14)}$$

with a fixed length L one can directly calculate reflection coefficient as if the function Z(z) is known. Function Z(z) is the change in the value of impedance with respect to distance z measured from source side towards the load.

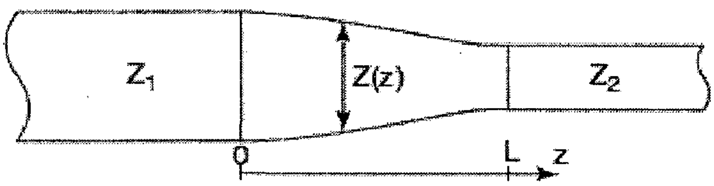
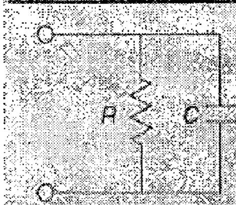
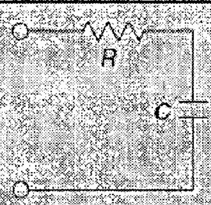
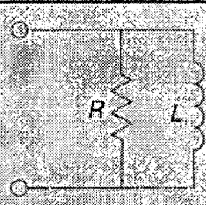
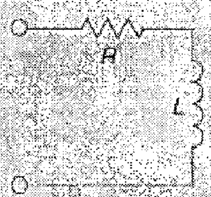


Figure 2.8: Shows a Tapered-Line Transformer

Table 2.2: Encompasses values of K for different types of loads.

Load Type			
			
$K = \frac{\pi}{RC}$	$K = \pi\omega_0^2 RC$	$K = \frac{\pi\omega_0^2 L}{R}$	$K = \frac{\pi R}{L}$

This was the basic concept regarding reflection coefficient and the design of tapered line. By this time we have not yet discussed about the bandwidth consideration of the tapered lines. The bandwidth for not only tapered lines but for a general RF circuitry can be given by equation (13):

$$\Theta = \int_0^{\infty}\ln\frac{1}{|\Gamma(\omega)|}d\omega \le K \quad \text{.......(2.15)}$$

the equation (13) is known as Fano's criterion, where the value of K depends on the value of R,L and C. Also the value of K are tabulated in table 2.2

Table 2.3: Tapered-line Impedance Z as a Function of position z (with Taper Length L)

Taper	$Z(z)$
Linear	$Z(z)=Z_1+\frac{z}{L}(Z_2-Z_1)$
Exponential	$Z(z)=Z_1e^{az}$ $a=\frac{1}{L}\ln\left(\frac{Z_2}{Z_1}\right)$
Triangular	$Z(z)=Z_1e^{2(z/L)^2\ln(Z_2/Z_1)}$ $for 0\le z\le L/2$ $Z(z)=Z_1e^{2\left((4z/L)-(2z^2/L^2)-1\right)\ln(Z_2/Z_1)}$ $for L/2\le z\le L$
Parabolic	$Z(z)=\left(\sqrt{Z_1}+az\right)^2$ $a=\frac{1}{L}\left(\sqrt{Z_2}-\sqrt{Z_1}\right)$
Klopfenstein	$\ln(Z(z))=\frac{1}{2}\ln(Z_1Z_2)+\frac{\Gamma_0}{\cosh A}A^2\phi\left(2\frac{z}{L}-1,A\right)$ $A=\cosh^{-1}\left(\frac{\Gamma_0}{\Gamma_m}\right),\Gamma_0=\frac{Z_2-Z_1}{Z_2+Z_1}$

	$$\phi(x,A) = -\phi(-x,A) = \int_0^x \frac{I_1\left(A\sqrt{1-y^2}\right)}{A\sqrt{1-y^2}}dy$$ $I_1(x)$ = first-kind modified Bessel function Γ_m = maximum desired reflection coefficient
Hecken	$$\ln(Z(z)) = \frac{1}{2}\ln(Z_1 Z_2) + \frac{1}{2}\ln\left(\frac{Z_1}{Z_2}\right)\psi\left(2\frac{z}{L}-1,B\right)$$ $$B = \sqrt{(\beta L)^2 - 6.523}$$ $$\psi(x,A) = -\psi(-x,A) = \frac{B}{\sinh B}\int_0^x I_0\left(B\sqrt{1-y^2}\right)dy$$ $I_0(x)$ = first-kind modified Bessel function β = maximum desired reflection coefficient

2.3 TUNABLE NETWORKS

The matching networks that we have presented so far are used to match a fixed load. Sometimes, the impedance of the load changes and a tunable matching network becomes necessary. Tunable matching networks can be divided into two categories: Adaptative tunable matching networks and selective tunable matching networks. In the former case, the tunable matching network makes it possible to keep a good matching over a variable condition. This variation may come from manufacturing tolerance, temperature change, aging effects, and interaction with the surroundings (detuning effects), to name only a few examples. In the latter case, the matching network is used to select an appropriate value, such as a frequency band in a filter, a particular gain in an amplifier, an operating frequency in an oscillator, or a beaming angle in a scanning beam antenna.

Such a tunable matching network is then an effective tool to accomplish critical tasks. The adaptative or selective networks are mostly designed using three categories of elements: varactor diodes, RF micro electro mechanical systems (MEMS), and ferrite or ferroelectric materials. Principal characteristics of these elements are briefly explained as follows. Ferrites have been widely used and are well documented in the literature and thus are not included here.

2.4 VARACTOR DIODE TECHNIQUES

Semiconductor diodes are used to create variable-capacitance components such as varactors. When a reverse voltage is applied to the diode, a depletion region is created whose thickness can be tuned electronically, thus modifying the capacitance. Varactor diodes have been widely used as tuning elements for more than 40 years. This is a very mature technology with a wide range of commercially available components. The principal limitation in a varactor diode is its low quality factor, which suffers from high series resistance of the diode junction.

Chapter 3: Plasma Chambers [14, 15, 16]

Physics and chemistry define plasma as partially ionized particles, with a certain proportion of electrons which makes it possible to conduct electricity to high extent. A raw definition for PLASMA can be given as an electrically conductive gas consisting of neutral particles, ionized particles, and free electrons, but which as a whole, is electrically neutral Due to presence of electrically charged materials plasma strongly responds to electrostatic as well as electromagnetic field. Since the properties of plasma do not matches solids, liquids and gases which made scientists to consider it as state of matter, like gases plasma does not have a definite shape or size, unlike gases it responds to magnetic fields.

Plasma was first identified in the year 1879 by Sir William Crooke in Crooke's tube. After that a lot research has been made on plasma, in the year 1928, Irvin Langmuir defined a lot of properties of plasma. Now a day's high definition plasma television are in use, not only this but also plasma sources are used in various research laboratories for nuclear and atomic research. Plasma chambers are used in laboratories so that as an ion sources. Usually an RF source provides energy to the plasma chamber where gas to be ionized is filled at required pressure. Since gases are poor conductors of electricity, hence initially no conduction is there. But as energy is provided to plasma chamber, gas filled starts heating. Due to heating effect, dissociation of gas filled in the chamber starts. Due to availability of free ions conduction starts gradually. Plasma chambers are classified in the following categories:

1. Capacitively Coupled Plasma Chambers (CCP).
2. Inductively Coupled Plasma Chambers(ICP)
3. Wave Heated Plasma Chambers
4. Glow Discharge Chambers.

3.1 CAPACITIVELY COUPLED PLASMA CHAMBER

CCP plasma chambers consist of a parallel plate capacitor, one of which is grounded and another one supplied with RF energy. The gas filled in between the plates get heated, due to excessive heating gaseous atoms start dissociating in ions, positive ions being heavier and high inertia move directly towards the grounded plate, the negative ions consisting of electrons have low inertia and hence start oscillating with the field generated between the plate. The oscillating frequency of negative ions is same as the frequency of RF energy. Generation of ions suddenly increases conduction between the plates. The plasma generated in between the plates can further be accelerated for other purposes. Figure 3.1 shows a capacitively coupled plasma chamber.

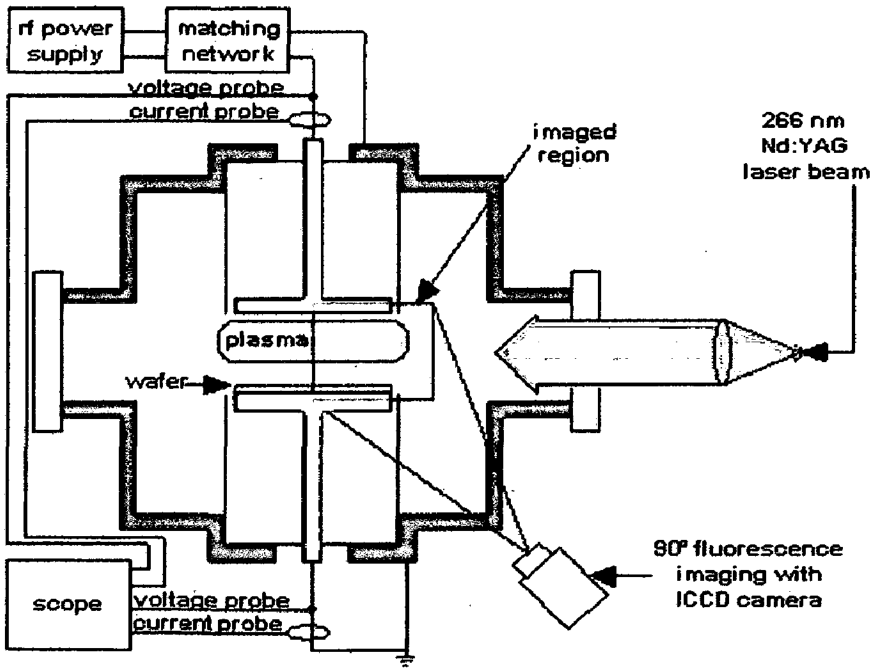


Figure 3.1: Capacitively Coupled PLASMA Chamber.[17]

3.2 INDUCTIVELY COUPLED PLASMA CHAMBER

Inductively coupled plasma (ICP) chamber uses a solenoid in which an oscillating current is made to flow. This oscillating current induces an oscillating magnetic field; the gas to be ionized is filled between this solenoid. Plasma generation phenomenon is same as in capacitively coupled plasma chambers. Unlike the capacitively coupled plasma chambers the inductance as well as resistance of the changes as more and more energy is passed into this coil. Figure 3.1 shows one of such plasma chambers.

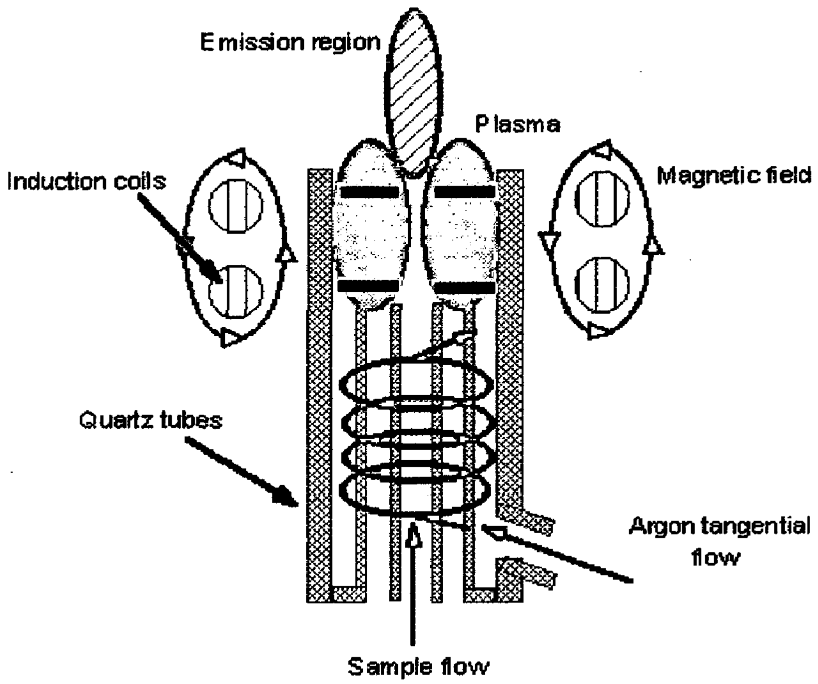


Figure 3.2: Inductively Coupled Plasma Chamber (ICP). [19]

3.3 WAVE HEATED and GLOW DISCHARGE PLASMA CHAMBERS

In wave heated plasma chambers electrostatic as well as electromagnetic fields for generation of plasma. This achieved by coupling both Inductively coupled plasma chambers and then accelerating generated plasma with an electrostatic field, while glow discharge plasma chambers are CCP chambers but use a low frequency for plasma generation. This frequency ranges from 10 kHz to 1 MHz. Some examples of these are High Definition Plasma Televisions and glow discharge tubes. Figure 3.3 shows one of the glow discharge plasma tubes.

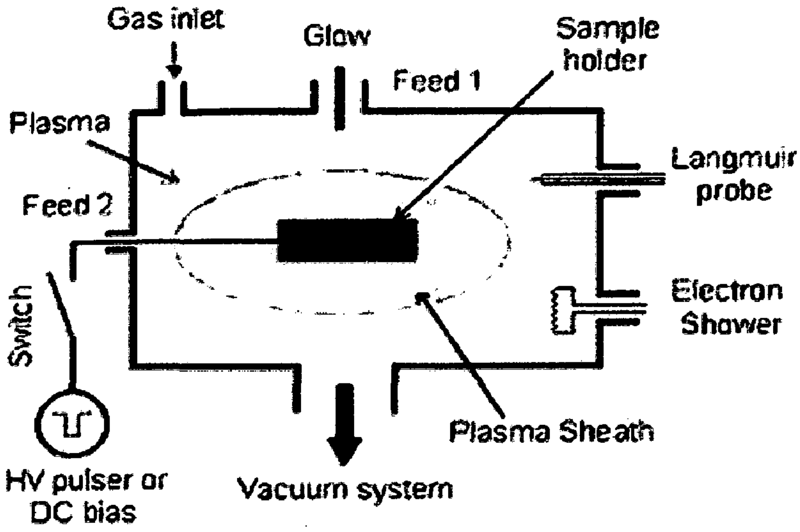


Figure 3.3: Glow Discharge Plasma Chamber [20]

Chapter 4: Work Done

4.1 ELECTRICAL MODELLING OF PLASMA CHAMBER

Before designing control system and the matching network, it was first required to model the impedance of capacitively coupled plasma chamber. The equivalent circuitry of the plasma impedance can be given as parallel combination resistance and capacitance since the dielectric constant between the plates is same, but as the energy supplied to the chamber increases, conduction between the plates increases and the effective resistance decreases. The equvalent electrical model of the chamber consists of a variable resistance and shunt capacitance. As the overall impedance of the system always lies between 5 to 49 ohms. Therefore, L section shown in figure 2.2 (g) is used. It has been assumed that the source impedance is equal to 50 ohms.

In practical condition, impedance gradually decreases from 49 ohms to 5 ohms. But very minute changes in the impedances are not considered that practically exist in the system. Hence to simulate impedance of the chamber a number of cases on impedances have been taken and been simulated. These cases include that changes in impedance are sinusoidal, exponentially increasing, random in nature, Sinc changes,sudden changes etc. The plasma chamber taken into consideration is an Ozone filled capacitively coupled plasma chamber, distance between the plates to be 1 cm.

The dielectric cnstant for the Ozone has been considered as $\varepsilon r = 4.75$, length of the plates has been taken to be 52 cms and the breadth has been taken to be as 39 cms. These are specifications of a High Definition Plasma Television. Providing an aspect ratio of 16:9 and 17inch screen. Initial capacitance of between the plates can be given by the formula:

$$C = \frac{\varepsilon_0 \varepsilon_r l b}{d} \qquad (4.1)$$

where, 'l' is the length of the plates, 'b' is the breath of the plates, 'εr' is the relative permitivity of Ozone, 'εo' is the permitivity of free space and 'd' is the distance between the plates.

Putting all the values it is obtained that reactance offered by this plate configuration should be C = 420 pF, which means that the reactance provided by this network is Xc = 27.7 ohms. As the initial resistance offered between the plates is very high it has been assumed that resistance offered is 350 ohms. Parallel combination can be converted into series combination of variable resistance and variable capacitance. This combination is to be matched with the help of matching network.

4.2 DESIGN OF MATCHING NETWORK

Matching network because of less complexity has been chosen to be an L section (with controllers)[17, 18]. The reson for chosing this network is that the load lies in a specific region of Smith Chart, the operating frequency is less i.e. 13.56 MHz and the required bandwidth is very less (because of operating frequency), while designing this network it has been assumed that the insertion losses due to insertion of L section is zero.

Using analytical approach the value of maximum and minimum value of inductor and capacitor to used can be derived from the equation given below:

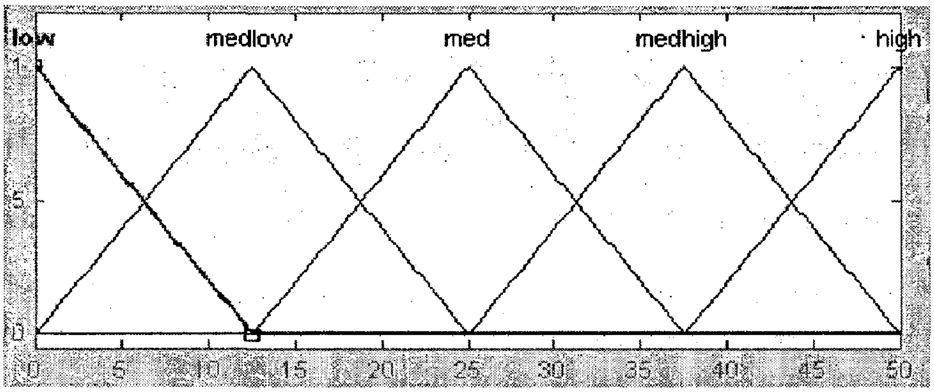
$$C = \frac{1}{\omega} * \sqrt{\frac{(R_S - R_L)}{R_S{}^2 R_L}} \quad \text{.....(4.2)}$$

$$L = \frac{1}{\omega} * (X_2 + \sqrt{R_2(R_1 - R_2)}) \quad \text{.....(4.3)}$$

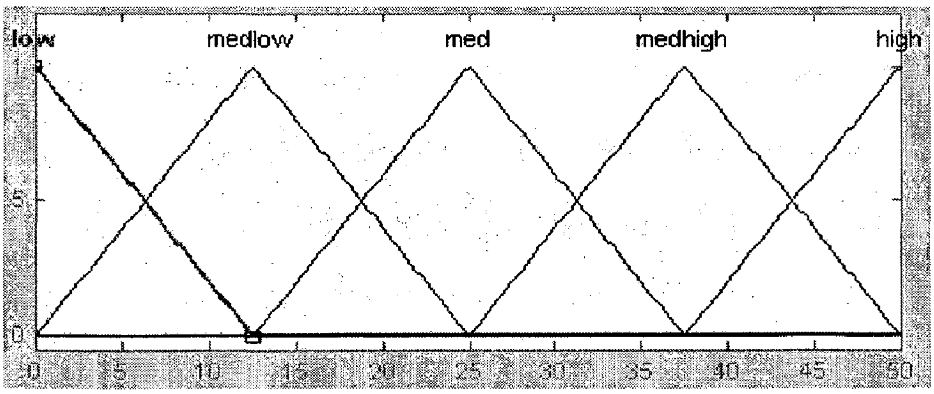
where C is the capacitance of L-section to be inserted, ω is the operating frequency in rad./sec., Rs is the source resistance, R_L is the real part of load impedance, L is the value of inductor to be used in L-section, X_2 is the reactance of load. From the above equations the value of L and C can easily be calculated. R_2 is varying with respect to time.

4.3 DESIGN OF FUZZY CONTROLLER

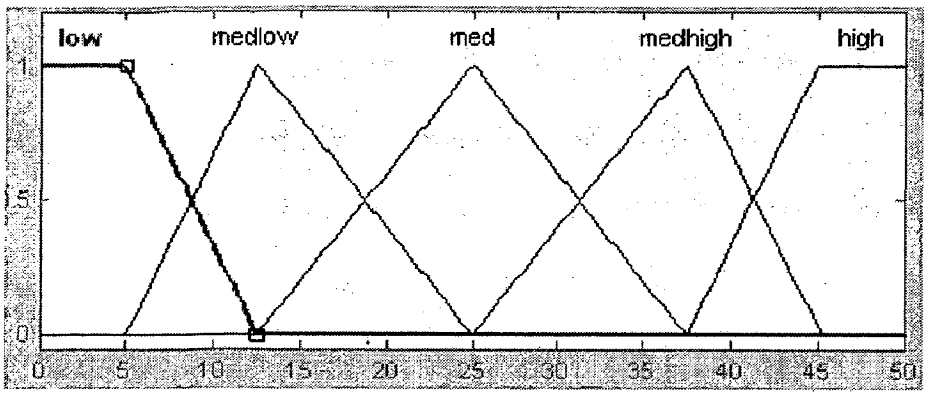
Fuzzy controller is the best solution when there is uncertainity in the inputs, since the impedance due to disturbance is not known only relation between input and output is known. From the equations it is known that there are going to be 2 inputs and 2 outputs[18, 19]. The ranges in which values of L and C vary are known, hence input and output membership functions can easily be normalized. The whole range of the input and output has been divided into 5 membership functions viz. Low, Medium Low, Medium, Medium High, and High. The output and the input membership function can be given as below:.



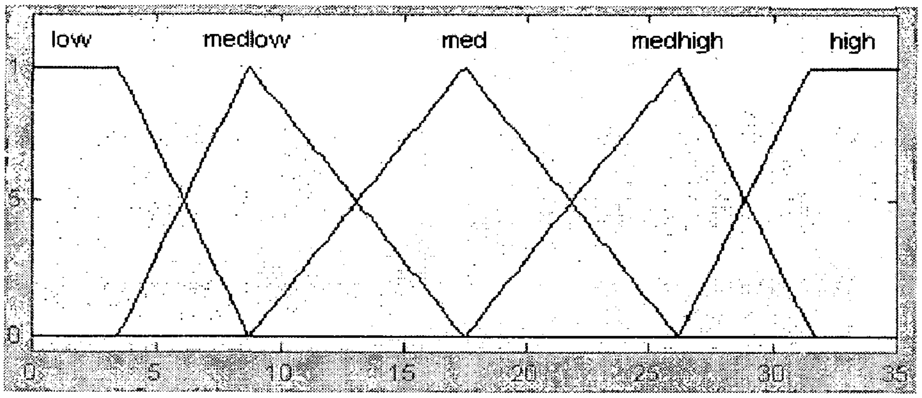
(a) Membership function for Real value of load impedance as input.



(b) Membership function for Imaginary value of Impedance as input.



(c) Membership function for Inductive Reactance of L-section as output.



(d) Membership function for Capacitive Reactance of matching network as output.

Figure 4.1 (a, b, c, d): Designed Membership Functions for Fuzzy Controller.

Previously, so as to design the rule base of a fuzzy controller, trial and error method was used, in this dissertation a new method of defining the rule base has been proposed. The rule base can be defined on the basis of knowledge some input and output relationships. As the relationship between input and output is known and the rule base is designed on the basis of this relationship.

In equation 4.1, it is clearly evident that only real part of the impedance is the governing factor, hence the rule base for calculation of capacitive reactance can directly be calculated, or a new variable is entered that is rate at which the real part changes. The rule base designed for both the controller can be given as:

IMAGINARY

		Low	ML	Med	MH	High
R	Low	Low	ML	Med	ML	Low
E	ML	ML	Med	MH	Med	ML
A	Med	Med	MH	High	MH	Med
L	MH	Med	MH	High	MH	Med
	High	Med	MH	High	MH	Med

(a) Rule base for Xc

IMAGINARY

		Low	ML	Med	MH	High
R	Low	High	High	High	High	High
E	ML	MH	MH	MH	Med	Med
A	Med	Med	Med	Med	ML	ML
L	MH	ML	ML	Med	Med	Med
	High	Low	Low	Low	Low	Low

(b) Rule base for X_L

Figure 4.2 (a, b): Rule base for the controllers

According to Power Transmission theorem, maximum power that may be transmitted if the angle of the load is opposite to that of the source and the magnitude is equal to the source.

named as "lost condition." This consumes a lot of time to achieve matched condition and is not applicable to all loads in the tuning range. The next and the most unidentified condition that has yet not been faced are of nonlinear changes in the impedance as temperature is changed. Also it is not ever thought of using both the error signals into consideration for changing the each element. This can be easily done with the help of fuzzy logic because in fuzzy logic one can define simple IF-THEN rules to implement the matching controller instead of defining complex matrix calculus equations. For each element we can define rules so that it can be controlled with the change in both error signals. One can apply fuzzy logic as one of the ways to implement control algorithm for the present condition. Fuzzy logic has been considered to have small number of steps such as defining linguistic variables, normalization, fuzzification, defining rule base, defuzzification and denormalization. These steps are taken by a reformulated structure known as Fuzzy Knowledge Base Control (FKBC) [10].

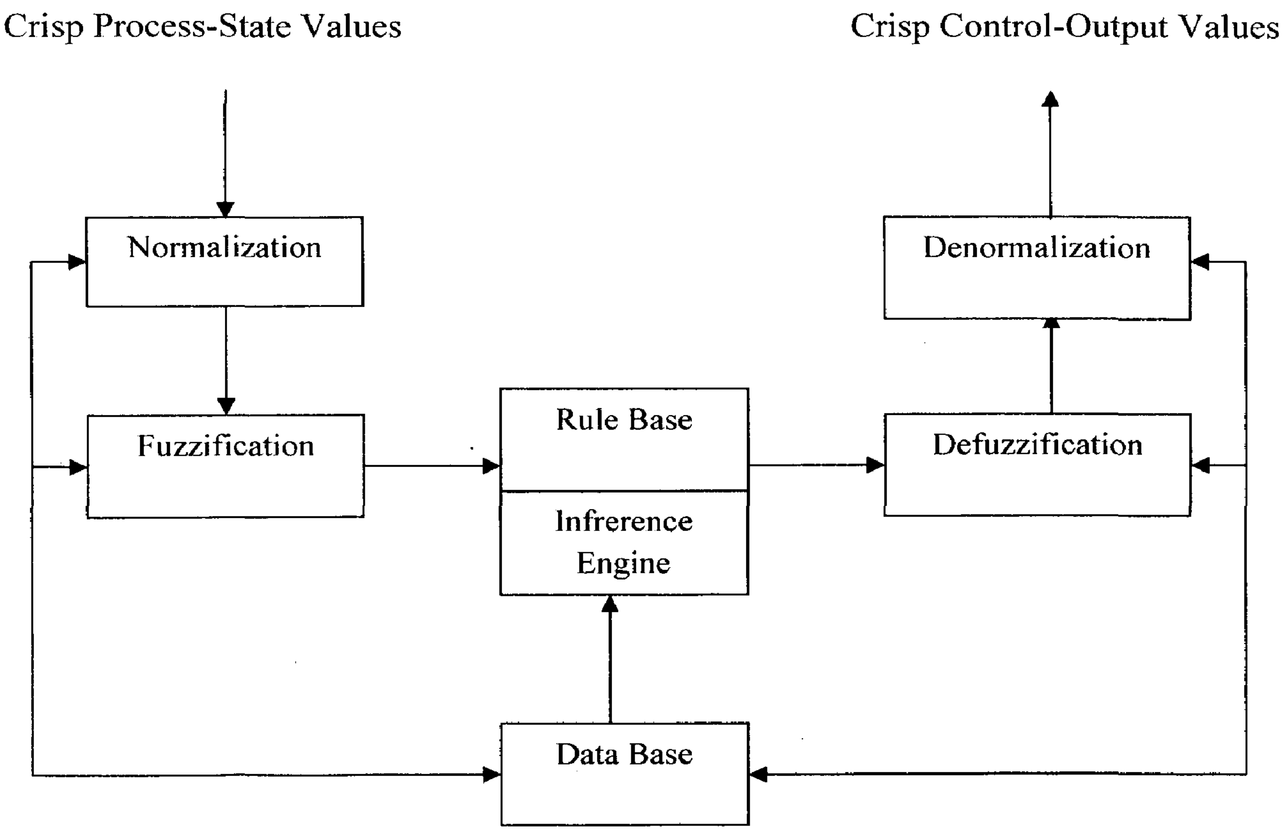


Figure 4.3: Structure of an FKBC

For the purpose of impedance matching we may use tuned circuits such as parallel or series tuned circuits. These are combinations of inductors and capacitors that give an impedance at the operating frequency. The value of impedance depends on the operating frequency, inductance and capacitance. Thus by adjusting the frequency, the inductance and the capacitance of the tuned circuit, we may get the required impedance. But in the present case the frequency of operation is constant, thus to adjust the magnitude and the angle of the impedance is the only way of matching. Thus, for matching the impedance we are required to have two error signals one for the magnitude and another for the angle. For each either the capacitance or the inductance or both are to be changed.

The basic difficulty is that the change in the impedance should be quick enough so that problems such as impedance lagging or the angle lagging factors are not faced. As per the classical method of impedance matching, the magnitude used to control one tuning element and phase error is used to control another tuning element. These error signals control the motors associated with the variable capacitors and the inductors. And the matching is assumed to be achieved when the error signal becomes negligibly small or zero. The biggest of all the difficulties is that if one try to tune one element with the help of one error signal then the other gets effected and thus making a shift in the matching condition. This effect of change in capacitance or inductance changes both the error signal and the magnitude signal. This sometimes causes both the tuning elements away from the matched condition which is not a reliable way of matching. This is because these two they does not provide enough information about the tune point thus causing matching conditions to be unachievable. Also the error produced by the movement in the tuning element depends on the position of the element at that instant. That is if the inductance is half of the max value the error produced is only 33 % but if it is at the max end then 10% change in the element cause a change of only 5%. This causes stability conditions to vary as the position of the element. The solution of the first problem is to use each error signal for both tuning elements, but for this it is required to have a sharp and fixed matching condition rather than a gradual transition. The next problem i.e. if the matched condition is lost can be solved by moving the elements to predefined position

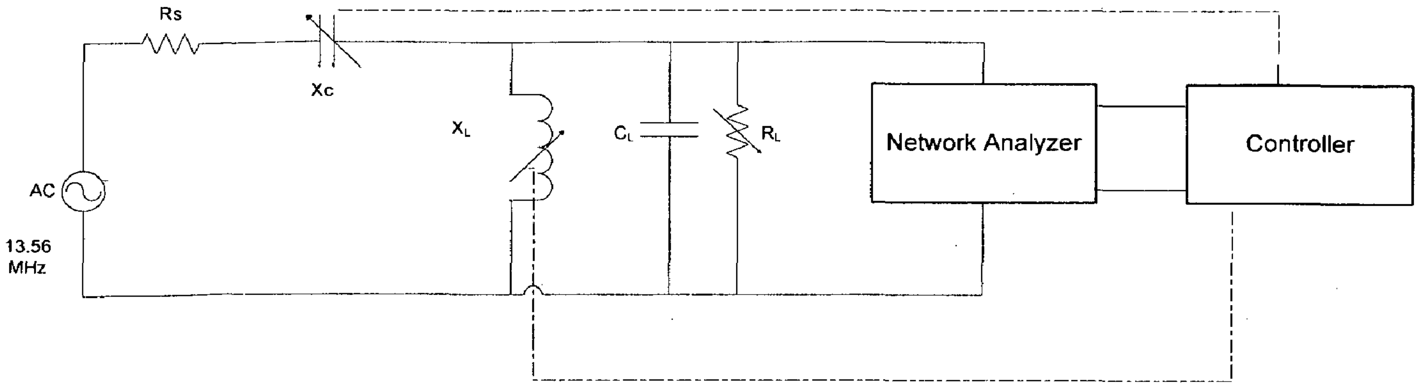


Figure 4.4: Diagram of the System containing a network analyzer, along with controller (ideal or fuzzy).

Chapter 5: Results and Discussions

The value of load resistance R_L is varied according to some predefined functions and an ideal controller has been designed. It is required that the results of the fuzzy controller should match with ideal controller. For three different values of R_L, input reflection coefficient, output reflection coefficient, S11, S22 for both the ideal and fuzzy controller has been found the results are given below. The model can be given as:

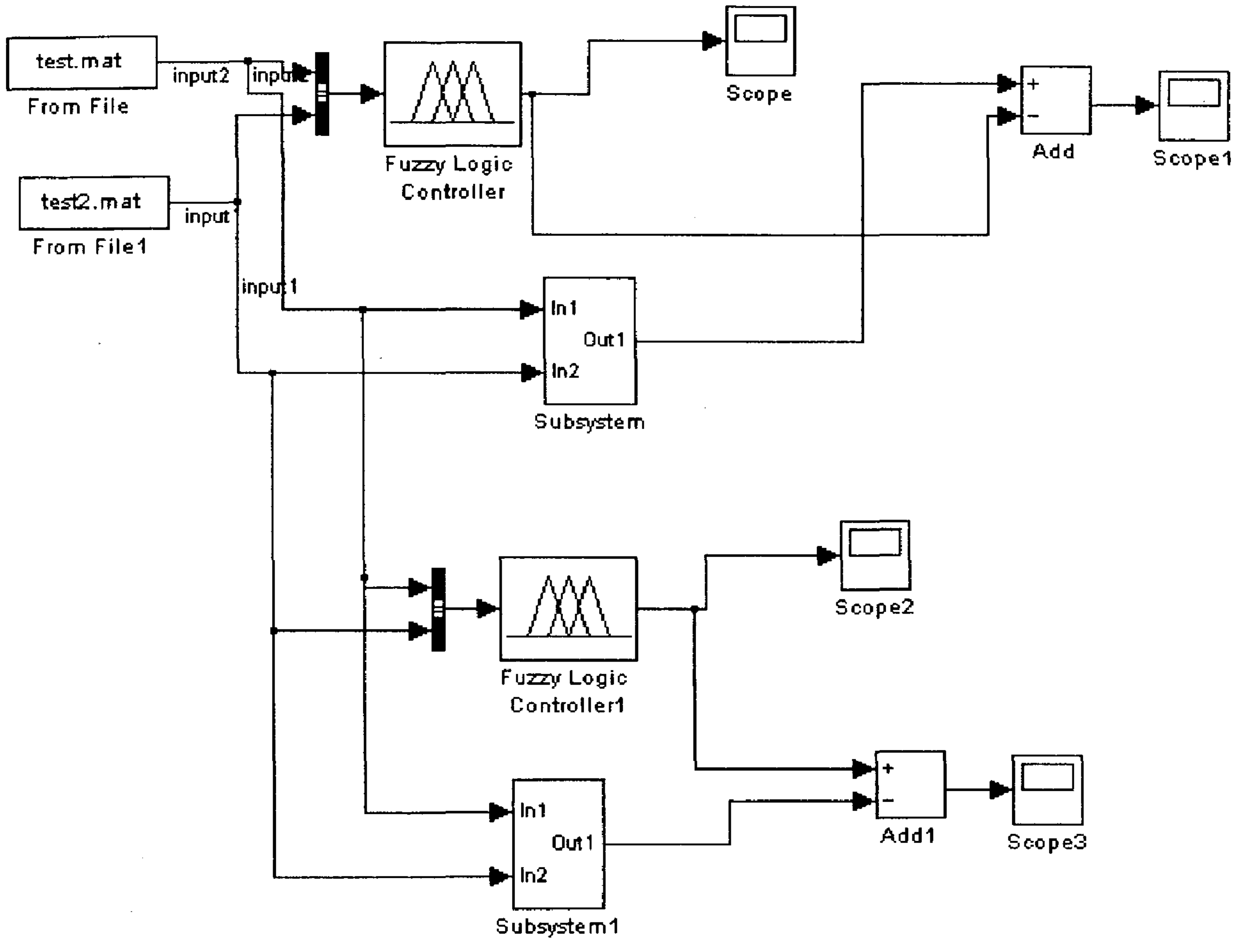


Figure 5.1: Model of system using Fuzzy Controller to tune matching network.

in which the Fuzzy Logic Controller gives the output for X_L and the Fuzzy Logic Controller1 gives the output regarding Xc on Scope and Scope 2 respectively, while the Scope 1 and Scope 3 give the error between ideal model and the fuzzy controller.

For changing the value of RL linearly from 5 to 49 the changes in the different values are given below:

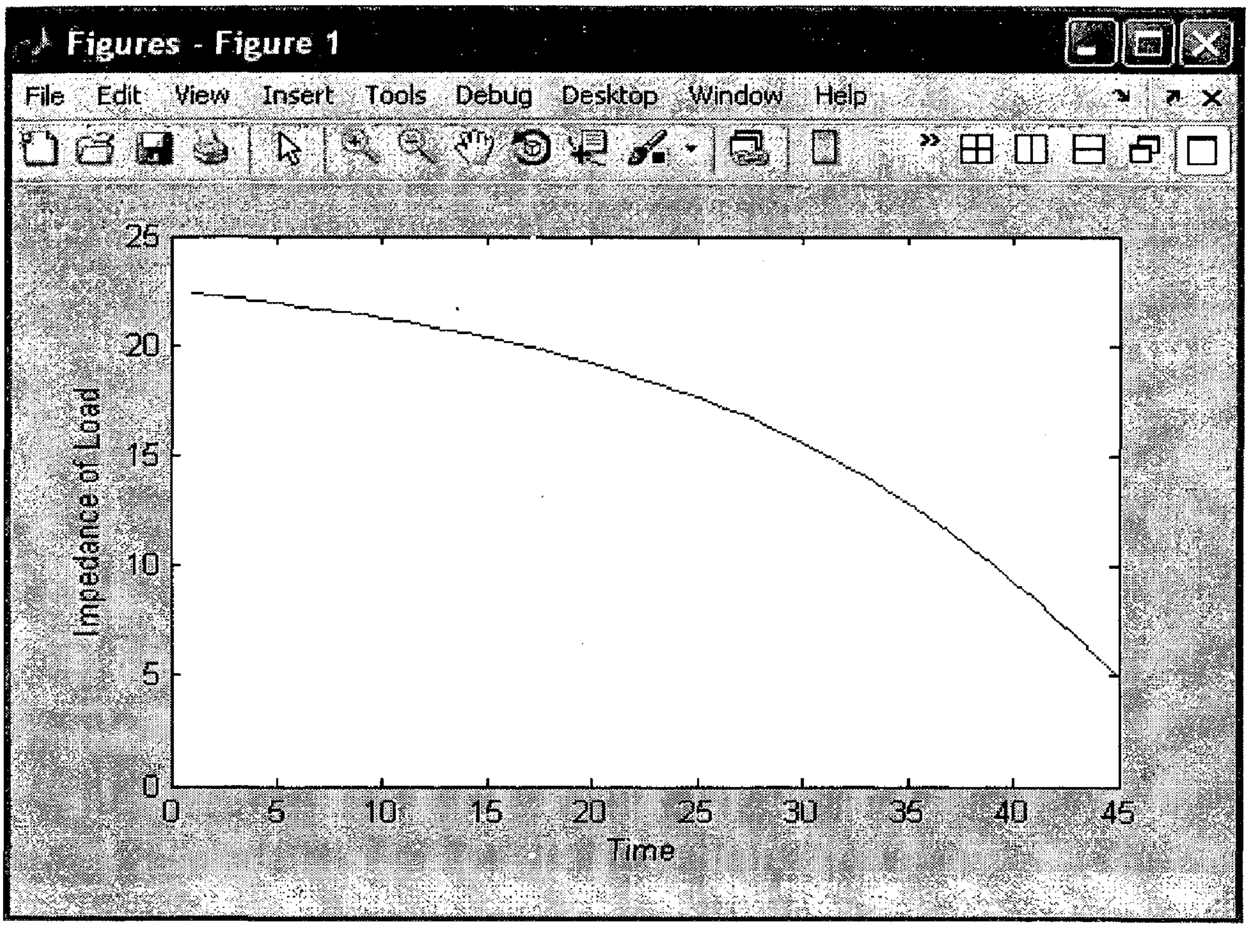


Figure 5.2: Shows change in absolute value of impedance with linear change in R_L

Three different values of R_L taken are:

1. $R_L = 25 + 20 * \sin(2 * pi * t)$ ....R_L1

2. $R_L = 25 + 20 * \exp(-3t) * \sin(2 * pi * t)$ ....R_L2

3. $R_L = 30 + 15 * \exp(-3 * t) * \sin(2 * pi * t) + 10 * n(t)$ .... R_L3.,

where n(t) is white gaussian noise.

above values are arbitrary and taken as an exponentially decaying sinusoidal beacuse we are unceratin about the conduction at any instant of time, hence a very rapidly varying

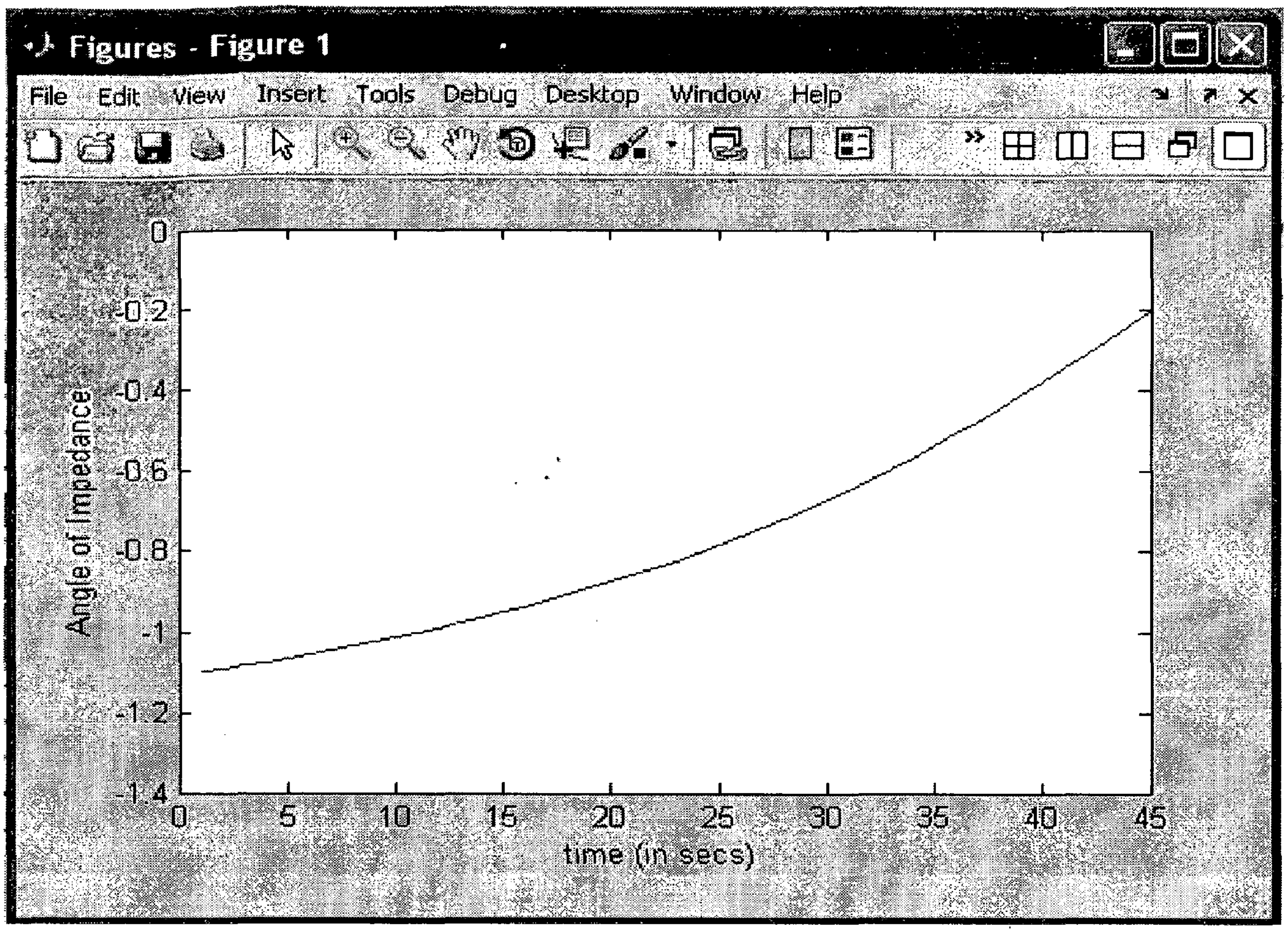


Figure 5.3: Shows the change in angle of impedance for linear change in R_L

function has been taken. Now the output value (input reflection coefficient, output reflection coefficient, S11, S22). The results for R_L1 are given below:

The maximum error is obtained at highest value of impedance i.e. 70 ohms and above. This error is of about 6 ohms which makes an error of about 9%, and the lowest error is obtained at load resistance equal to 30 ohms, giving an error of 6%, thus it can be said that the maximum error in calculating reactances of matching network is 9% with the help of fuzzy controller. Figure 5.5 shows scattering parameter S11 of the circuit when ideal matching is done, while Figure 5.6 shows the scattering parameters when fuzzy controller is used.

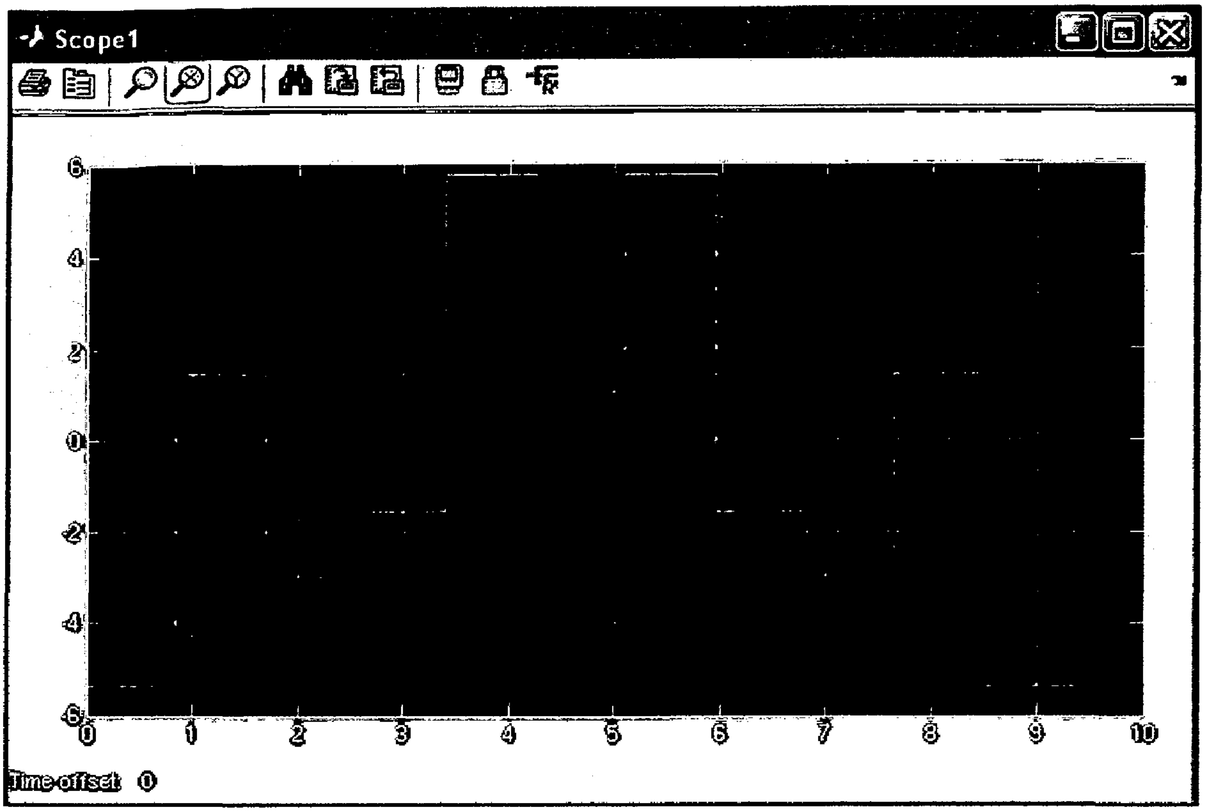


Figure 5.4: Shows error between Fuzzy controller and ideal controller.

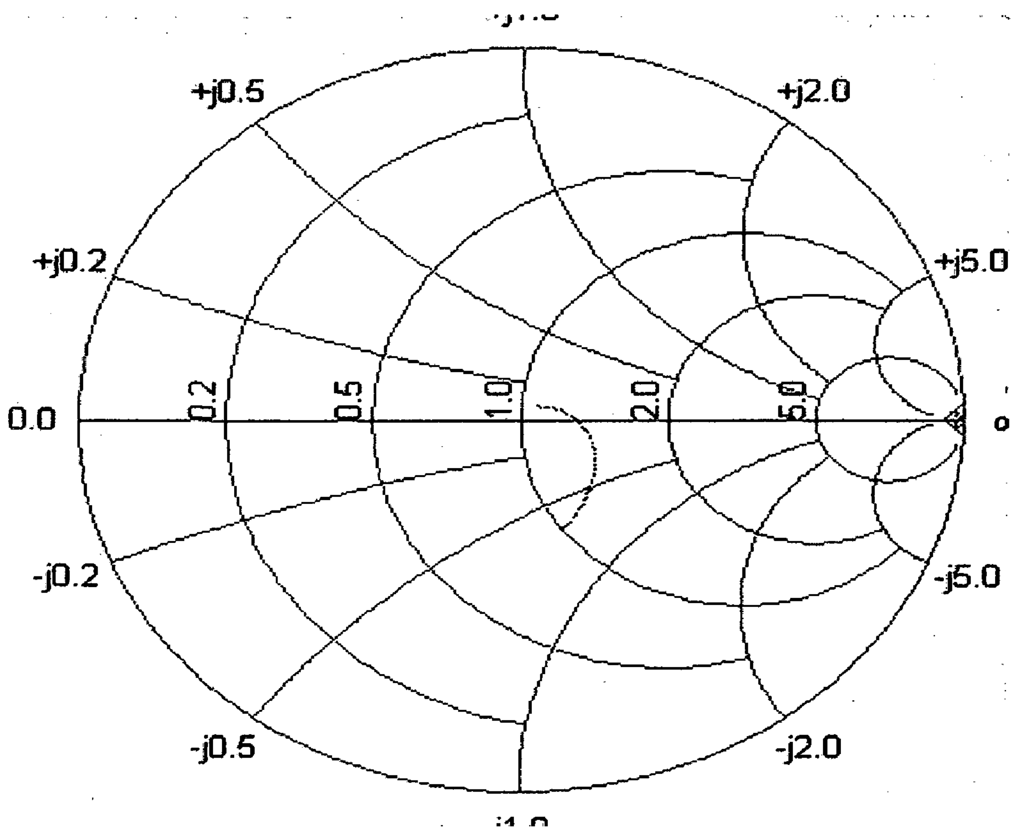


Figure 5.5: 'S11' parameter of the system when ideal matching is done

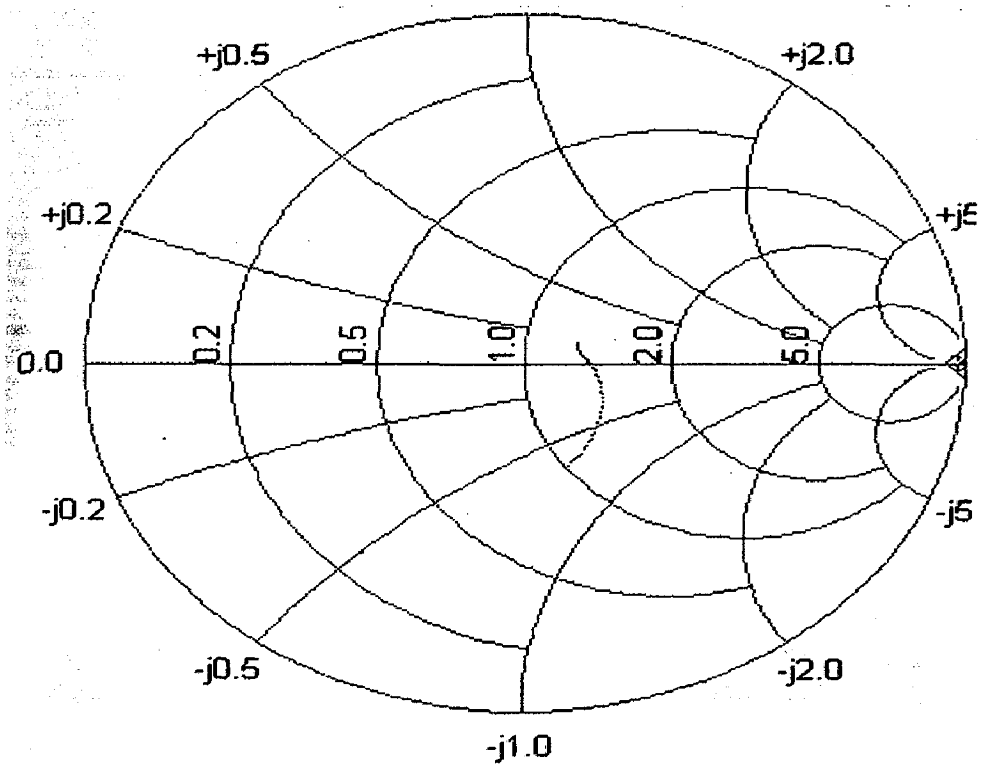


Figure 5.6: 'S11' parameter of the system when Fuzzy controller is used.

The changes in the values of input reflection coefficient, output reflection coefficient, S11 and S22 with respect to time are as follows:

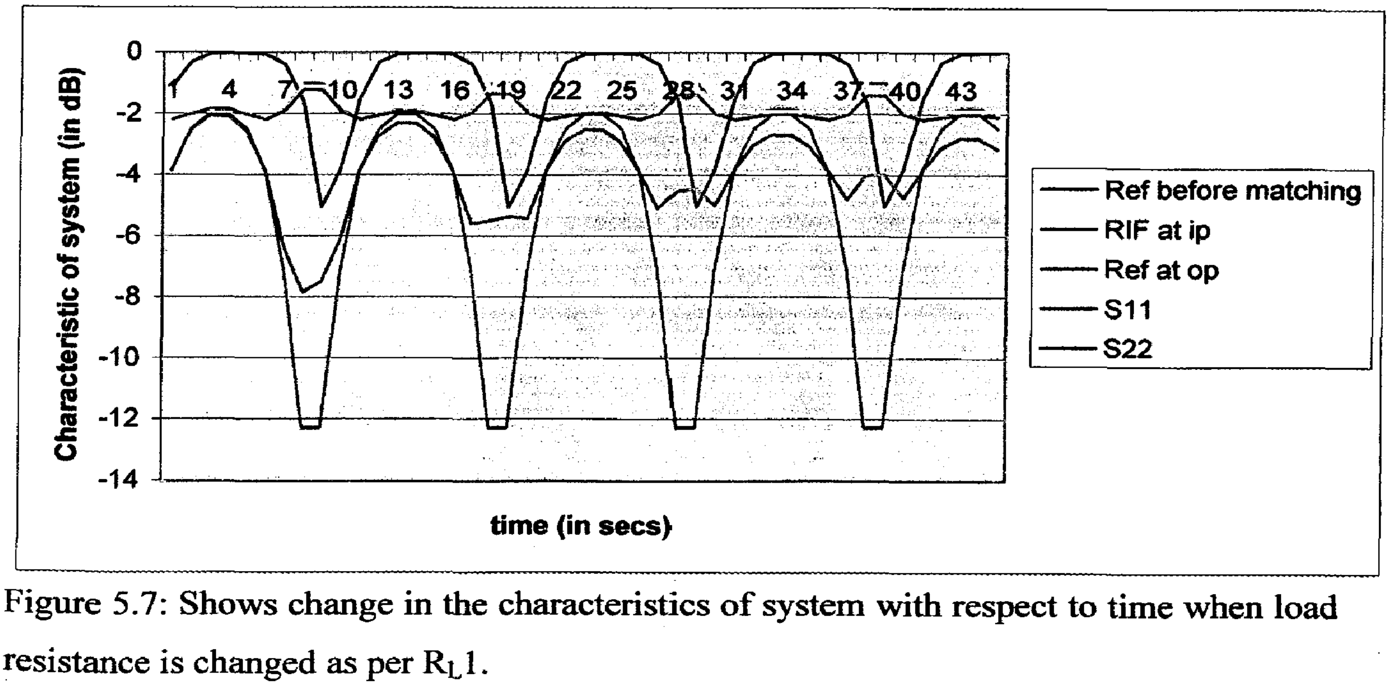


Figure 5.7: Shows change in the characteristics of system with respect to time when load resistance is changed as per R_L1.

imilarly the results for RL2 and RL3 can be given as:

The maximum error for change in load resistance as per R_L2 becomes 8.9%, while the min error goes down to a value of 4.56%. And the error remains same for changes as per R_L3.

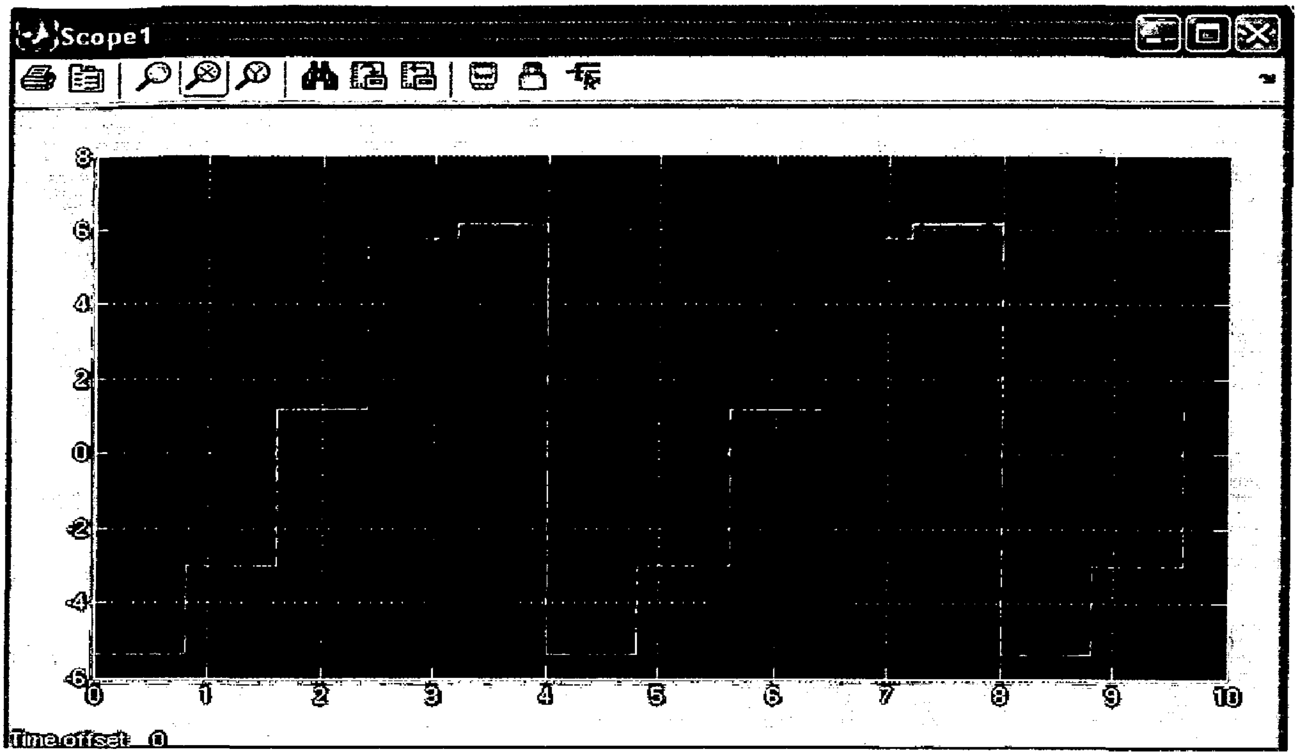


Figure 5.8: Error in reactance value when load resistance is changed as per relation R_L2.

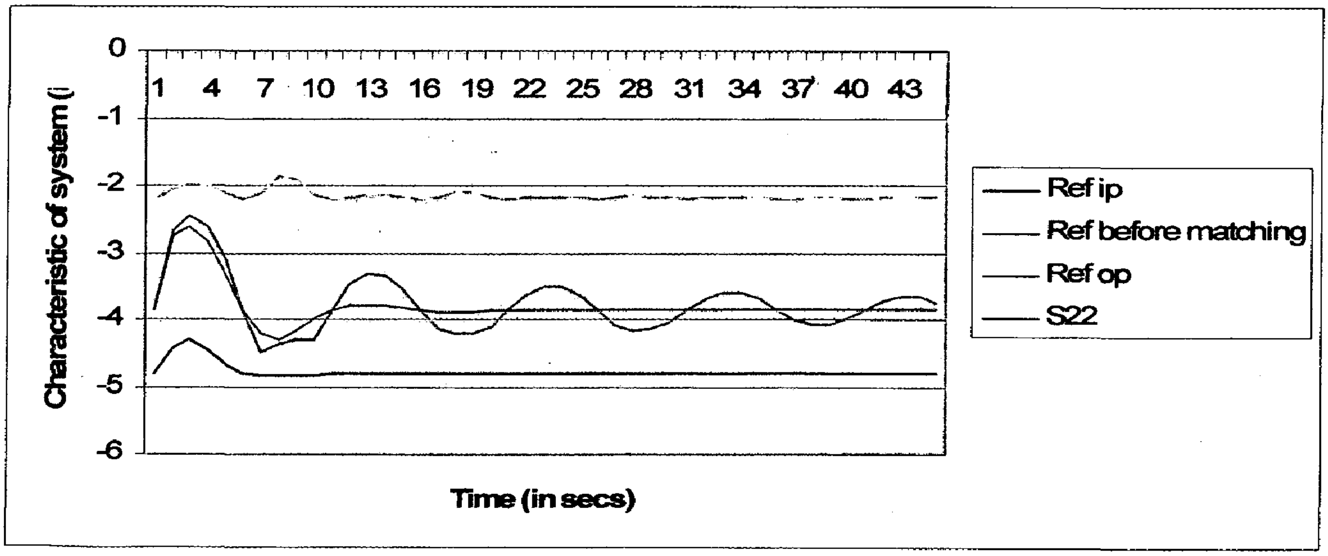


Figure 5.9: System characteristics with respect to load resistance as per relation R_L2.

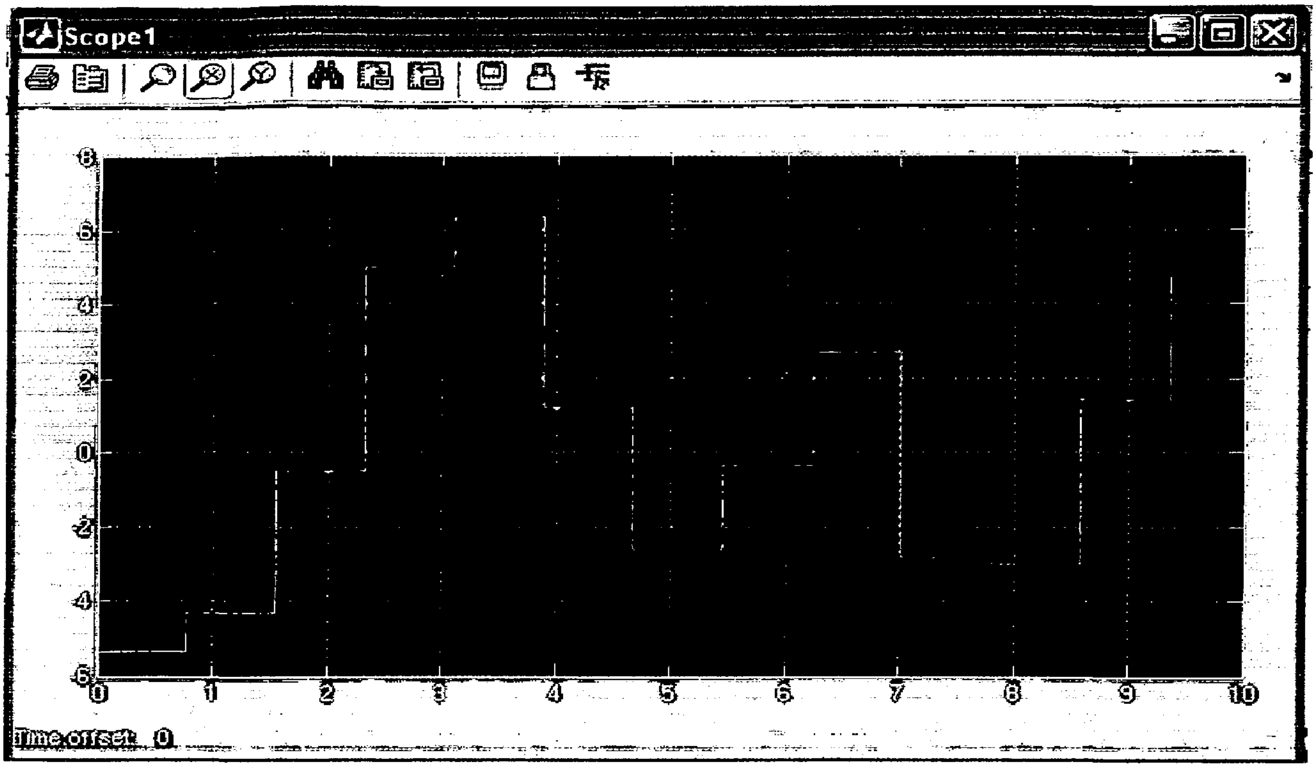


Figure 5.10: Error in reactance value when load resistance is changed as per relation R_L3.

Similarly, system characteristics for changes as per the relations R_L2 and R_L3 can be given as:

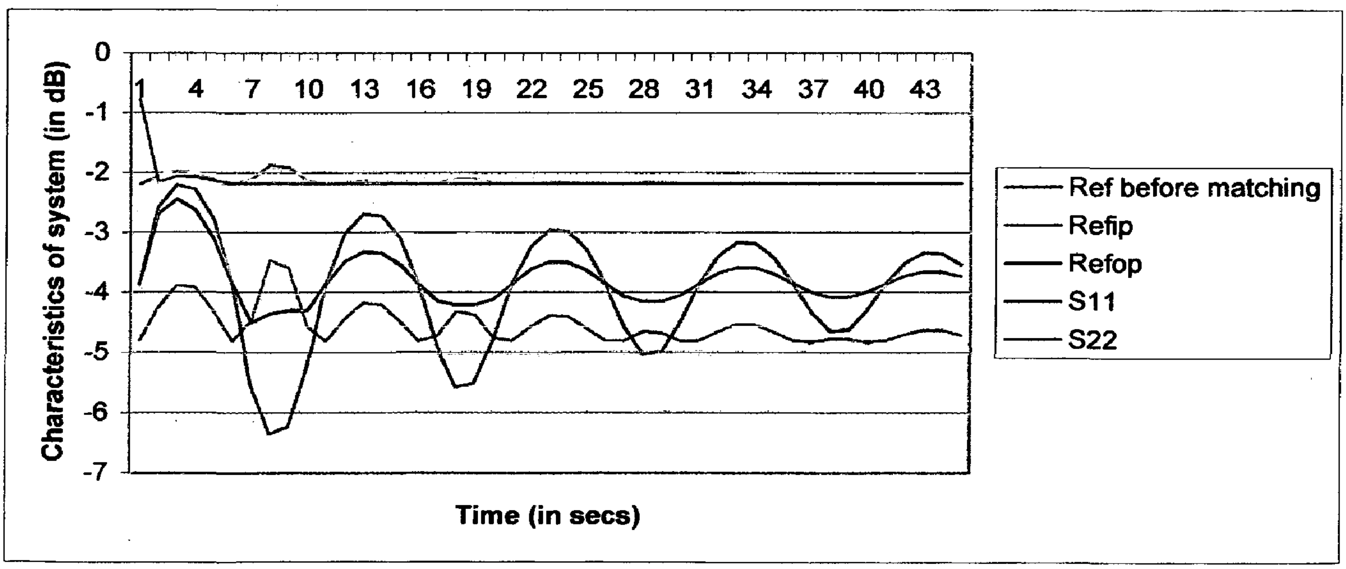


Figure 5.11: System characteristics with respect to load resistance as per relation R_L3.

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