A Low Cost Impedance Analyzer for Fault Detection in Piezoelectric Materials

Author
Syed Muhammad Hassan Maqsood
00000277529
Supervisor
Dr. Hamid Jabbar

DEPARTMENT OF MECHATRONICS ENGINEERING
COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY
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Author

Syed Muhammad Hassan Maqsood

00000277529

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Thesis Supervisor:

Dr. Hamid Jabbar

Thesis Supervisor's Signature: ________________________

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Declaration

I certify that this research work titled "*A Low Cost Impedance Analyzer for Fault Detection in Piezoelectric Materials*" is my work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged/referred.

Signature of Student

Syed Muhammad Hassan Maqsood

00000277529

Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical, and spelling mistakes. Thesis is also according to the format given by the university.

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Syed Muhammad Hassan Maqsood

00000277529

Signature of Supervisor

Copyright Statement

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Abstract

Piezoelectric devices are widely used in many industries in the application of sensors, actuators, energy harvesters, and piezoelectric transformers. For this reason, different testing techniques have evolved over the years to measure the properties of piezoelectric material during production and while in the application as per the required specification. While in production, these testing techniques ensure that the piezoelectric materials are defect-free, and in the application, they should have a life more or equal to the product lifetime. This testing becomes critical during applications such as structural health monitoring where piezoelectric materials are embedded or glued with the structures and cannot be removed or replaced. These testing techniques generally involve studying the impedance response of piezoelectric material to analyze the health of piezoelectric material which can be related to the device/application health. An impedance analyzer is one of the tools with the help of which one can determine the behavior of piezoelectric material by analyzing its internal impedance. Impedance analyzer has the property to convert complex electrical signals into wave frequency, and by these wave frequencies, one can determine whether the piezoelectric material is working well or not under different circumstances, how much the piezoelectric material has degraded over time, is the material is cracked or physically damaged. In this thesis, a complete layout, design, and fabricated low-cost impedance analyzer has been developed for testing and analyzing piezoelectric ceramic materials. The impedance data acquired is compared with the analytical calculations to detect physical damage, faults, and degradation over time. The main feature of this analyzer is cost effectiveness and its comparison with various high-end impedance analyzers. The accuracies of 89% and 76% are achieved over the range of 10-100 kHz and 100 kHz to 215 kHz respectively. The goal is to develop a robust analyzer that can make tasks easier for the scientists, researchers, and manufacturers who are working on the fabrication, testing, and analysis of piezoelectric material and make the system IoT enabled to communicate with cloud for further smartness and real time defect detection by using complex algorithms.

Key Words: *Impedance Analyzer, Resonance Frequency, Piezoelectric Materials*

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Chapter 1: Introduction

1.1 Piezoelectric Materials

There are certain materials that have the ability to provide electric charge when mechanical stress has been applied to them, similarly these materials mechanically deform when electrical charge is applied to them. Such materials are known as piezoelectric materials. There are some piezoelectric materials that are naturally available while the other ones are fabricated by researchers and scientists primarily associated with materials or metallurgy labs.

1.1.1 Types of Piezoelectric Materials

There are different types [1] of piezoelectric materials discussed as follows.

- Single-Crystalline Piezoelectric Materials such as Quartz, Barium Titanate, and Lithium Tantalate
- Piezoelectric Ceramic Materials, the most common example of piezoceramics is PZT (Lead Zirconate Titanate).
- Piezoelectric Semi-Conductors like ZnO_2
- Piezoelectric Polymers like PVDF.
- Piezoelectric Composites
- Glass Ceramics like $Li_2Si_2O_5$ and Ba_2TiSiO_6
- In integrated circuits (ICs) piezoelectric materials such as AlN (Aluminum nitride) are used

1.1.2 Equivalent Circuits for Piezoelectric Materials

Piezoelectric ceramics are used as a sensors, actuators, energy harvesters and transformers (generally called as piezoelectric devices). This physical material has electrical properties, which varies with applied voltage and applied mechanical stress. Piezoelectric materials are manufactured in different shapes and sizes, and work on their resonance frequency range. If the piezoelectric material is attached to a mechanical structure, the fundamental resonance frequency will be lower than that of piezoelectric ceramic and it can be called as system resonance frequency.

To model and understand devices behavior, generally these materials are represented as an equivalent circuit (in the form of resistance, capacitance, inductor and ideal-transformer) for design, simulation and to understand its working performance and material properties. Equivalent circuit models [2] can help to understand concepts better while working with mechanical systems. It can make the calculations easy and understandable as well. By having equivalent circuit models and their respective approximations we can easily design the electronic circuitry that is required to drive the mechanical model or in our case piezoelectric material. While working with piezoelectric materials, equivalent circuit models are important. As in piezoelectricity, one has to deal with electrical as well as mechanical stresses so there should have been the concept of basic analogies of the electrical and mechanical model of piezoelectric materials. In this section, the equivalent circuit models of piezoelectric ceramic materials will be discussed along with their figures. The basic discussion of impedance and piezoelectric material properties are available in [3].

First of all, a brief explanation of Lead Zirconate Titanate (PZT) equivalent model (a very common piezoelectric material, usually available in disk or ring shapes) have been shown. Piezoelectric materials are generally used in their resonance frequency range; therefore, in this resonance frequency range an equivalent circuit representing the resonance is required. In the following figure, the equivalent model for PZT is shown in resonance frequency, also known as Van Dyke model [4]. This circuit is resonance circuit, which means at resonance point the behavior of PZT will be similar as the behavior of the circuit shown in figure 1.1. The piezoelectric material have many resonance frequency modes, but generally operated at fundamental frequency range (for both material or system level).

The equivalent circuit has a series string of an inductor, capacitor, and resistor and all connected/shunted with a second capacitor [5]. The capacitor Cb represents the static capacitance (between two electrodes) of piezoelectric material (generally measured at 1kHz). Resonance branch is formed by R , L and Ca. The L and Ca forms a frequency, and R represents the losses. This equivalent circuit represents the input immittance (admittance & impedance; as a combined concept) of a piezoelectric material in the vicinity of a single resonance frequency range. It is assumed that the piezoelectric material (such as disc) is not freestanding, but is instead loaded at its mechanical ports (nodes) for operation as a transducer. The represented equivalent circuit elements are constant in value [5, 6].

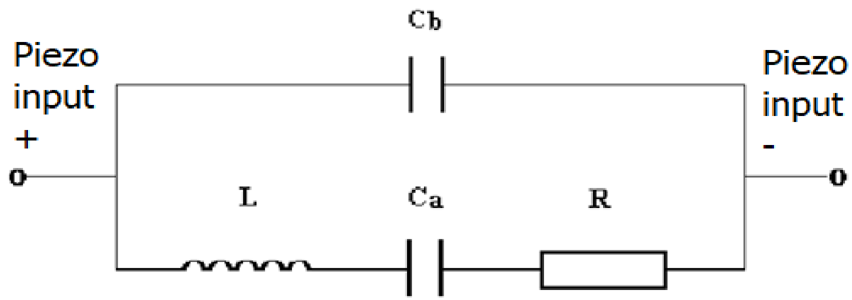

Figure 1.1. Equivalent Circuit Model for PZT [7]

Similarly, when operated at low frequencies (tens of Hz at systems level) an equivalent circuit model as shown in the figure 1.2 is used. This equivalent circuit model is generally used in energy harvesting applications [8], where low frequency vibrations are converted to useful energy.

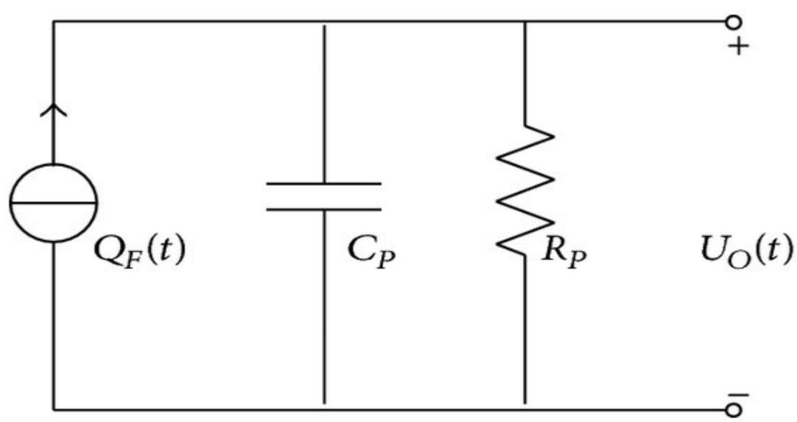

Figure 1.2. Equivalent Circuit Model for PVDF in Energy Harvesting Mode [6]

In the above circuit, the electrical components Q_F(t) , Cp and Rp are explained [9]. In the low-frequency range the piezoelectric material shows a behavior of a capacitor with high input impedance.

- $Q_F(t)$ here, replicates the power provided to the disc or the material in the form of electric power, the power is termed in the form of current in the whole circuitry for better understanding.
- Rp is the internal resistance, that disk has attained while in working condition. Higher is the value of Rp lower is the current generation during energy harvesting.

1.1.3 Resonance and Anti-resonance Frequencies

Resonance is one of the most important phenomena of mechanical vibrations. While dealing with piezoelectric materials, mechanical vibrations are very important and beneficial. While theoretically talking about the resonance frequencies of piezoelectric materials, it is the natural frequency of the material, where it vibrates at its fullest giving the better efficiency. Such kind of phenomenon is important while dealing with materials's vibration. Different type of piezoelectric materials have different kind of resonance frequencies they primarily depend on the thickness of the material, nature of the material, shape of material, and size of the material. In the same way, anti-resonance is the natural frequency of the system where the amplitude of vibrations are minimum when a system undergoes an abrupt shift.

In the following graph obtained from COMSOL Multiphysics, it shows an impedance graph with labelled resonance and anti-resonance points.

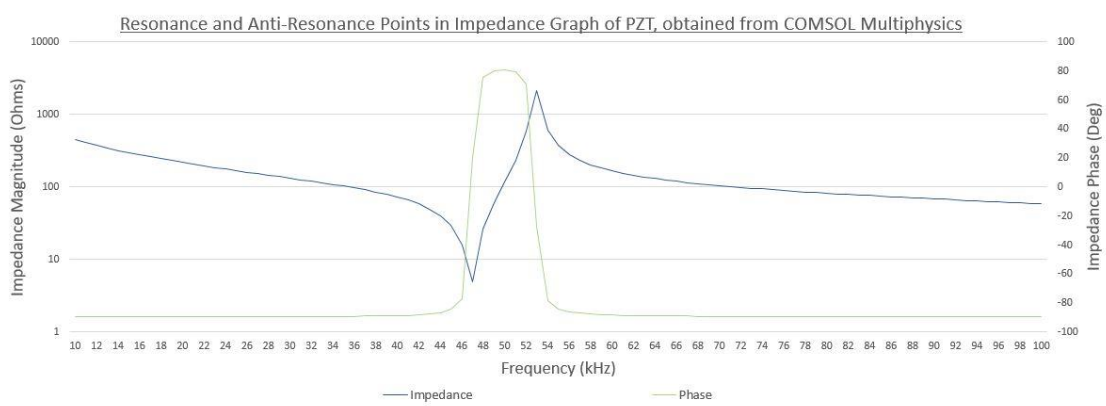

Figure 1.3. Resonance and Anti-Resonance Points in Impedance Graph of PZT along with Phase Angle Graph, obtained from COMSOL Multiphysics.

In the figure shown above there are two points labelled. One is f_r which is resonance frequency of the system whereas other is f_a which is anti-resonance frequency of the system.

1.1.4 Advantages of Operating PZT at Resonance Frequency

As the basic concept of resonance frequencies are explained in the previous subsection. In this subsection, a few concepts regarding advantages of resonance frequencies are discussed.

- At resonance frequency point PZT material gives maximum and efficient output, both electrically and mechanically (this frequency is different from system's resonance frequency which be lower if the same material is attached with a mechanical structure). When a system vibrates in its natural frequency it will give maximum displacement, and when this natural frequency point has reached lower voltage of electrical power is required to run the system, that is the reason lesser energy is required to run the PZT at its natural frequency giving maximum output, this point is known as resonant point, and at that point maximum efficiency has been achieved [10]. In simpler words, where we want to obtain mechanical vibrations from some electrical signal it is important for PZT to run in frequencies between resonance and anti-resonance points. The resonance frequency point has lowest impedance-magnitude value, but it is difficult to operate the material at a single point, as changes in applied load and ambient conditions can change this frequency point. At this point the impedance-phase is at zero, thus material will act as a resistor only.
- By obtaining, these two points (resonance and anti-resonance), we can fine tune our electronic system, in order to run the system primarily in this frequency range. So that maximum output in the form of vibration can be achieved. Generally, the electrical driving circuits in piezoelectric actuators operate between the resonance and anti-resonance frequency, where the phase angle is 90 degrees and thus piezoelectric material behaves as an inductor.
- All the ferroelectric materials are piezoelectric but not all the piezoelectric materials are ferroelectric in nature. There is difference between both of these materials.

Piezoelectric materials have the ability to convert electrical energy into mechanical energy and vice versa. Whereas is ferroelectric the polarization can be changed by applying external electric field.

1.1.5 Resonance Frequencies Graphs w.r.t shape of the material

The resonance graph is different for different shapes of material which are disk, ring, square, or stack etc. A brief explanation of each graph will be discussed here. A simulation of each shape of PZT will be discussed in this section which will give better view of how shape will affect the impedance graph. One thing must have mentioned here that all of these disks have same material properties.

Expansion in piezoelectric is a very interesting phenomenon, when the direction of polling and electric field is parallel, the material expands, and when both of these are anti parallel, they tend to contract. If the electric field is applied to the crystal, the positive and negative charges are not coincided with each other, and move along the direction of the polarization, thus it makes the crystal to expand, in the same way, when you remove the electric field which means now the direction of the field is in the opposite direction, thus the material now contracts as the charges moves in the inward directions. [11]

While working with the simulation in COMSOL Multiphysics, Ansys, and ABAQUS one must give importance to the material properties that are being provided as an input to the software. These material properties provide a very prominent role in the development of the results which are in the form of graphs or animation. While working with piezoelectric materials, we have come across a factor which is electromechanical coupling, which is defined with the help of following equation. [12]

$$electromechanical\ couplign\ coeffcient = k2 = \frac{ouput\ electrical\ energy}{input\ mechanical\ energy}\ or\ \frac{putput\ mechanical\ energy}{input\ electrical\ energy} \quad (1)$$

so the electromechanical coupling is defined as the ability of the material to convert electrical energy into mechanical or vice versa. As discussed earlier, these factors primarily depend on the impedance data of the material i.e. natural frequency of the system so in this way this k factor also effect the impedance of the system. That is the reason why correct material properties are important while working with simulations of piezoelectric material in different software.

1.1.5.1 Resonance Frequencies of PZT Disk

Resonance frequencies of different type of material has been done for this section. In this section, three different shapes of same material have been simulated in COMSOL Multiphysics. The properties have been same but there are some differences in the dimensions of each of the material's shape that has been observed for simulation.

- First of all, a piezoelectric disk has been considered. Following are the properties of the piezoelectric disk that has been observed here.
    1. The radius of the disk is 25mm and thickness is 0.5 mm.
    2. The Material chosen for the disk is PZT-8A.
    3. For Elasticity Matrix, Young modulus, and poison ratio has been provided manually in COMSOL Multiphysics so a value of 640GPA, 0.31 has been added respectively.

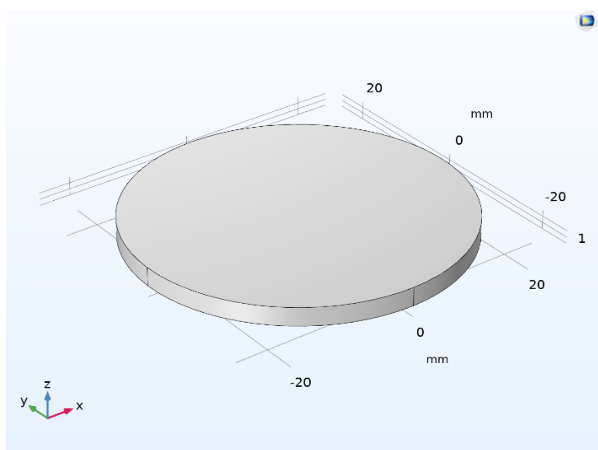

Figure 1.4. Geometry of Disk

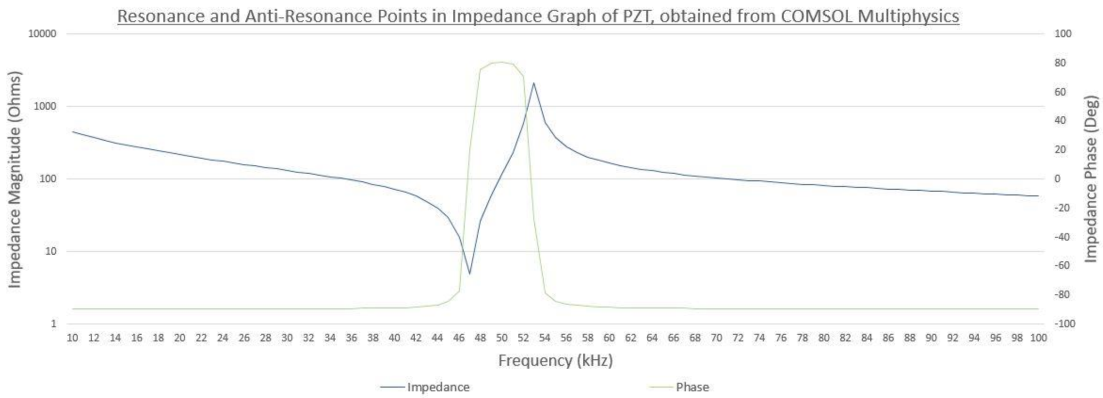

Figure 1.5. Impedance and Phase Angle Graph for PZT Disk

1.1.5.2 Resonance Frequencies of PZT Ring

In the same way a PZT ring is considered in COMSOL Multiphysics. This disk has following properties some of them are similar to the last part some are different.

1. The radius of the ring 25 mm and thickness is again 0.5mm.
2. A patch of radius 2.5mm is removed from the center in order to provide a ring shape to the body.
3. The material selected for this simulation is again PZT-8A.
4. For Elasticity Matrix, Young modulus, and poison ratio has been provided manually in COMSOL Multiphysics so a value of 640GPA, 0.31 has been added respectively.

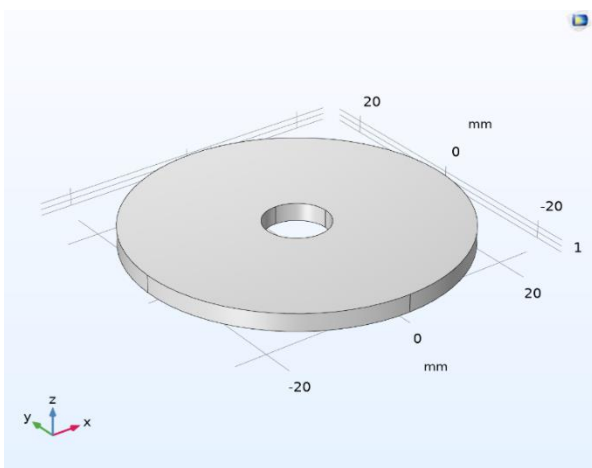

Figure 1.6. Geometry of PZT Ring in COMSOL Simulation

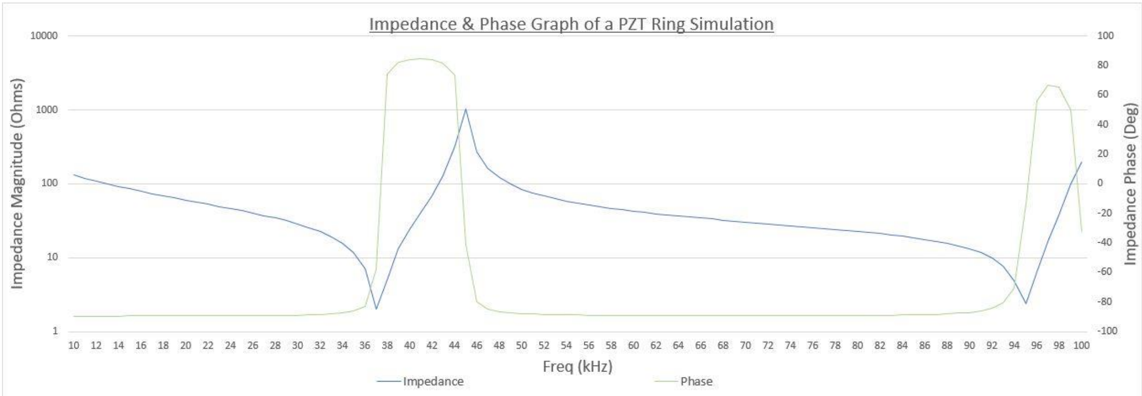

Figure 1.7. Impedance and Phase Diagram of PZT Ring

1.1.5.3 Resonance Frequencies of PZT Rectangle

For the third experiment, a rectangle body has been considered having following features.

1. As far as dimensions are considered, length of the rectangular bar is set to 5mm, with 2.5mm width and a 0.4mm thickness.
2. The material selected for this simulation is again PZT-8A.
3. For Elasticity Matrix, Young modulus, and poison ratio has been provided manually in COMSOL Multiphysics so a value of 640GPA, 0.31 has been added respectively.

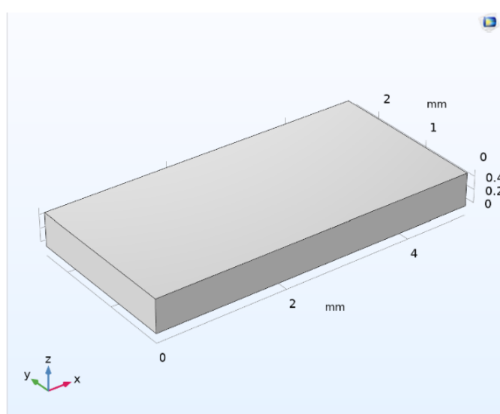

Figure 1.8. Geometry and Impedance Diagram of a PZT Rectangle Simulation

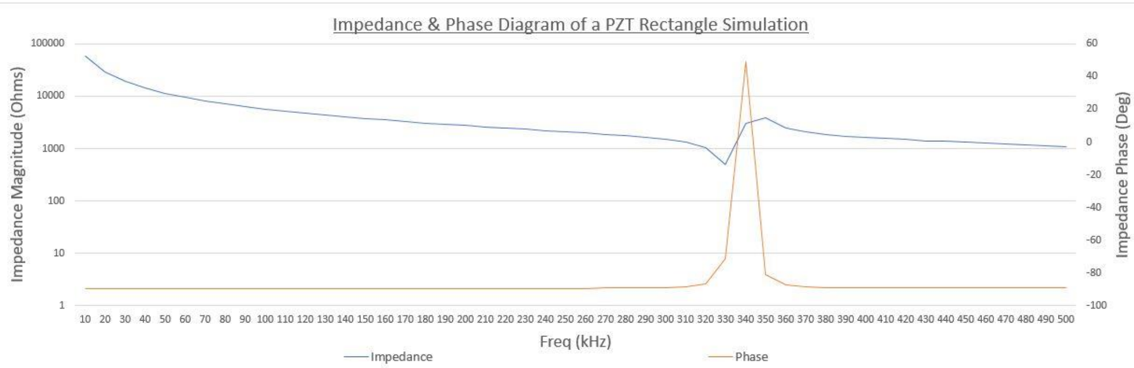

Figure 1.9. Impedance and Phase Diagram of Rectangular PZT

1.2 Impedance Analyzer

Impedance spectroscopy is performed by applying an alternating voltage to a sample/device-under-test and measuring its voltage and the current response, which is then represented in the form of impedance (in some applications areas, admittance, which is an inverse of impedance is widely used). An impedance analyzer is a device, which is used to measure the impedance of different electrical components such as resistors, capacitors, and inductors. It is also used to measure different sensors, actuators, and antennas as these have complex impedances.

Piezoelectric materials are widely used as sensors, actuators, energy harvesters and piezoelectric materials. These versatile materials are tested using impedance analyzers. When piezoelectric materials are attached to the mechanical structures (for structural health monitoring, buzzers, microphones, accelerometers, and energy harvesters etc.) the impedance analyses are used to predict the performance of the structure. Impedance analyzer has the property to convert the electrical impedance into frequency waveform with the help of which the scientist can easily observe the properties of piezoelectric material and the structure attached to it.

The impedance graph of piezoelectric materials is characterized by the resonance peaks at different frequencies, which are related to the mechanical dimensions, shapes and bending modes of the material. Cracks, manufacturing faults, degradation over time, loss of polling, change in applied forces and stresses are reflected in the impedance graph of the piezoelectric materials. While working with piezoelectric devices, the main issue that occurs is its non-linearity and transient behavior**.** Transient behavior in mechanical systems occur when the system disturbs from its equilibrium state. As during testing of piezoelectric materials, or working with them there are different frequencies involved, so for this reason the response of the piezoelectric material becomes abrupt and they have shown transient response. With such issues one cannot observe whether our device is working correctly or not so for this purpose an impedance analyzer is required which tells us about the behavior of piezoelectric material and with the provided data sheets and related calculation we can determine that up to which extent the material shows abnormal behaviour [13]. Piezoelectric material analytical and simulated impedance data is used as a reference to find the abnormality, fault and degradation over time. With complex shapes of piezoelectric materials, FEM simulations are carried out to acquire the closest match of impedance with the real manufactured disc as analytical equations cannot predict the multi frequency behaviors and too complicated to be solved [14].

It is important to measure the impedance of a certain piezoelectric material. There is a certain frequency which is known as resonance frequency (actually two frequency points, one is known as resonance frequency and other is known as anti-resonance frequency, between these two points the value of impedance and its phase will change) where piezoelectric material gives maximum efficiency [15]. When the piezoelectric material is attached with any substrate or structure the system has now different resonance frequency based on its geometry, shape, manufacturing process and piezoelectric material type. The impedance has to be measured at certain ranges of frequencies in order to validate the performance of material. It also helps to show any fault that occur during the manufacturing process of piezoelectric material. To improve the fault detection accuracy and wide data acquisition frequency range, expensive equipment such as impedance analyzer are used. With the help of impedance analyzer, we will not only obtain the fault of the fabrication process but also the unknown material properties and any cracks or stresses applied on material after it has been manufactured. In this thesis, the main goal is to develop a low cost, precise, and more accurate impedance analyzer that can work on different piezoelectric materials to obtain their impedance at wider frequency ranges.

1.2.1 Admittance

Admittance (reciprocal of impedance) is the ease by which the electrical current can flow inside a body, component, or a material. In simple words, it is the resistor, and it helps the current to flow easily inside a body. Depending on the applications, admittance or impedance both are used in the representation of piezoelectric materials. As admittance is the inverse of resistance, so the formula or the mathematical calculation for this factor is as follows.

$$Y = G + jB \tag{2}$$

$$Where\ Y = Admittance \tag{3}$$

$$G = Conductance \tag{4}$$

$$B = SUspectance \tag{5}$$

The unit for admittance is normally siemens.

1.2.2 Impedance

Impedance is basically resistance but with the phase. Resistance only has magnitude but impedance has also phase associated with it. There are two parts of impedance, real part of impedance is resistance and imaginary part is reactance. The formula for impedance is as follows.

$$Z = R + jX \tag{6}$$

$$Where\ Z = Impedance \tag{7}$$

$$R = Resistance \tag{8}$$

$$X = Reactance \tag{9}$$

1.2.3 Immittance

By combining admittance and impedance another phenomenon has been created which is immittance.

In simple words, the impedance is same as our resistance in electrical circuits. The higher the impedance the higher is the resistance and the current will face difficulty to flow in a designated area. The symbol used widely for impedance is **Z** and is measured in ohms, mostly the impedance magnitude **|Z|** and impedance phase θ is used instead of **Z** in piezoelectric ceramic material studies [16].

1.2.4 Methods for Measuring Impedance and Admittance

There are various techniques involving measuring impedance some of the are listed below [17].

- Bridge method
- Resonant method
- RF I-V method
- Direct I-V method
- Network Analysis method
- Auto Balancing Bridge method

Among all the above-mentioned methods there are 3 most important impedance measuring techniques or methods one of them is direct I-V method [18] it is very impactful when frequency ranges are lower like in the range of micro Hz and impedance level are higher like in the order of 10's of tera ohms. Auto balancing bridge method [19] is again an important technique used for slightly higher frequencies like one in the range of MHz and relatively lower impedances like in the level of mega ohms. RF-IV [20] method is the third most important technique in this list which work in the mediocre frequencies and impedances.

1.2.5 Advantages of Impedance Analyzer

There are several different advantages associated with impedance analyzer which make it better choice as compared to oscilloscope (current and voltage can be measured using oscilloscope to obtain an impedance), LCR meters (L from inductance, R from resistance and C from capacitance) and other related devices. In the following lines, different advantages of are enlisted.

- While compared with LCR meter, impedance analyzer is better in a way that in LCR meter we can only measure at single frequency and get numerical results. Some LCR meters give values at fixed frequency (100 Hz, 1 kHz, 100kHz). Some high end LCR meter can work on range of frequencies, generally 100Hz to 100/200/300 kHz range, they can give impedance values at user selectable frequency range, generally 201 frequency points data is available. In impedance analyzer graphical representation along with numerical values can be obtained in addition to the high end LCR meters. [21]

- They have the ability to provide equivalent circuit analysis which cannot be done in any other devices [22]. This equivalent circuit is the representation of material or device performance in the mentioned frequency range and is utilized in the SPICE circuit simulation software to develop the related circuit and to find the power consumption and frequency response.
- Network analyzer can be used as a replacement for impedance analyzer, but this network analyzer is again having some of its limitation when compared with impedance analyzer. [23]. Network analyzers are generally tuned for antenna related applications, works at higher frequency range.
- There are several impedance meters available in market, with the help of which we can easily measure impedance of different materials, and structures depending on their polarity and dipole moments inside the structures. Impedance analyzer as discussed earlier have an edge above these meter as it gives as test frequency output also so that we can observe the behavior of the material as well along with numerical values. [24]
- Another perspective arouse here that we can measure the resistance directly as some people have confused impedance with resistance due to their same formula and units. The main difference between resistance and impedance is that impedance only blocks the flow of AC source while resistance has done work for both AC and DC, so a proper device is required to measure the impedance so a impedance analyzer is needed here. [25]
- Using basic laboratory equipment such as Function generator and an oscilloscope, impedance measurement can be performed. But this requires precise control of device, data acquisition interface and computer interface. Generally, this impedance technique is utilized when the AC signal value are higher (greater than 2Vrms).

1.2.6 Dis-Advantages of Impedance Analyzer

In the same way there are certain disadvantages associated with impedance analyzer as well. These disadvantages are enlisted as follows.

- These analyzers are very costly that are available in market.
- They have not better accuracy at lower frequencies.
- Some of the available analyzers are very complex and are difficult to use.
- Active circuits have different components attach with them, all of them have different resonance frequencies so that is the reason it becomes difficult to measure the resonance frequencies for those components using such analyzers.

1.2.7 Application of Impedance Analyzer

As discussed, earlier impedance analyzer has a very important application of measuring impedance of piezoelectric materials and ceramics in order to validate their performances. The main aim is to fabricate a multi frequency impedance analyzer with the help of which we can observe the behavior of piezoelectric material that is fabricated in lab or is being utilized in an application. This will be an important breakthrough for the researchers that have been working in the field of piezoelectric fabrication, application and maintenance engineer. With the help of this impedance analyzer, we cannot only test one kind of piezoelectric material but also with slight change in the hardware and software settings every type of piezoelectric material (having different size, dimension, shape, piezoelectric material type) can be tested. Following are the few other applications where we can use impedance analyzer.

- While working with electronic components it is important to characterize them in different groups like electronic circuits, components, and materials. For this purpose, impedance analyzer can be used and with the help of waveform obtained we can discriminate between the above-mentioned categories. [26]
- It is a very important component while working in biomedical application and tactile sensing as in that case very low resistance or voltage value is important. The most common example is tissue surgery, geological sample gathering etc. [27]

- They are very useful where high accuracy and precision is required, for e.g., in military units like tanks where a small degree rotation of gun is very important, in bio medical where small signal of probe is very useful, in angiography where the traveling of needle required precision in millimeters and often in micrometers. [28]

The use of impedance analyzer in different technical fields are listed below in the table.

Table 1.1. Application of Impedance Measurement in different Technology Sectors along with their Usage.

Sr No.	**Application Area**	**Usage**
1	Automotive Industry	They are used for battery diagnostics [29], at power lines for load distribution [30], and for validation of sensors like traction control, push start, and radar etc.
2	Biomedical	Impedance measurement, rectification and getting better values from it are a very important part in biomedical industry. They are mostly used in wearable health devices [31], biomedical surgery [32], and for diagnosis purposes [33].
3	Defense	In defense infrastructure they are used as to detect faulty systems [34], to observe different parameters of outside environment [35], and to tune radio frequency [36] so that communication becomes easy.
4	Piezoelectric Fabrication Industry	An important part in this industry in order to validate the performance of piezoelectric material [22], [23], [31], [35], [37].

1.3 LCR Meter's Comparison with Impedance Analyzer

The most competitive challenge for a researcher working on impedance analyzer is to compare it with LCR meter. They both are of same kind of instrument and have more or less same kind outputs. In this section a brief discussion having comparison between the two instruments have been explained and why impedance analyzer is better than LCR meter.

- LCR meter generally works on the single frequency whereas Impedance Analyzer works for multiple frequencies. Impedance analyzer has also the ability to measure sweeping frequency with graphical results as well. [38]
- LCR meters are mostly used as indicators while for better results impedance analyzer are preferred. [39]
- LCR meter & impedance analyzer both required 20-30 min setup time before running in perfect condition. [40]

Figure 1.10. LCR meter and its Numerical Output [41]

Figure 1.11. TH2829C Impedance Analyzer [42]

1.4 Network Analyzer Comparison with Impedance Analyzer

Similarly, there are other competitors for impedance analyzer are available in market. In this section comparison between network analyzer and impedance analyzer has shown. Following are the few attributes why impedance analyzer is better than network analyzer.

- Network analyzer is also used for measuring impedance. This can be used for higher frequencies unlike other measurement tools which can be used on lower frequencies like sine wave generator, amp meter, and voltmeter. [43]
- Both network analyzer and impedance analyzer have worked on same working principle the main difference is network analyzer has the ability to individually measure each channel's input current. [44]
- Technology provider, Keysight technologies have compared their two basic models of network analyzer and impedance analyzer and conclude that their, in impedance analyzer the frequencies ranges from 20Hz to 130 MHz while in network analyzer the frequencies ranges from 5Hz to 3GHz. [45]

Figure 1.12. Conventional Network Analyzer

1.5 Literature Review of Low-Cost Impedance measurement

A lot of research has been carried out in recent time related to impedance analyzer. The impedance analyzer is important in a way that it has its importance related to piezoelectric fabrication as well. Researchers and labs working on piezo fabrication need impedance analyzer type instruments for the validation of fabricated piezoelectric materials.

The most important thing requires in an impedance analyzer is accuracy and precision. For this purpose, different researchers had used AD5933 IC (by Analog Devices, 1 MSPS, 12-Bit Impedance Converter, Network Analyzer) which helps in self calibration, accuracy, and precision during impedance measurement. In [46] by **Telfor et al.**, the researcher has proposed an AD5933 based complex impedance analyzer with the help of which the data can be stored in an SD card. This complex system has also the ability of self-calibration and the accuracy that has been provided by their experimentation is up to 90%. Their system is designated to bio-medical applications. Similar research by [47] has been carried out for irrigation system which doesn't require that much accuracy, but they have required large spectrum of frequencies to work on. Their frequency ranges from 5Hz to 100kHz. The system has additional remote monitoring system with the help of Bluetooth as well. Flow chart of this research has been shown in the following figure. Another similar article, in which AD5933 based impedance analyzer has been discussed but this time the device is wearable with the help of which the all the data has been acquired on a small device. This device has a wide range of applications as it is small in size so it can be used in spectrum spectroscopy, electrochemical analysis, and non-destructive testing. All of these fields are new and have many possible research gaps so a lot of output can be obtained from such devices. [48]. A flow chart from the article [49] has been shown as follows for better understanding of impedance analyzer along with its data processing interface.

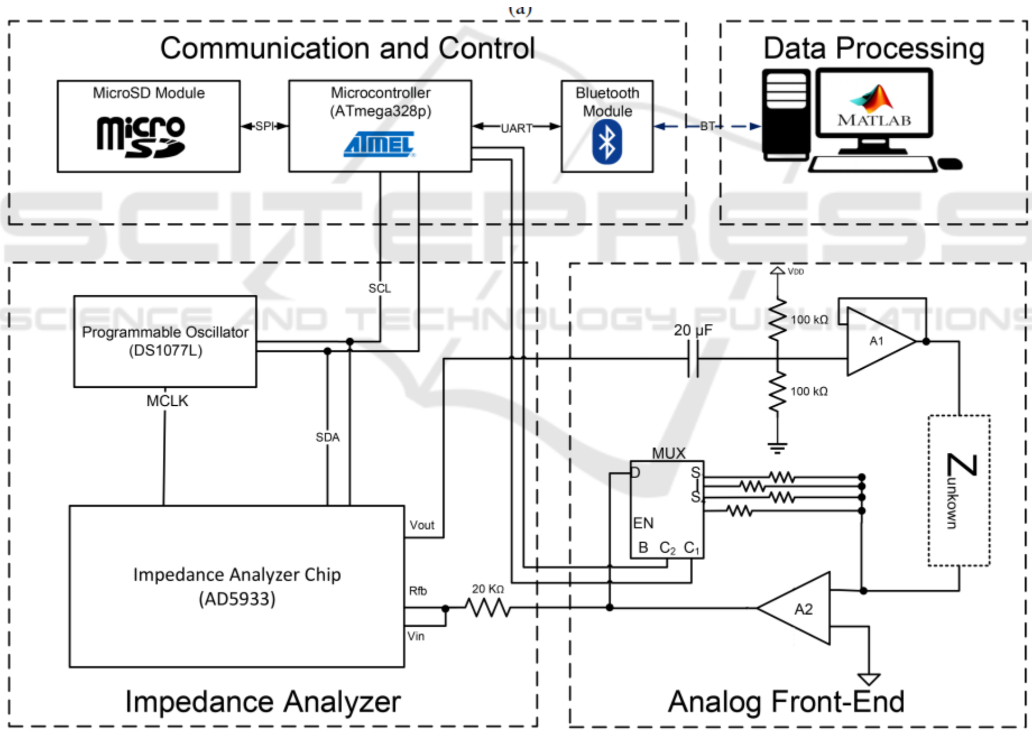

Figure 1.13. Impedance Analyzer with Communication, Control, Data Processing, and Analog Front-End [49]

1.6 Crack Detection from Resonance Peak

In biomedical industry impedance is a very prime component to consider as all the values of probes during surgeries, angiography even milli ohm values are very important for data processing. For this purpose, CMOS based impedance analyzer are very common. A research team [50] has proposed a design of impedance analyzer with the help of which a frequency range from 10kHz to 100 MHz with a step of 1kHz. They have obtained their results and compared it with LCR meter and turn out that this design has only 0.8% error. Similar research [51] has been carried related to CMOS based impedance analyzer. Their application is specific to cell substrate and their values. As we know that human cells are at very small in size like in nano meters which means the impedance is also lower, so a perfect accuracy is required. The results have shown a 0.4% capacitance and 0.1% at resistance level which are very magnificent results at such lower level. The same research [50] has also been carried out in article. The author has developed an impedance analyzer which is application specific towards electrochemical spectroscopy. CMOS based impedance analyzer are very common these days towards bio medical application so testing mechanism is required to test such instruments. For this purpose, research has been carried out to develop a test bench for such impedance analyzers which can validate the performances of such devices. [51]

1.6.1 New and Intact Piezoelectric Materials

In the following figure, there is a graph shown which shows the impedance of the material at different frequency levels.

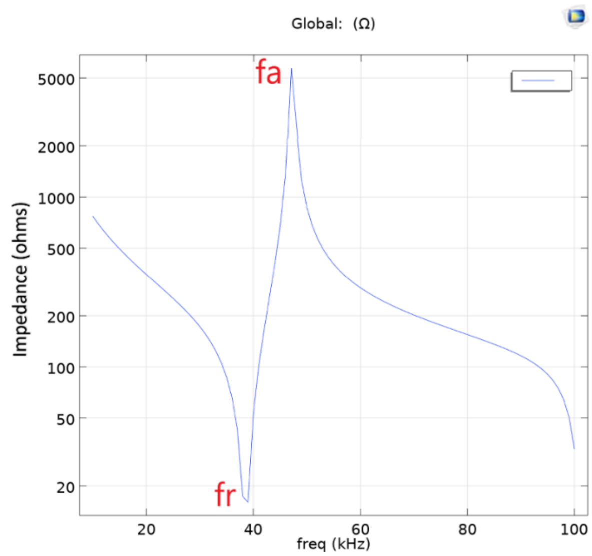

Figure 1.14. Impedance as a Function of Impedance Graph when there is no Crack or Defect

From the figure shown above, it can be observed that the figure has only one resonance point at f_r and one anti-resonance point at f_a. this means the impedance is flawless and hence with the help of this graph we can easily say that there is no defect in this piezoelectric material that's impedance has been under observation.

1.6.2 Ceramic with Internal Crack

There can be a possibility that you may have ordered a piezoelectric material or any other ceramic, it may be new but due to shipment processes the ceramic may have faced some internal cracks. Following is the impedance graph obtained if there are internal cracks in the new piezo ceramics.

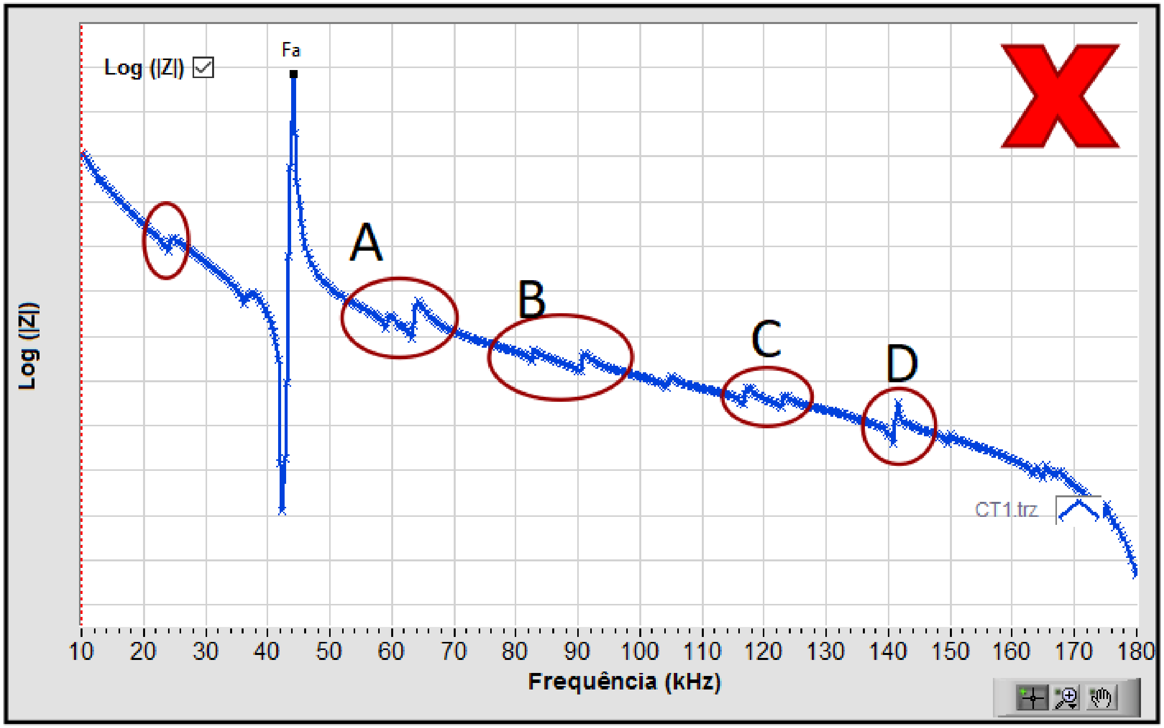

Figure 1.15. New Piezoelectric Material with Internal Cracks as explained in [49]

From the figure shown above the points A, B, and C shown.

Point A = Abnormality shown, this line should have been smooth.

Point B and C = this point must also be smooth for a flawless piezoelectric disk

Point D = At point D the wave is so small this must be the second resonance point of this disk if it is so, then this wave is bigger than the one shown and lesser than the main peak shown before point A in the above figure.

If the researchers or scientist have developed a new piezoelectric ceramic in lab and after observing its impedance graph, such kind of different peaks have obtained then this ceramic shouldn't be approve as it may have different cracks inside it which may have effect the performance of the piezoelectric material when we have to use it in different applications. To cope with this the scientists of the lab must review their fabrication processes which may cause these cracks in ceramics right after their fabrication.

1.6.3 Used Ceramics with Internal Cracks

There is another possibility due to which the ceramic may have faced wear and tear. For example, one may have used the piezo disk in some application like pavement paths, ultrasonic cleaners, or any other source. After sometimes you have observed the performance of these devices may have decreased so you should have observed the impedance of these ceramics, they may have produced cracks internally inside the ceramics. The graph of impedance when there are internal cracks in the ceramics is shown in the following figure.

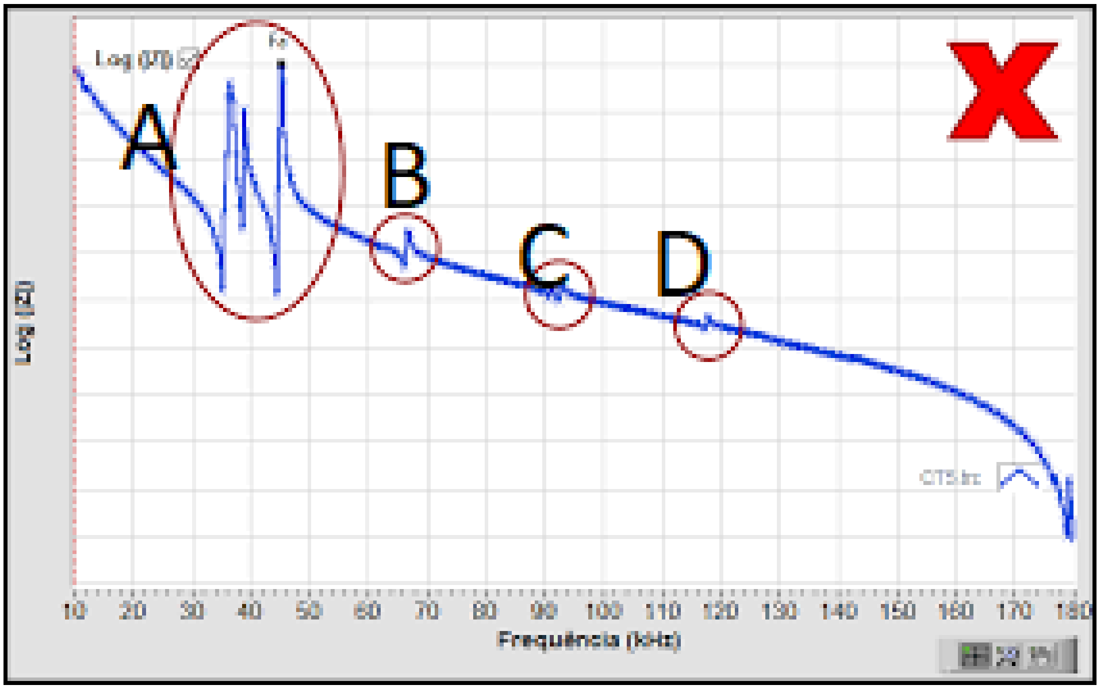

Figure 1.16. Impedance graph of a used Ceramic having internal cracks as explained in [49]

Point A = the peak is not in its pure form; this peak must have been smooth like the one observed in figure 1.12.

Point B = This may be second resonance point, but the size of the peak is so small.

Point C and D = Abnormalities, waves must have been smooth at that point.

Different labels are shown in the above figure. These are the noises that are caused by the internal cracks present in the piezoelectric materials. These are mainly due to manufacturing flaws. From the above graph it has been observed that there are disturbance in the main resonance mode of the piezoceramics. If such condition has occurred, this will indicate that the piezoelectric ceramic has completed it life and it may have been replaced, as due to continuous running the device may have been failed due to which there are internal cracks induced in the disk or the material. Before changing the disk, one must observe all the circuitry which is used to operate these ceramics or all the stresses which are applied otherwise this fault may have occurred again in the future.

1.6.4 New Ceramic with Unknown Defects

There may have been a possibility that the new ceramic may have shown different impedance graphs that have already discussed earlier. The reason can be the manufacturing errors during the fabrication processes of piezoelectric ceramic, as there are too many fabrication processes during the development of such ceramics. Following is the graph shown which will tells us the unknown defects associated with piezoceramics.

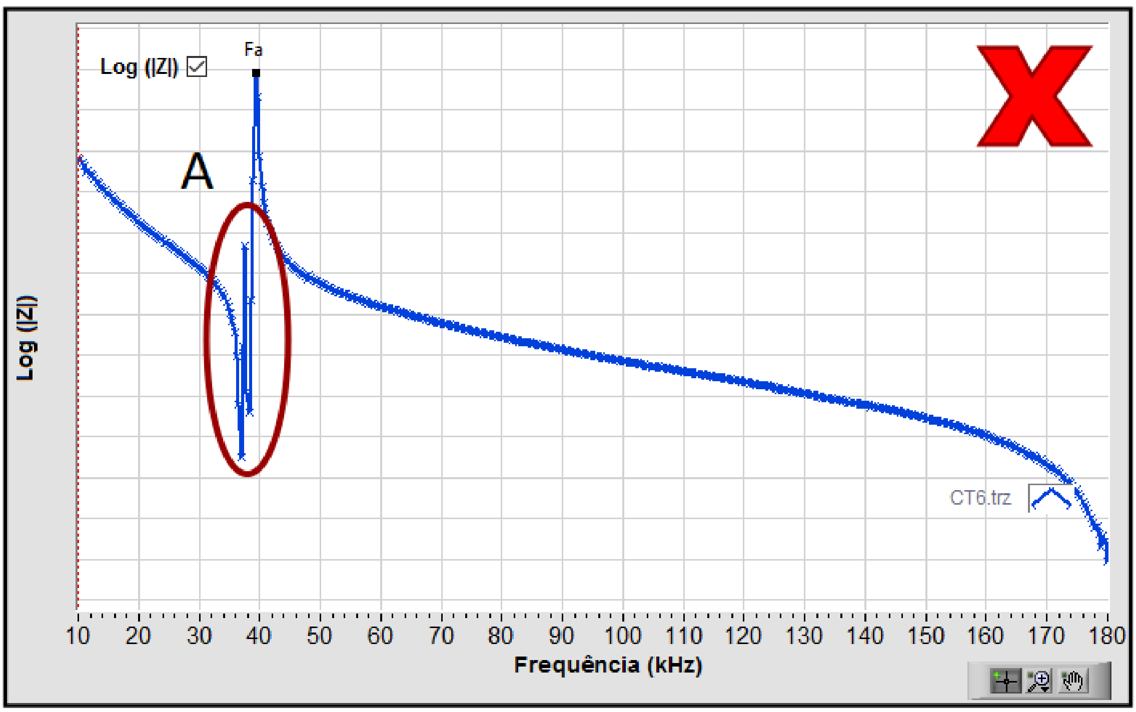

Figure 1.17. Piezoceramic with Unknown Defects as explained in [49]

Point A = there is a lot of abnormalities at a single point, the graph is smooth at the later parts, but this peak should have been like the one in the figure 1.12.

By observing from this graph, we cannot say that this may have an internal crack as the behavior of impedance graph with cracks associated with it were already discussed in the earlier subsections. So, from observing from the graph above this shows some other kind of defects which may have come during the fabrication and machining processes associated with the fabrication of such ceramics. All of these defects that have discussed here are proved by the ultrasonic testing as well. As ultrasonic testing is a difficult and expensive at the same time so there is a need of a device which may have check such ceramics with ease. So, for this purpose, such impedance analyzers are very much useful. By obtaining impedance graph of such ceramic and by observing them one can conclude different results from it.

Table 1.2. A Literature Review about different showing Defect Detection using Impedance Graphs

Serial	**Journal/ Conference**	**Year**	**Important parameters**	**Remarks/relative comments**
[50]	Sensors	2020	In this paper, the author has worked in shear lag, sensor debonding, sensor breakage and structural damage of piezoelectric material.	A phenomenon of electromechanical impedance has been proposed. With the help of this phenomenon different parameters have been obtained.
[51]	Journal of Physics D: Applied Physics	1996	Theoretical predictions of defects have been compared with the one obtained by measuring impedance of the material.	With the help of impedance graphs different defects in the piezoelectric materials have been obtained and the result is then compared with theoretically predicted calculations
[52]	Complexity	2021	With the help of simulations different defects like lag effect, transducer debonding, transducer breakage, and	The simulation graphs obtained from these results explains the reader about different

			interface detaching have been introduced in the material and related impedance graph has been obtained.	defects in the piezoelectric materials.

Chapter 2: Proposed Impedance Analyzer Design

In this chapter, a detailed explanation of the impedance analyzer will be shown. Every hardware component will be explained briefly and individually in later subsections. In this section, an explanation of the electronic circuitry will also be discussed. The electronic circuitry is used here to develop the impedance analyzer along with its components like AD5933 and others.

2.1 Introduction

For this thesis, an impedance analyzer has been designed and fabricated. In the modern world, impedance analyzer becomes very important device, especially in the field of piezoelectricity, MEMS technology, and electronics engineering. With the help of impedance analyzer, we can measure impedance of different devices and components. This impedance values later on, helps to find out the internal characteristics of components, materials, and circuits. There are following few advantages of impedance analyzer.

1. In order to find impedance graph. With the help of these graphs one can easily find resonant and anti-resonant frequency points. With the help of these points one can attain maximum efficiency from piezo disks.
2. With the help of an impedance analyzer, we can find the equivalent circuit of the piezoelectric device, with the help of these equivalent circuits the device can be analyzed in the SPICE circuit software (such as LTSpice and PSPICE) for circuit design and power consumption analysis.
3. Impedance analyzer data is utilized to obtain the complex material properties of the piezoelectric materials. The actual/fabricated material properties are essential to improve the simulation and design of the devices as the fabrication process is complex and material properties vary with a slight change in ambient conditions and concentration of precursors powder.
4. Impedance analyzers provide us the information of internal and external cracks in the material. This crack generates additional resonance peaks in impedance data. The magnitude of the impedance and its phase is related with the crack size [49].

5. In Piezoelectric ceramic material loss of polling occurs over time, which can be measured by comparing the impedance data with the one acquired at the time of manufacturing.
6. Any static loading, external stress information, or fault in the attachment of piezoelectric material can be analyzed from the impedance data.

A block diagram of the project is shown in the following figure.

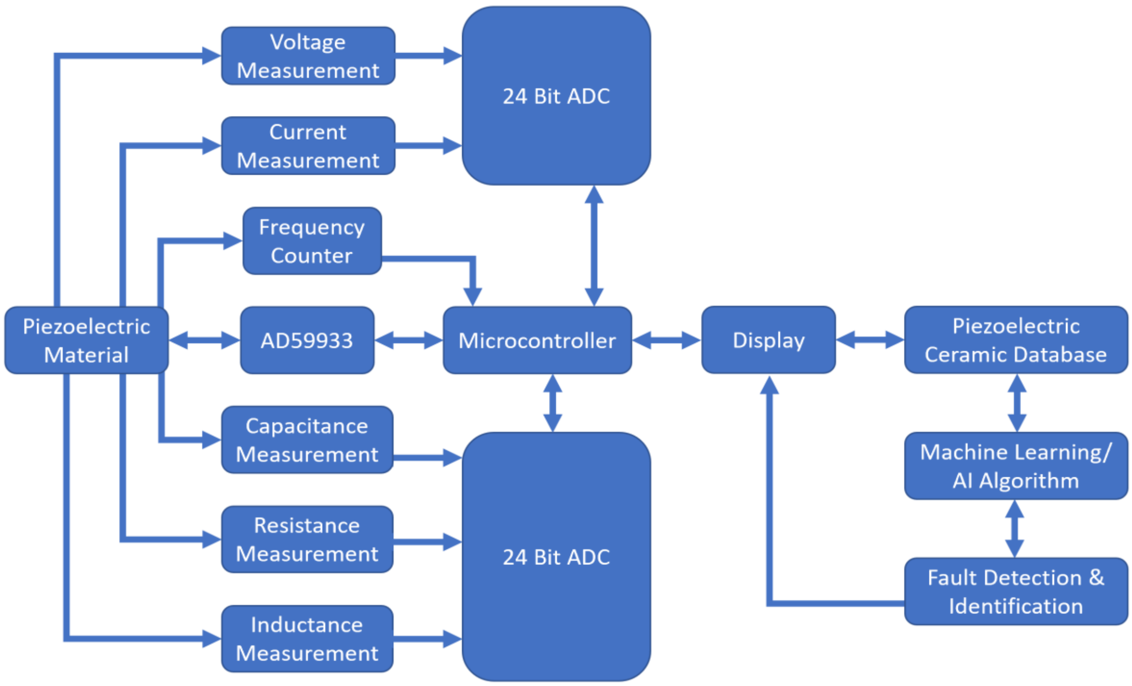

Figure 2.1. Detailed Block Diagram of how this Lo-cost Impedance Analyzer will work

2.2 Subcircuits of proposed designs

In this subsection, a brief discussion of each and every component that has been used for this project is enlisted here along with their brief description. Following are the components that have been used for the fabrication of this project.

In the following figure labelled diagram of complete circuitry has shown.

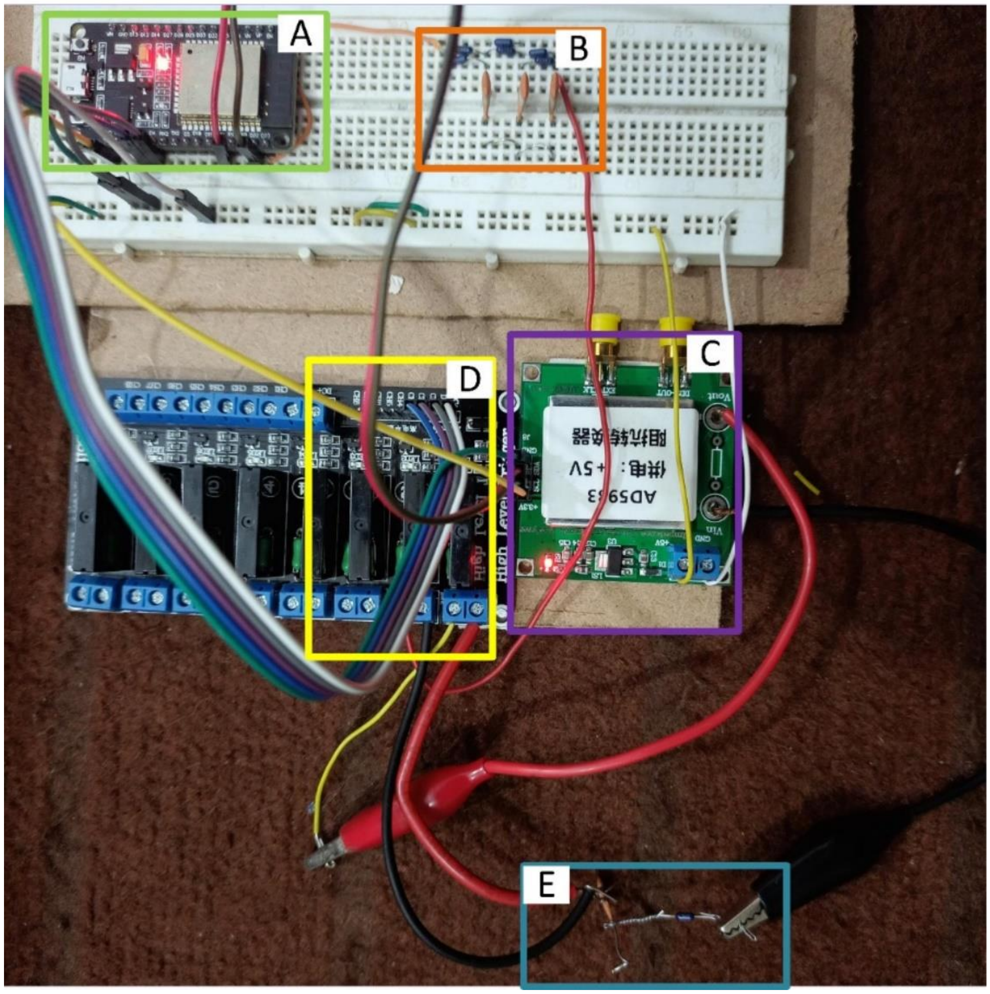

Figure 2.2. Labelled Diagram of Circuitry of Proposed Impedance Analyzer

From the above figure following are the labels of the components which are shown.

A= ESP 32

B= External Frequency Generator

C= AD5933 Board

D= Relay Switches

E= Device under Test

In every project related to electronics and especially in the field of mechatronics, the microcontroller is one of the most important part that has being used. Microcontroller is mostly referred as the brain of the project. In this project, ESP32 has been used as microcontroller. There are different features of this microcontroller which is the reason why it is preferred over the conventional microcontroller available in the market. The flow of ESP 32 is as follows.

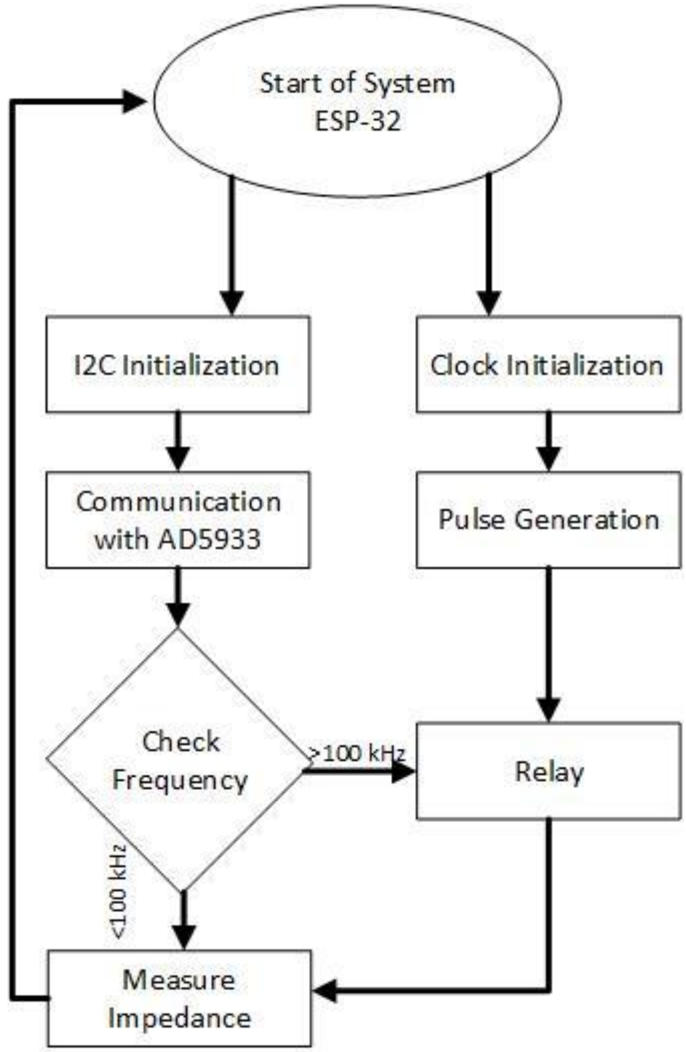

Figure 2.3. Role of ESP-32 in this Project

Relay has also been used in this project as well. Solid state relay has been used in this project for the switching purposes, as there are two signals that are inputs in our case. In order to switch, between the two frequencies a switching mechanism is required. While choosing the relay following points are taken into the considerations. With the flow chart shown above the role of relays in this project can becomes easier to understand.

AD5933 is basically an impedance converter with the help of which we can find out the impedance of different components and materials with different frequency variations.

There are other different ICs and circuits which can do the same task, like ADuCM350 and IM3570. There are different advantages of this board due to which it has been chosen for this project.

The advantages of using this AD5933 board are as follows.

- It is high precision converter, and its range lies in the area where many components' impedance lies.
- It has a 12-bit ADC with the help of which it can give precise impedance conversion in different frequency swept points.
- This board has the property to give impedance of the components and materials with exciting known frequency ranges.
- It requires very simple and easy circuit for calibration rather than complex circuitry as observed in other devices which are used for impedance measurement.

A block diagram on the role of AD5933 in this project is as follows

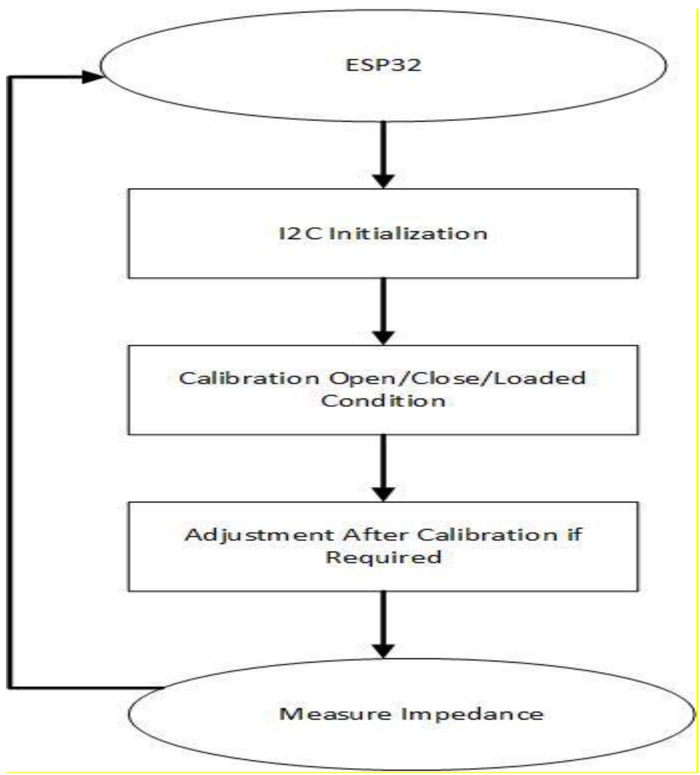

Figure 2.4. Block Diagram of Working of AD5933 with ESP32

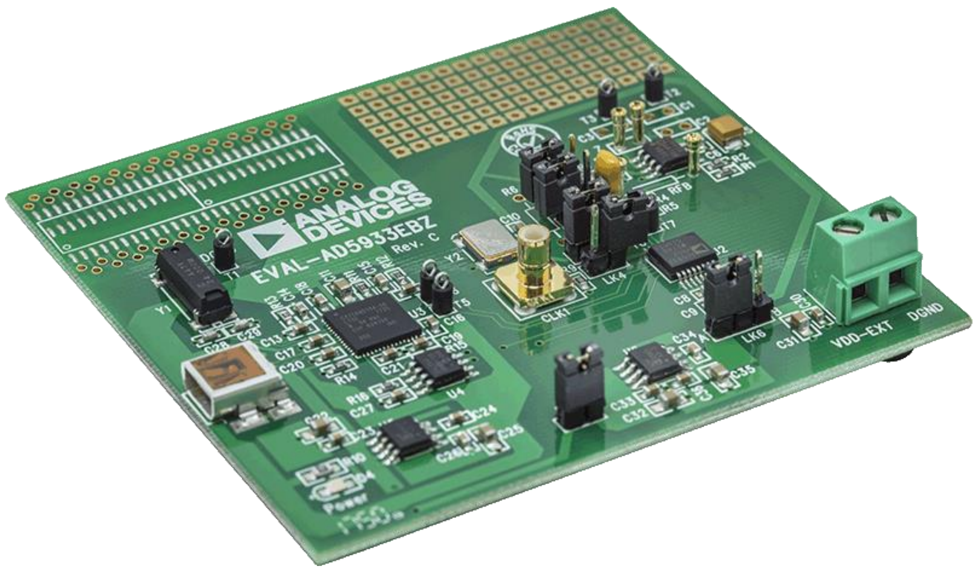

Figure 2.5. AD 5933 evaluation Board [53]

2.3 Block Diagram

While working with project, block diagram is one of the most important parts. This gives reader a clearer idea what has been developed in the project. A simple block diagram has developed for this project as well which defines the communication, roles of different components in a single frame. Following is the block diagram for this project after that explanation has been shown.

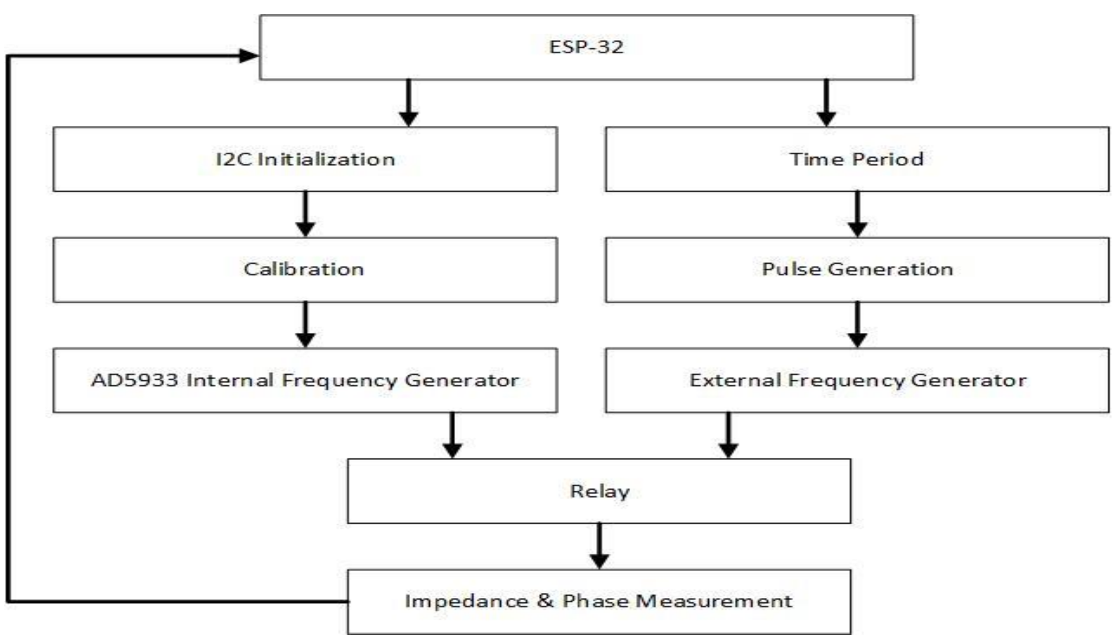

Figure 2.6. Block Diagram for Functionality of Proposed Impedance Analyzer

In the above figure block diagram of this project has been shown. The role of each component along with their communication protocols has been discussed as follows.

- Microcontroller is used here in order to operate the project. It is obviously the brain of the project which is coded. Due to this coding, it has the ability to control all the components of the project.
- The controller has been communicated with AD-5933 which is impedance analyzer's module using I^2C communication, so that the two-way communication can be initiated.
- The reason behind the two-way communication is because the controller not only gives commands to the AD-5933 but also obtain results from it.
- The obtained results are thus displayed on touch screen display using UART communication.
- The relay and the feedback circuit can also see in the block diagram as there are multiple input frequencies initiated and in order to keep these frequencies intact from each other.

Architecture of each and every component is shown as follows. This will gives more clearer and better view.

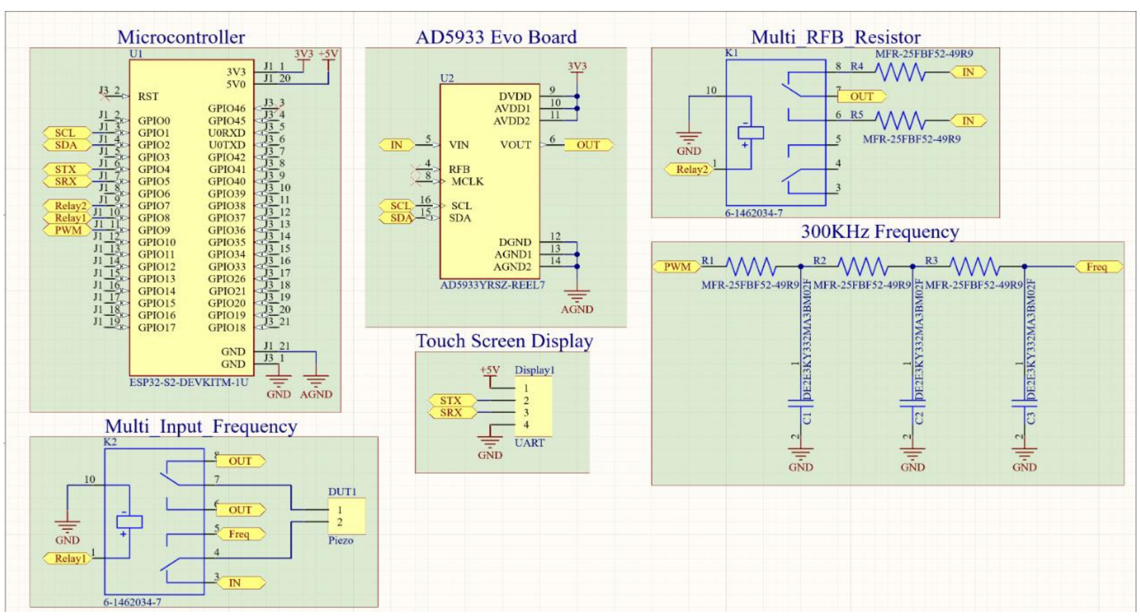

Figure 2.7. Components Configuration

2.4 Calibration Technique for this Project

For AD-5933 there are three types of calibrations have been required to initiate a project. A brief description of each type is shown as follows.

- For **Open Circuit Calibration,** Vin and Vout terminals on Ad5933 have kept open and then the impedance or in simple words resistance has been measured and this value will be subtracted when you have to measure the load resistance of the component under observation. For ideal condition the resistance in this case should have been infinite, but practically 10MΩ is enough.
- For **Short Circuit Calibration,** Vin and Vout terminals are kept short together and then the impedance is measured. This impedance is then again subtracted from the impedance that you have to measured for the component which is under observation. This impedance will be in the range of 100s while for the ideal case this impedance should be zero.
- For **Load Calibration,** a known load has been placed between Vin and V out. And then gain factor is calculated for system's impedance which is under observation.

Chapter 3: Impedance Data Acquisition

The main and most prominent goal of this thesis is to acquire data from our system. As discussed earlier in the previous chapters the importance of impedance and its phase while working on piezoelectric devices. In this chapter, a detailed discussion of how data can be acquired from this system has been discussed. The data has been acquired using the device that has been developed for this thesis and is compared with different standardized equipment available in different Research Laboratories in Pakistan. The data acquired from the device we have fabricated for this thesis has been compared with the different other available devices as well. These different models of impedance analyzer or network analyzers have been discussed in the later subsections. Following are the names of these instruments enlisted.

1. SSA3021X (Network Analyzer)
2. TH2829C (Precision LCR Meter)
3. Self-developed Impedance Analyzer (Developed for this thesis)

A brief discussion of results obtained from these instruments has been shown in the following subsections.

3.1 SSA 3021X Network Analyzer

The most important point in acquiring data from a newly fabricated device is to measure the data from an already calibrated device and to compare those results from the device that has been developed. In this way, a complete scenario can build up with the help of which one can obtain the accuracy of the system. For this purpose, the data has been tested on SSA 3021X network analyzer which is available at the University of Lahore's (UOL) Lab. This equipment has the following salient features.

- The frequency range of SSA3021X is 9.1kHz to 2.1GHz which is a very high range while considering the nature of piezoelectric material or small electronic components.
- The resolution bandwidth for this device is also very high. Its resolution lies in the range of Hz due to this nature it has high accuracy and gives better results.

- This device can only give an impedance graph. In other words, we have an only magnitude of impedance, with the help of which we can determine resonance and anti-resonance points of components.

3.1.1 Data Acquired from SSA 3021X

Data that has been acquired using this device is very simple. This device has BNC connectors attached same as some conventional oscilloscopes. The wires that have been attached with the BNC connectors have two clips with the help of which the data can be shown on the screen. This data can be saved in the form of an excel file having some data points at different frequency levels. This data can, later on, be fabricated in the form of graphs, and resonance and anti-resonant points can be obtained thereafter.
The data obtained from this device is shown in the following figures. The explanation of the data is given at the end, after the figures.

3.2 TH2829C (Precision LCR Meter)

The data has also been validated using a precision LCR Meter having model number TH2829C available at UET Lahore, Punjab, Pakistan. The reason behind using this LCR meter is to validate our results with this device to obtain accuracy and precision. This device has some additional features which are why this device has been selected for validation. These features are as follows.

- This device has a range of 1MHz, which is lower as compared to the last one but the main feature that fascinates researchers are its resolution which is in the range of mHz. This range can be very beneficial while working with piezoelectric materials or other electronic components.
- It has a 7-inch LED display which shows better results. This device not only gives real-time graphs for impedance but also tables corresponding to each frequency step.
- There are certain drawbacks as well like it can only measure 200 step size in one reading as the technology is very old.
- This device can also give results while we change temperatures and on each temperature step.

- The data can be acquired using different ports. These options are GPIB, RS232, USB, and LAN Cable.

3.2.1 Data Acquired from TH2829C

The data has been recorded in the form of a CSV file on a USB. The data has only **201** swept points which means the total range of frequency has been divided into 200 step sizes. This device has the ability to not only provide impedance magnitude but also its phase angle as well.

On this device a piezoelectric disk having 50mm dia has been used to measure impedance and phase graphs. This piezoelectric material having model number PZT-5H having following properties shown in the table.

Figure 3.1. Piezoelectric Disk with 50mm diameter

Table 3.1. Internal Properties of PZT-5H

Property	**Units**	**Value**
Young's Modulus	GPa	83 ± 10
Poisson Ratio	N/A	0.31
Curie Point	°C	195
Q_E	N/A	40
K^T_{33}	N/A	3400
K^T_{11}	N/A	3130

The results that have been obtained by using the above-mentioned device has been shown in the following figures.

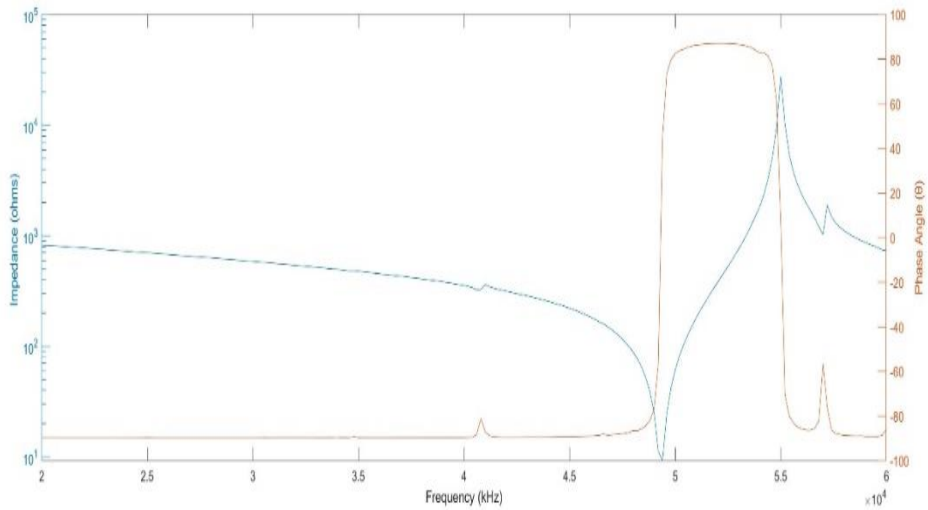

Figure 3.2. Impedance and Phase Graph of 50mm Piezoelectric Disk (PZT-5H)

From the figure that has been shown above, we have observed that there are two data sets available one is impedance shown with blue color and the other one is phase angle graph shown with orange lines in the graph. The bottom axis, i.e., the x-axis has been labeled with the frequency. The frequency that has been set on TH2829C is from the range of 20kHz to 60kHz for this experiment and as observed from the figure as well. From the figure, we can conclude that approximately there is a resonance point at 48kHz and at 56kHZ there is an anti-resonance point. There is another point after the first mode has been shown. This is the second mode of resonance which is shown here. This second mode has again resonance and anti-resonance points as well.

3.3 WB 6500B Impedance Analyzer

This impedance analyzer is available at SCME, NUST. At this impedance analyzer we have obtained the impedance and phase graph for BLT Transducers. The figure of BLT along with its impedance and phase graph is shown in following figures.

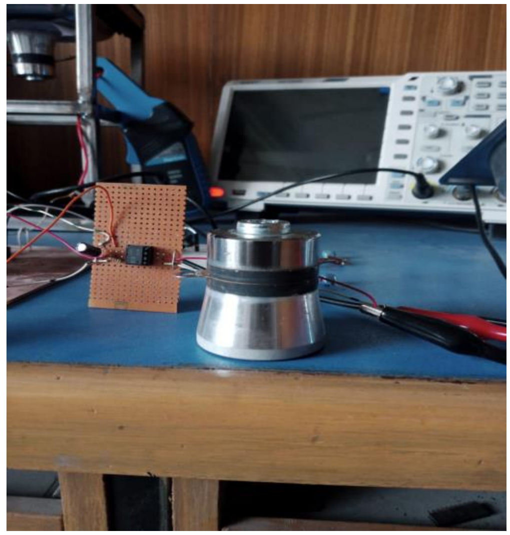

Figure 3.3. BLT Transducer

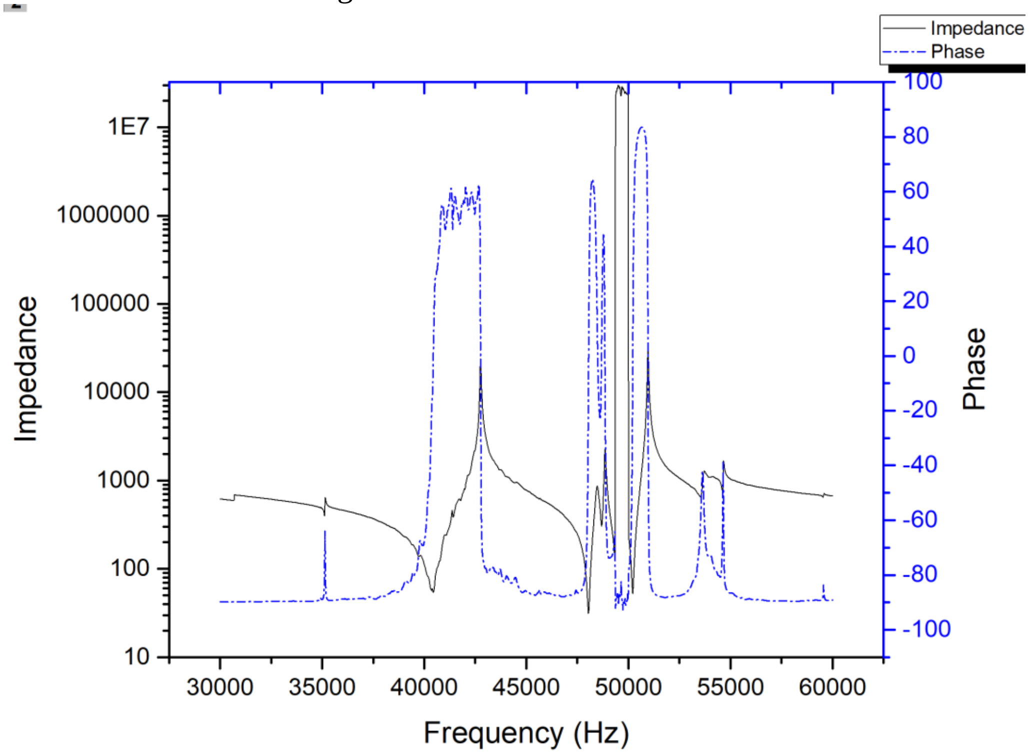

Figure 3.4. Impedance and Phase graph of BLT Transducer

3.4 Self-Developed Impedance Analyzer

The most important section of this thesis. The results of this device have been discussed in this subsection. There are a few observations that should have been discussed before going forward. These observations have been enlisted as follows.

- This device has a range of 10MHz. it gives accurate results when a piezoelectric device or a buzzer has been tested with the range of about 300kHz. The range of AD5933 is 1kHz – 100kHz, so the range of measurement is enhanced in this thesis. When we test electronic components like capacitors, inductors, resistors, etc. with this fabricated device the accuracy has increased up to the range of **MHz**.
- This device can provide a low-cost solution for measuring impedance for piezoelectric devices as compared to other expensive instruments.
- This device is easy to use and simple as with the help of this device one can only measure impedance. As all the other devices have other different functionalities as well which make them complex to use.
- Due to its small size one can lift the setup easily and can do the measurements relatively easier as compared to the other giant systems associated with such experiments.
- The device is able to generate the equivalent circuit of piezoelectric materials.
- It can create a database of the piezoelectric material
- It compares the acquired impedance data with the simulated one to find fault and performance.

3.4.1 Data Acquired from Self Developed Impedance Analyzer

The data acquired from this device is discussed here. With the help of this device which has been fabricated/developed for this project gives only graph of impedance both magnitude of impedance and its phase. This means we can only obtain multiple resonance data (one resonance data contain two important points, the resonance points and the other one is anti-resonance point).

Following is the graph of impedance with respect to different frequency level has shown. One thing must have observed here that this data has 89 percent accuracy when compared with the standard impedance analyzer.

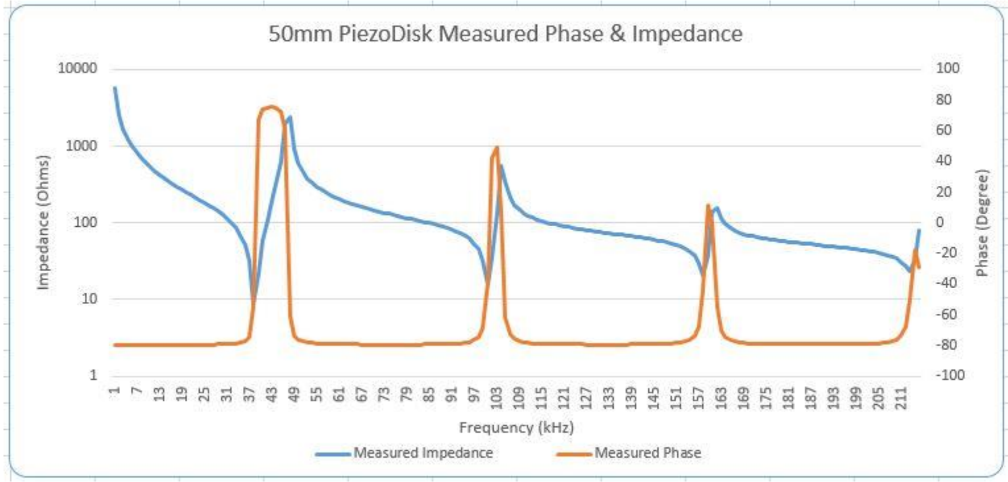

Figure 3.5. Impedance and Phase Graph of 50mm PZT Disk

3.5 Simulation Results

The results of the similar 50mm disk on COMSOL Multiphysics has been shown as follows. The impedance and phase graph of a piezoelectric disk with the properties shown in the previous tables are discussed here. It is important to discuss the equations associated with impedance and phase which are required while working with COMSOL Multiphysics.

3.5.1 Equations associated with Impedance and Phase

There are different equations which are associated with COMSOL Multiphysics here the two main equations for impedance and phase are discussed below respectively.

$$|z| = \frac{1}{abs\,(es.Y11)} \theta = -atan2(imag(es.Y11), real(es.Y11)) \qquad (1)$$

Where es.Y11 is the admittance of the system on the basis of which the COMSOL processed all the simulations.

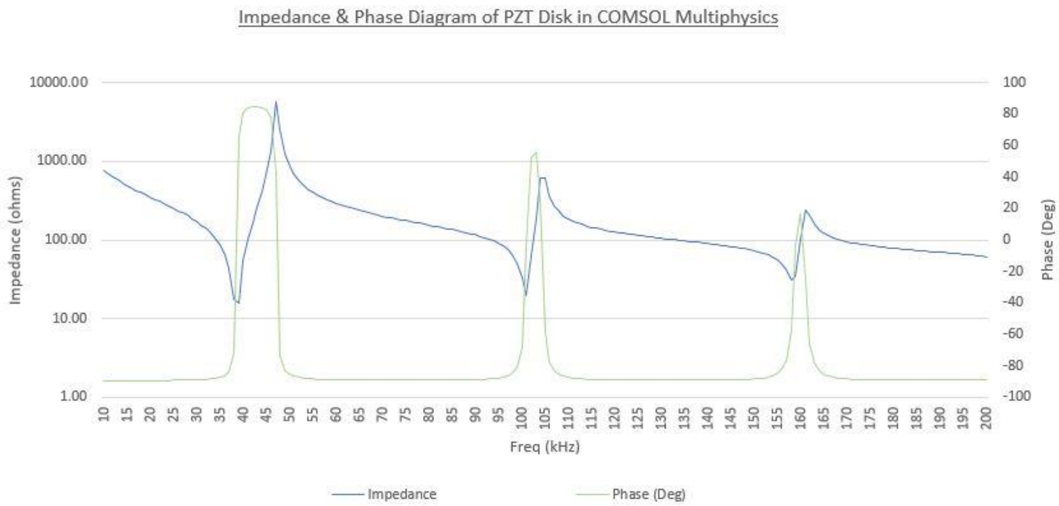

Figure 3.6. Impedance and Phase graph of 50mm PZT Disk

3.6 Impedance Obtained from Proposed Impedance Analyzer

The most important of this thesis is the results obtained from the developed device. Following is the figure shown, showing impedance of the proposed impedance analyzer. This impedance is obtained from the 50mm piezoelectric disk, which is simulated, and the data has already been obtained from other impedance analyzers and precision LCR meters.

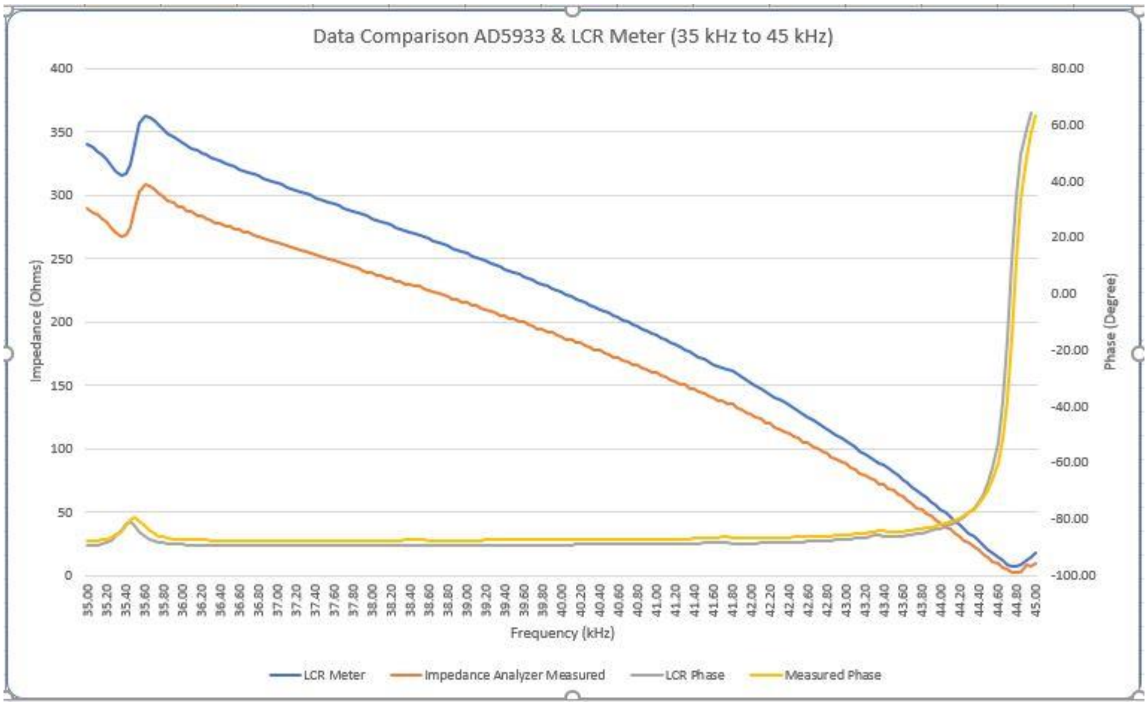

Figure 3.7. Results obtained from proposed Impedance Analyzer with (35kHz - 45 kHz)

From the figure shown above it is clear that the resonance frequency of PZT 50mm disk is almost 35.5kHz whereas anti resonance point occurs at 35kHz. The simulated results show the same results at 38 and 40kHz respectively. So, there is a small difference between both the values, and we can say that these results are 90 percent accurate.

3.6.1 Comparison of Results

Different results have been obtained from the proposed impedance analyzer and the same data has been acquired from the standard LCR meter TH2829C. In figure 3.8 a comparison between 35- 45kHz has been shown. In the same way another experiment's comparison has been shown as follows. For this experiment the frequency has been set from 25 kHz to 38 kHz and compare it with standard LCR meter TH 2829C. the graph has shown that a very little inaccuracy is present in the data.

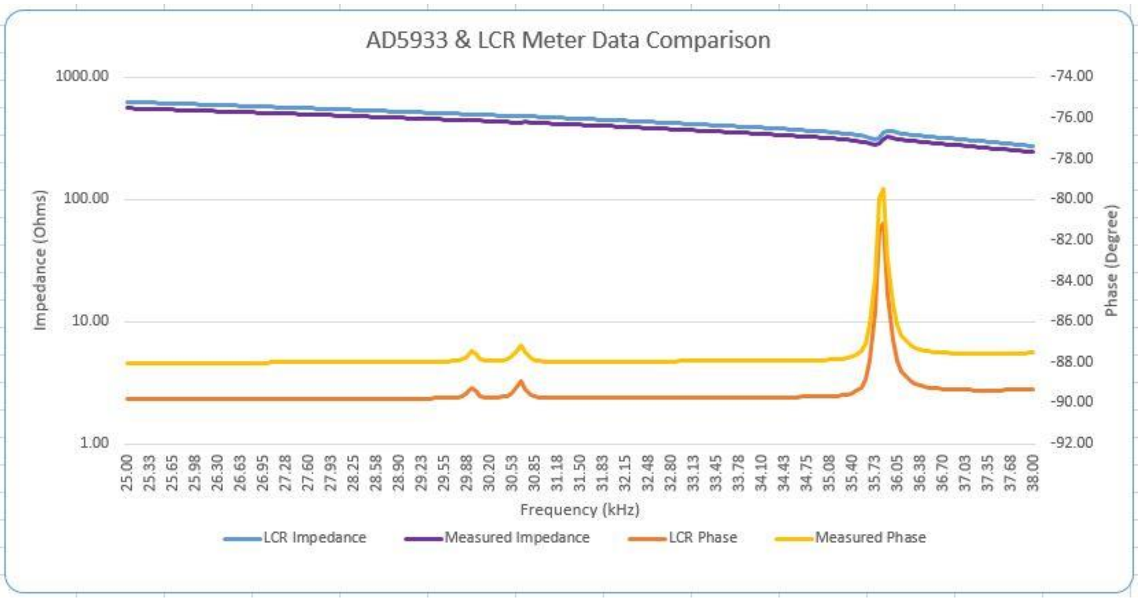

Figure 3.8. Comparison of AD 5933 and LCR meter Data from 25 - 38kHz

Chapter 4: Equivalent Circuit Model For Piezoelectric Disks

Scientists and researchers that have been working with piezoelectric discs and materials are very keen to learn about the equivalent circuit model of these materials. By having equivalent circuit models of these materials, it can make calculations and numerical evaluation easy. By having these numerical data, it becomes easy to obtain and validate data from any impedance analyzer, and precision LCR meter.

4.1 Importance of Equivalent Circuit Model

By having an equivalent circuit model of a device, mechanism, or project it becomes easy to find out the operational characterization that happens inside a mechanism. With the help of an equivalent circuit model, the operation inside a battery can be calculated numerically and the researchers or mathematicians can perform assumptions based on these models. There are different kinds of equivalent circuits that have been studied in early and basic electronics. By converting a mechanical model into an electrical model or electrical equivalent circuit it becomes easy in calculate and make assumptions. The equivalent circuit model of different piezoelectric materials has been shown in the earlier sections as well. In this section, their importance will be discussed. Following are the reasons why equivalent circuit models are important in the calculations related to piezoelectric materials.

- Equivalent circuit models help the readers to understand better the inside situation of a mechanical or material device. In this way, one can predict the behavior of teg mechanical model.
- With the help of equivalent circuits, the model has been divided into simple circuit elements like inductors, resistors, and capacitors. In this way, it becomes easy to understand the inputs, outputs, and internal behavior of the system which is under the observation of the user.
- As discussed in the earlier sections, the piezoelectric materials exhibit transient behavior both in direct piezoelectric and indirect piezoelectric effects. So, it becomes easy to understand them on the basis of simple electronic circuitry.

- By having all the related circuit models, one can design the circuitry which is required to run the piezoelectric disks. For example, in the case where these are used to generate energy at different frequency levels, here equivalent circuit models, help the researcher to make the circuitry with the help of which the piezoelectric material work with its full efficiency like working in resonance mode.

4.2 Equivalent Circuit Models for Different Materials

In the field of materials, mechanical, and electrical there is a need to convert mechanical models into electrical so that the calculations have become easy. For that purpose, different equivalent circuit models are presented here which shows different equivalent models for different materials.

4.2.1 Equivalent Model for PZT

PZT is a very well-known piezoelectric material and is used in many applications. The equivalent circuit model for that material is shown in the following figure. The main concept associated with this circuit are basically two frequencies. The series resonance frequency, which is fs, is obtained by LC branch shown in the figure. Whereas the other frequency fp which is obtained from the resistive or the impedance of the complete model.

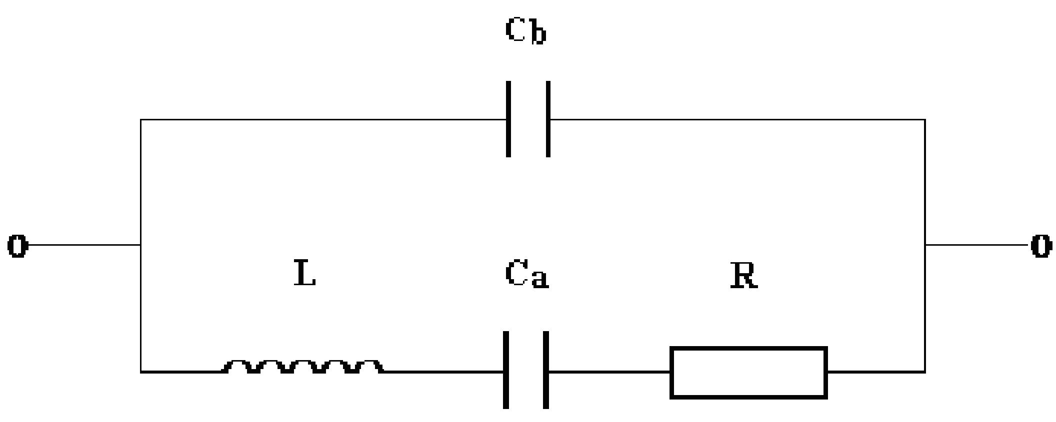

Figure 4.1. Equivalent Circuit Model for PZT

4.2.2 Equivalent Circuit Model for PVDF

An important piezoelectric ceramic can also be converted into equivalent circuit's model. Following figure shows the equivalent circuit model for PVDF ceramic.

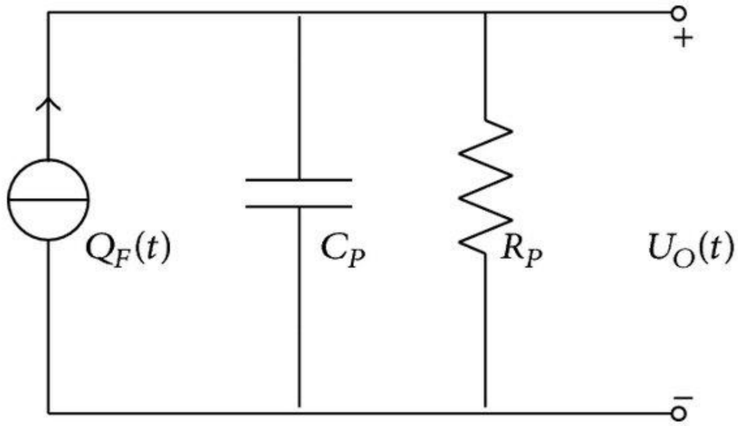

Figure 4.2. Equivalent Circuit Model for PVDF Ceramic

Chapter 5: Crack And Defect Detection

There are some piezoelectric materials that are very sensitive in nature i.e., their properties can be changed when there is a change in temperature, pressure, or any external environmental condition. Due to these small changes in properties and if these properties last longer, they can harm the internal important properties of piezoelectric material. Having flaws in these internal properties results in a change in the performance of piezoelectric materials. So, there should have been a proper mechanism with the help of which one can test these cracks and defects of piezoelectric materials. In this section we will discuss the crack and defect detection related to piezoelectric materials, what is their importance keeping in mind the performance of piezoelectric material, and how our device helps to find out the crack and defects in the materials by calculating the impedance of the materials.

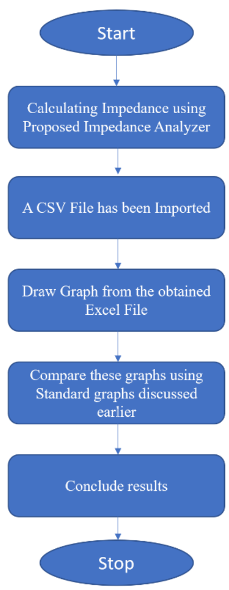

Figure 5.1. Block Diagram for Defect Detection

5.1. Importance of Crack and Defect Detection

One of the most important parts when we are dealing with piezoelectric materials, cracks and defects must be considered in order to calculate or assume any approximation while working on the performance of the piezoelectric materials. There are a very few impedance analyzers that can provide us the data about the crack and defect detection otherwise one has to observe manually from the impedance or phase graph of the material and compare it with the standard one. The impedance and phase graph can be disturbed by a big value when there is any crack or defect has been present in the piezoelectric material. There are many important points with the help of which one can understand why the crack and defect detection in piezoelectric materials are important, these points are as follows.

- During the piezoelectric material fabrications, there are many processes involved. A lot of research, and time has spent to develop a single piezoelectric disk or a stack. As there are many processes involved in the development and fabrication of piezoelectric materials, so there is a possibility of cracks and defects when the scientists who are operating these processes are new to this field. So, a proper device is required which can detect such defect and cracks so that the process can be done better before developing a whole piezoelectric material. So, a low-cost impedance analyzer, if it can detect cracks and other defects it will become easy and reliable for the researchers to develop piezoelectric materials flawlessly.
- By operating piezoelectric disks continuously like that in the case of sonicators (ultrasonic cleaners), the disk may have wear and tear so in order to test such devices we can use this low-cost impedance analyzer to detect any defect or cracks in the materials.
- By finding these defects or cracks one can replace these disks so that the systems in which piezoelectric materials are serving don’t break out when the defects or the cracks become extremely which may have an effect on the performance of the whole system.
- There are electrodes in the piezoelectric disks usually mounted at the top and the bottom surface of the materials. There is a possibility of a flaw that these electrodes may wear out so for detecting those flaws impedance analyzers can also be used.

5.2. Cracks and Defects Nature by observing Impedance Graph

As the impedance analyzer gives the graph of impedance and phase. Here the impedance is simply the magnitude and for the direction nature of the piezoelectric phase graph has been used. By observing these graphs, we can conclude different results by the nature of the graphs. There is the following kind of graphs obtained and we can take different results from them.

From all the details and discussion shown above it is proved that how can we detect different defects and cracks by using simple impedance analyzer, precision LCR meter or even simple Digital Signal Analyzer. As discussed in the earlier chapters such impedance graphs can also be obtained from the low-cost impedance analyzer which has been developed for this thesis. So, by observing the graphs from this low cost impedance analyzer we can conclude that defects and cracks can also be detected by using this device. This device can be very useful for such labs where people are working on piezoelectric fabrications, this will save time and work of the worker as well.

5.3. Impedance and Phase Graphs

As discussed in the earlier sections, a specimen of a 50mm dia piezoelectric disk has been under observation throughout. There are different experiments performed on the disk some of them are as follows.

5.3.1. Experiment # 1 (35-45kHz applied on 50mm PZT Disk)

First of all, an experiment has been performed on 50mm dia disk and the frequency range has been set from 35-45 kHz as shown in the following figure.

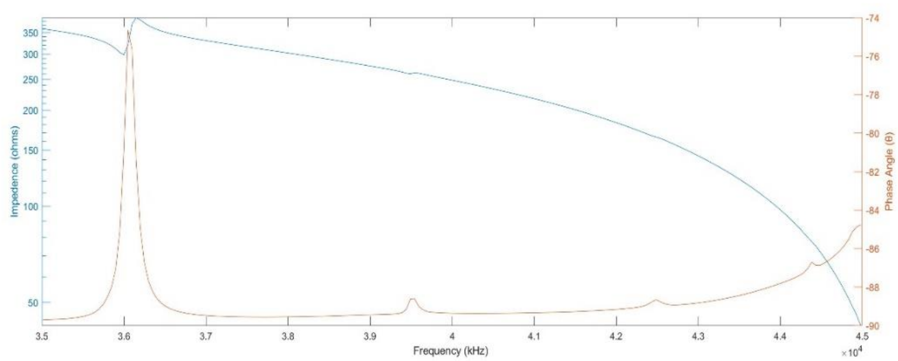

Figure 5.2. Impedance and Phase graph of PZT (50mm disk) frequency ranges from 35-45 kHz

In this experiment a disk of PZT having 50mm diameter has been under observation. From the graph shown above one can observe a peak at 36 kHz which is its first resonance point.

After that there is a small peak at between 39-40 kHz which is not an abnormality in this case, as it is second resonance point.

5.3.2. Experiment # 2 (24-38 kHz applied on 50mm Piezo Disk)

After that another experiment has been performed with a frequency range between 24-38kHz. The impedance and phase graph for that particular experiment is shown as follows.

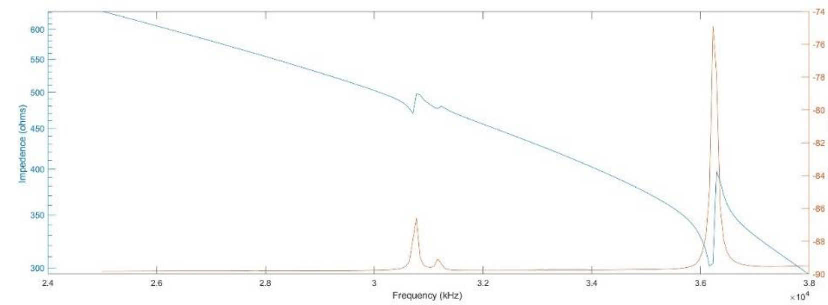

Figure 5.3. Impedance and Phase graph of PZT (50mm disk) frequency ranges from 24-38 kHz

From the figure shown above, the experiment has to be performed in order to find abnormality in the graph. As observed that there are some abnormalities at 31kHz. This abnormality is not a defect, on the basis of which the researcher should be worried as this is due to soldering or may be due to position of electrode on the disk.

5.3.3. Experiment # 3 (20- 60 kHz applied on 50mm PZT Disk)

For the third time, the frequency range has been set from 20-60 kHz. The impedance and phase diagram for that particular experiment has been shown as follows.

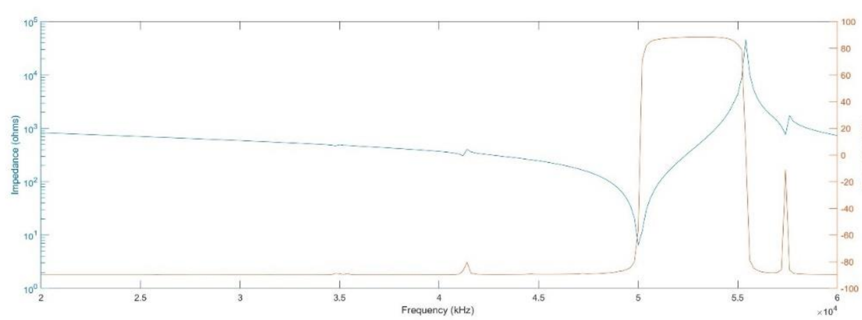

Figure 5.4. Impedance and Phase graph of PZT (50mm disk) frequency ranges from 20-60 kHz

From the above figure, we have observed that there is a resonance peak at 50 kHz and an anti-resonance peak at 55kHz. So, all the previous observations that this disk has a resonance frequency at around 35kHz can now be excluded from our observation. That peaks are the abnormalities which occurs due to soldering issues, or wires internal impedance, or other losses.

5.3.4. Experiment # 4 (1 uF Capacitor's Impedance Measurement)

In this experiment, a 1uF capacitor has been used and its impedance has been measured. The impedance graph obtained from the capacitor's impedance is as follows. From the graph we have observed that on increasing the frequency the impedance get to its lowest drastically.

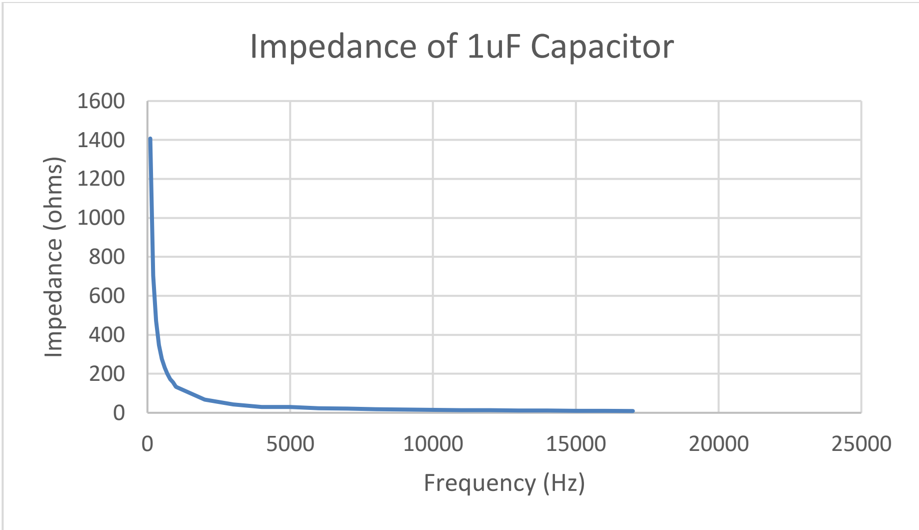

Figure 5.5. Impedance Graph of 1uF Capacitor

5.3.5. Experiment # 5 (Resistor's Impedance Measurement)

In this experiment Impedance of a resistor has been measured at different frequencies. The impedance graph of the resistor has been shown as follows.

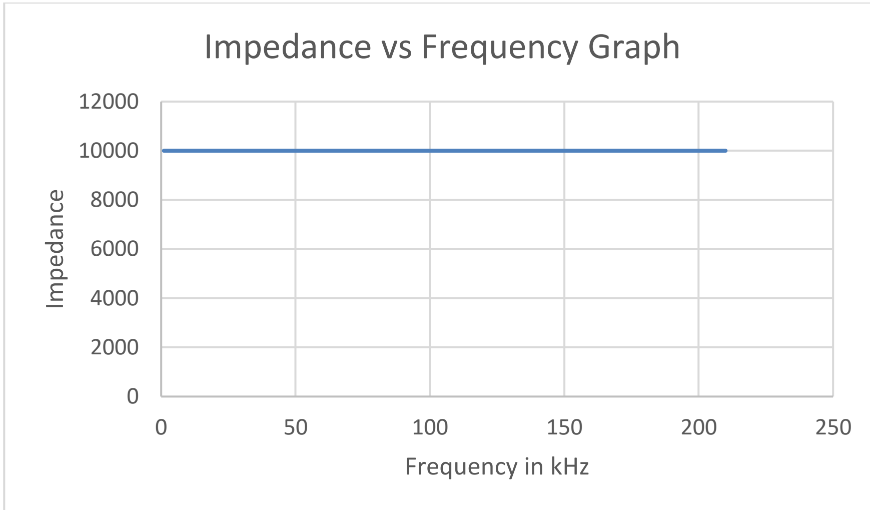

Figure 5.6. Impedance of 10kohm Resistor

From the figure shown above, the impedance of 10kohm resistor is shown. We have observed that it is a straight line as the impedance of the resistor does not depend on the change in frequency.

5.3.6. Experiment # 6 (30mm Defected PZT Disk's Impedance Measurement)

Another experiment has been performed which shown the defects in the piezoelectric materials. For this experiment, a cracked piezoelectric disk has been kept under observation and its related impedance graphs has been obtained.

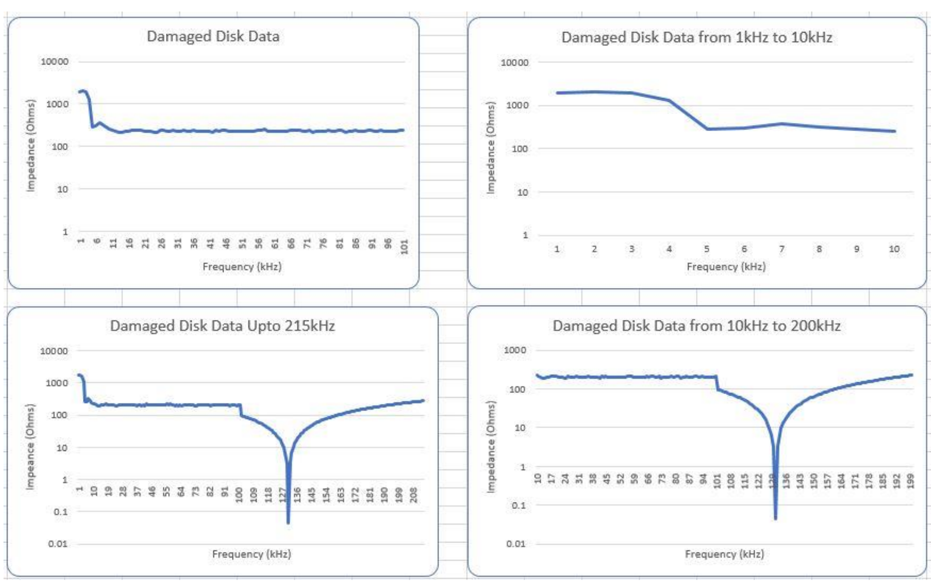

Figure 5.7. Impedance Graph of a 30mm Defected Disk obtained from Proposed Impedance Analyzer

5.3.7. Experiment # 7 (150 pF Capacitor's Impedance Measurement)

A 150-pF capacitor has been used for this experiment and its impedance has been measured. The result of this capacitor is shown as follows. The frequency has been set up to 300 kHz and is supplied by the external frequency generator that has been designed for this thesis.

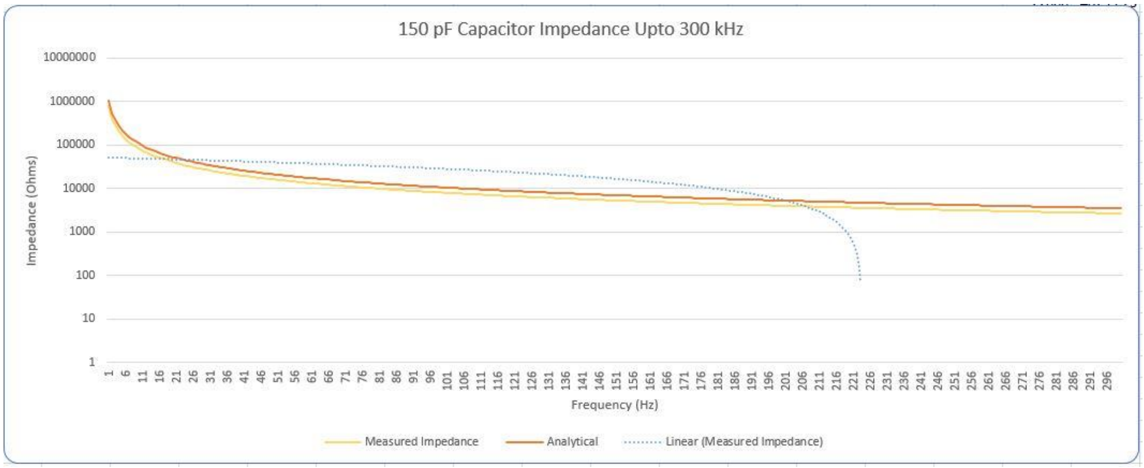

Figure 5.8. A 150 pF Capacitor's Impedance Measured from Proposed Impedance Analyzer and its comparison with Analytical value.

5.3.8. Experiment # 8 (15.4 kohms resistor's Impedance Measurement)

For this experiment a resistor has been kept under observation in the proposed impedance analyzer. The following graph has been obtained.

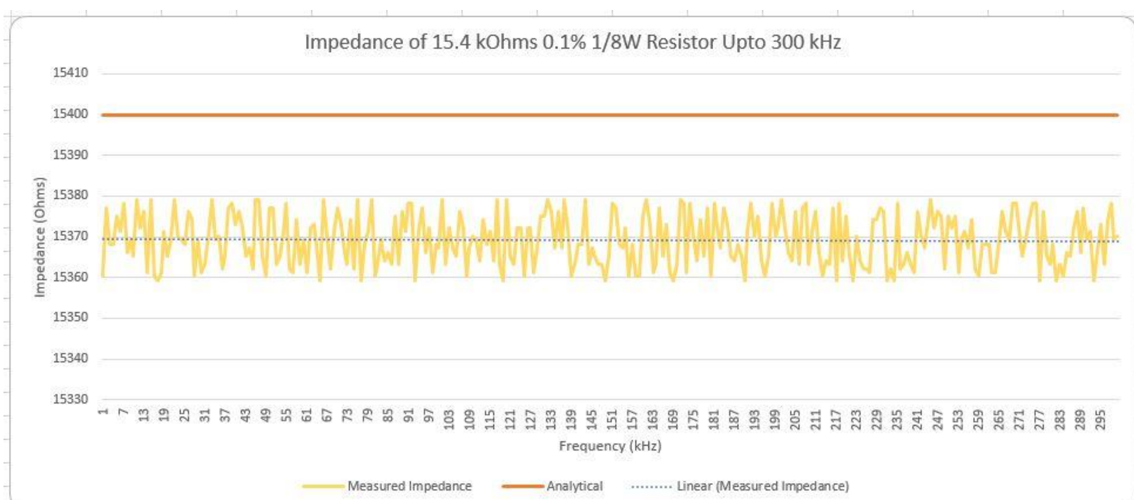

Figure 5.9. Impedance of 15.4 kOhms Resistor

Chapter 6: Data Logging And Defect Detection Using AI

Using the state-of-the art IoT and Artificial intelligence techniques, we can make a data log of piezoelectric materials and devices in production. By applying the AI techniques of the data, we can identify the problems in the manufacturing process and item.

6.1 Artificial Intelligence in Low-Cost Impedance Analyzer

Artificial intelligence is another important part in this project. The system with the help of microcontroller can make decision on the basis of which accuracy and precision of the system will be determined. The artificial intelligence that has been used in this project will be explained in this section. The system will first calculate capacitance, resistance, and inductance of the material and on the basis of which the system will give the impedance of the under observed material. The system based on the following decision tree can take a decision and shows us the impedance. This impedance is the calculated impedance not the measured as discussed in the earlier sections.

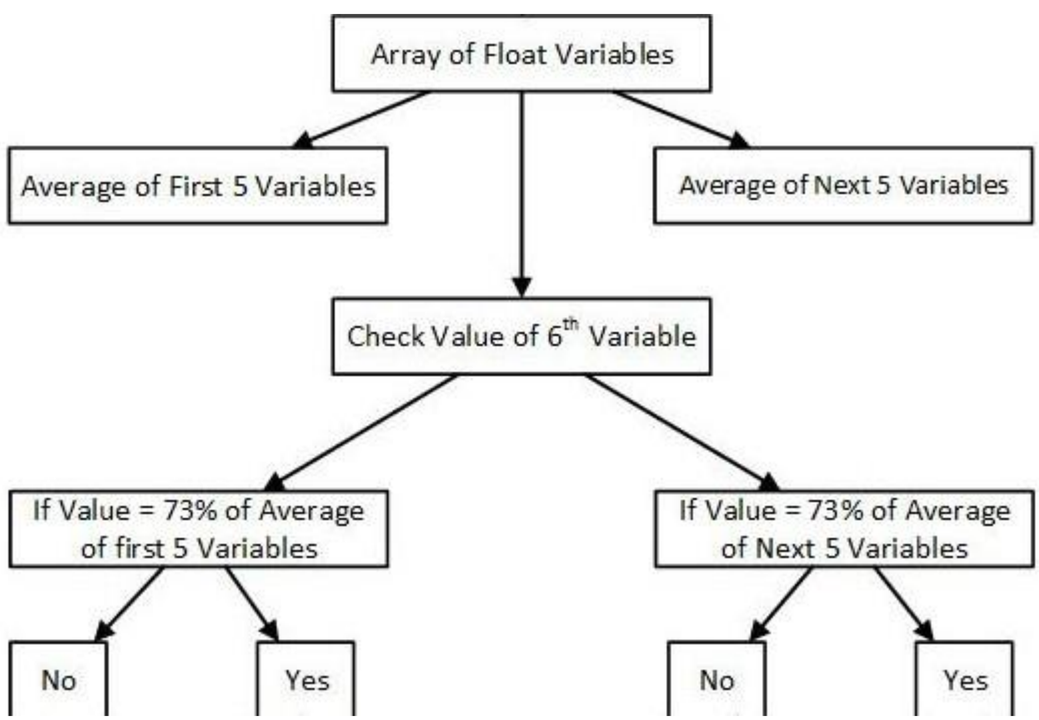

Figure 6.1. Decision Tree Based on which Low-cost Impedance Analyzer can make decisions.

The decision taken by the system is by considering all the inputs like diameter of the disk, thickness of the disk and different resonance modes of the piezoelectric material which is under observation. On the basis of these inputs and individual resistance and capacitance, the system will formulate the data with the help of which of accuracy can be defined and little manipulation, if possible, can be done in the data so that the results can be more accurate and closer to the actual theoretical data.

A decision tree was implemented on the system in which it first takes the input from user regarding device under test and then start the system, an array of 600 variables were made and then each reading obtained is then predicted with the next and previous 5 readings of the system with the accuracy of 89% and 73% with the accuracy with AD5933 and with external frequency generator, respectively.

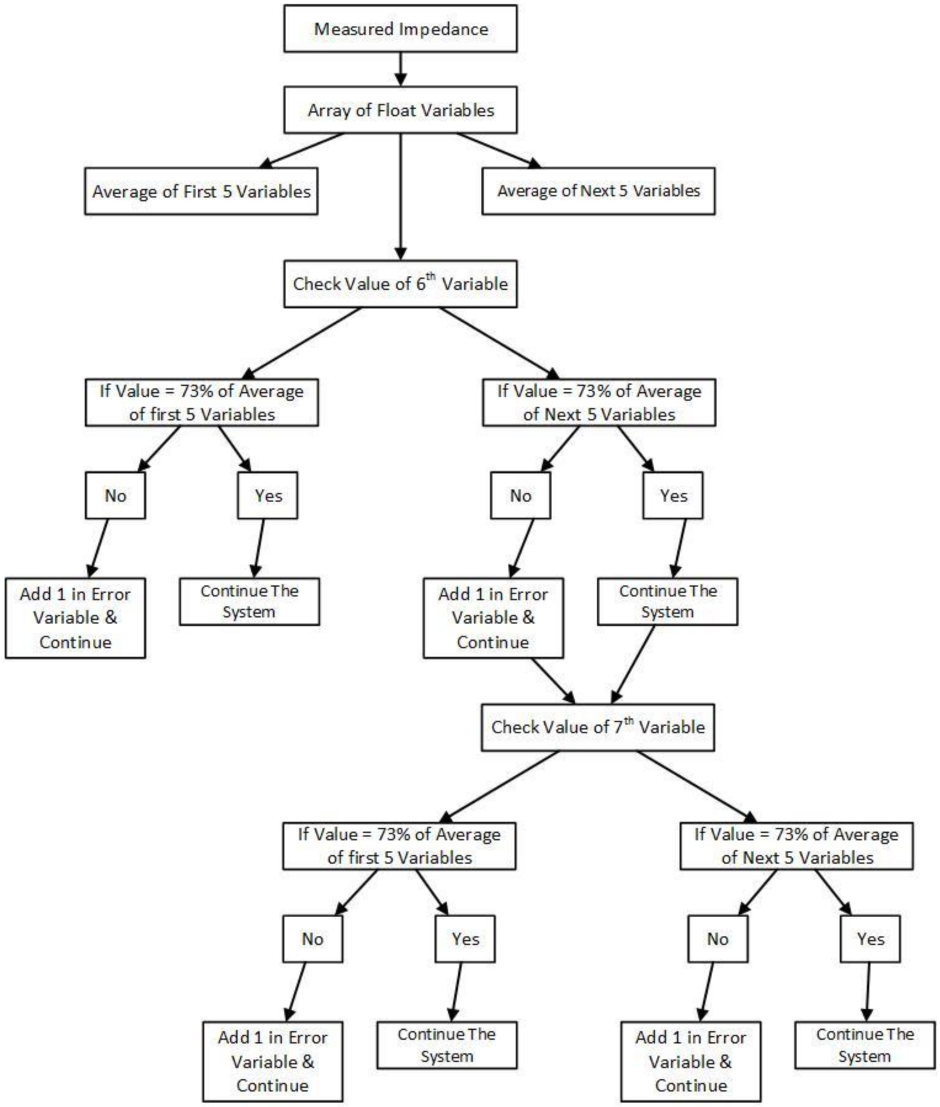

Figure 6.2. Decision Tree Proposed for this Thesis

6.2 IoT in Low-Cost Impedance Analyzer

Data Logging is an important factor when it comes to engineering works. for this low-cost impedance analyzer one can also add IoT with the help of which all the data can be stored on the cloud and can be observed and reached by the group of researcher whenever they want. By adding IoT, we can mark different check and AI based algorithms also on the basis of which the cloud can take smart decisions and can inform the user about the situation of the material under observation. To include IoT in this impedance analyzer we can have following advantages.

- If a layman working with this impedance analyzer and if this device broke out or give false results on the basis of AI, the machine can turned off or give signal to the concerned authorities to take precautionary steps before the machine completely broke out.
- With the help of IoT, we can also acquire all the data with storing capabilities on clous so that the data can be used and later on can be worked on when required.
- While having IoT with such devices these devices can work better as different AI algorithms works along with such clouds, so the work becomes easy.

Conclusion

As already stated, the goal of this thesis was to design a cost-effective Impedance analyzer with maximum features. Impedance analyzer, that has been developed has a frequency range of 1kHZ-300kHz. The cost of this impedance analyzer is about to 60 dollars as compared to other analyzers available in the market that cost hundreds of dollars to the end-user. This would help researchers and students to work efficiently without having to stress upon the cost.

Another interesting thing about this analyzer is its small size. Its smaller size makes it mobile, and the person could carry it without any hassle. Apart from impedance, this device gives us the phase as well which is quite rare compared to the other products. Temperature controlled impedance data can be taken from this device as well. This would increase the overall efficiency and results that need to extract from the device.

Piezoelectric materials may have some defects in them. By using this device, those defects can be found by analyzing the impedance graphs being taken during the experimentation. This would save a lot of time and will result in increased performance.

Furthermore, this device can give us equivalent circuit models as well. With the help of these equivalent circuit models, we can develop our own circuitry at the back end. This will help in understanding the systems more efficaciously. It can also come handy inn future research as well.

This system is designed in such a way that it can be made a smart device by implementing IoT. The data can be logged to a cloud and then used for different analysis. Apart from this, Artificial Intelligence algorithms can also be implemented. This implementation would result in generating a sort of warning signal or data before the device breaks down so that necessary actions could be taken accordingly.

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Completion Certificate

It is certified that the thesis titled "***A Low Cost Impedance Analyzer for Fault Detection in Piezoelectric Materials***" submitted by CMS ID. 00000277529, NS Syed Muhammad Hassan Maqsood of MS-2018, Mechatronics Engineering is complete in all respects as per the requirements of Main Office, NUST (Exam branch).

Supervisor: ___________________

Dr. Hamid Jabbar

Date: ____ August 2022

Thesis Acceptance Certificate

Certified that final copy of MS thesis written by Mr. Syed Muhammad Hassan Maqsood, (Registration No. 0000277529), of College of Electrical and Mechanical Engineering has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is within the similarity indices limit and is accepted as partial fulfillment for the award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature: ______________________________

Name of Supervisor Dr. Hamid Jabbar

Date: ________________________

Signature (HoD): ________________________

Date: ____________________________________

Signature (Dean/Principal): __________________

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