Design Calculator and Performance Analyzer Software Tool for Step-down Piezoelectric Transformer

MUHAMMAD ABBAS
00000238342
Supervised by
Dr. HAMID JABBAR

DEPARTMENT OF MECHATRONICS ENGINEERING
COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY
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MUHAMMAD ABBAS
00000238342
A thesis submitted in partial fulfillment of the requirements for the degree of
MS Mechanical Engineering

Thesis Supervisor:
Dr. HAMID JABBAR

Thesis Supervisor's Signature:____

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I certify that this research work titled "*Design Calculator and Performance Analyzer Software Tool for Step-down Piezoelectric Transformer*" 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 to.

Muhammad Abbas
00000238342

Language Correctness Certificate

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

MUHAMMAD ABBAS
00000238342

Signature of Supervisor

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I would like to thank my parents for their love, support and prayers. I would also like to thank my sister who always encouraged me and motivated me in my hard times.

Dedicated to my parents and sister

Abstract

Piezoelectric is a versatile material used in sensors and actuators. Piezoelectric transformers (PTs) convert electrical energy into electric energy by using mechanical vibration energy. Both converse (actuator) and direct (sensor) piezoelectric effects are utilized simultaneously in Piezoelectric transformers operation. On applying voltage, the input of the transformer works as an actuator, which generates vibration in the output structure (sensor) thus stepping up/down the input voltage. These are typically manufactured using piezoelectric ceramic materials that vibrate in the resonance frequency range. Piezoelectric transformers are very energy efficient when operated in the resonance frequency range (between resonance and anti-resonance frequencies). With appropriate designs, it is possible to step up and step down the voltage between the input and output of the piezoelectric transformer, without making use of wires or any magnetic materials. The purpose of this thesis is to develop a step-down piezoelectric transformer design software as per user requirements. The software tool first generates the estimated different electrical circuit and mechanical dimensions parameters for initial analysis as per user-supplied data. Then using SPICE and FEM analysis results, the software can generate a prototype step-down piezoelectric transformer design for prototyping. The prototype design experimental data is then used by the software tool to analyze the design parameters as per the user requirements. The proposed design calculator is developed using MATLAB. Analytical equations are implemented in MATLAB which generates the piezoelectric transformer equivalent circuit and structural dimensions. The equivalent circuit is then simulated using LTSPICE and SIMULINK through the MATLAB interface. After design iterations and improvement, the structural parameters are used to perform FEM analysis of the PT in COMSOL. The comparison of design, SPICE and FEM simulation is done in the MATLAB software. After prototyping, the experimental resonance frequency, voltage and power data are compared with the design and simulation result for optimization of the design. All steps are performed in this thesis for the validation of the designed software tool.

Key Words: *Piezoelectric Transformer, Equivalent electrical circuit, design calculator, experimental verification*.

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CHAPTER 1: INTRODUCTION

Piezoelectric is a versatile material, which is used in a variety of applications. It is utilized on a large scale as a sensor, actuator, energy harvester and electrical transformer. When stress is applied to a piezoelectric material it produces an electric charge which is called piezoelectricity. The phenomenon of piezoelectricity is reversible i.e. when an electric field is applied to a piezoelectric material it produces stress in the material. This effect is known as the converse piezoelectric effect. This forms the basis of the piezoelectric transformer (PT). In piezoelectric transformers, the electromechanical phenomenon is utilized in such a way that it transforms one level of AC voltage into another level of AC voltage through mechanical vibrations.

Piezoelectric material application as a transformer was known for a long time [1], but its large scale utilization was in LCD from the year 2000-2010 [2], [3], [4]. A Step-up Rosen-type ceramic piezoelectric transformer was used in LCDs for backlight high voltage generation. Rosen-type transformer was installed in the inverter circuit of the backlight display (also known as driver or blaster board). Other uses of step-up piezoelectric transformer included cold cathode fluorescent lamp (CCFL), but now LED technology has replaced the LCD.

Figure 1.1: Piezoelectric inverter circuit for backlighting LCD [5]

Though step-up piezoelectric transformer technology was commercialized for LCD and it replaced the magnetic transformer in these applications, the use of Step-down Piezoelectric ceramic transformer is still in limited application. But step-down piezoelectric transformer is being widely studied for commercial applications in battery chargers, smart-phone chargers, switch-mode power supplies [5], [6], [7], [8], [9]. The following sections explain in detail the piezoelectric transformer technology and my motivation in studying this technology for possible future applications.

1.1 Background, Scope and Motivation:

The research on piezoelectricity started in the late 1920s by Alexander McLean Nicolson who used two single-crystal blocks of Salt Rochelle fixed in a frame. One crystal is used for an input AC signal that produces vibrations and the second crystal converts vibrations back into an electrical signal. This piezoelectric transformer was limited in performance due to being the only material available at that time [10].

In the 1940s barium titanate ($BaTiO_3$) arrived as a new ferroelectric ceramic and in the 1950s it became commercially available for use in piezoelectric applications. In this period Charles Abraham Rosen started his doctoral research on piezoelectric transformers using barium titanate (BaTiO3). He used a single block of barium titanate polycrystalline ceramic, rectangular in shape and made two polarization zones by using unconnected electrodes and different polarization voltages. Input electrodes were in thickness polarization direction and output electrodes in longitudinal polarization direction. Rosen-PT works with high efficiency when the frequency of the input signal is close to the resonance frequency of the device.

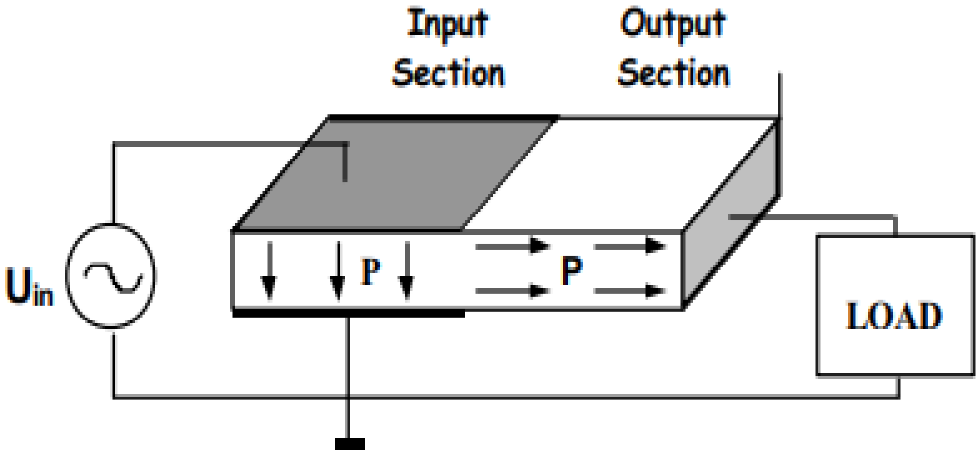


Figure 1.2: Basic Rosen type piezoelectric transformer

In the 1950s Bernard Jaffe realized the importance of the Lead Zirconate Titanate (PZT) family of ceramics and in the 1960s a research group under the supervision of B. Jaffe at Clevite Corporation worked on this subject and developed the entire family of PZT piezoceramics. After this H. Jaffe and D. A. Berlincourt at Clevite Corporation developed a piezoelectric ceramic resonator for voltage transformations. It was a ceramic resonator but the topology developed can be used for piezoelectric transformers. This research was also carried out by other researchers. The design consisted of a disc with single-polarization in thickness direction using distinct electrodes for input and output.

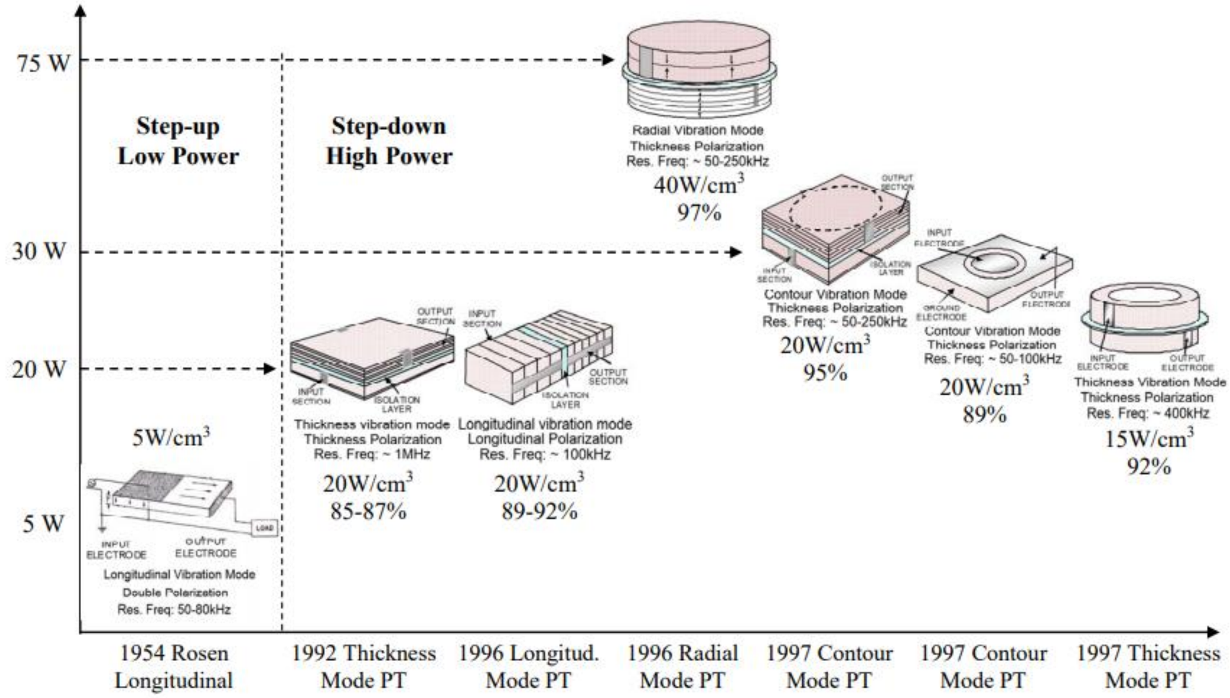


Figure 1.3: Different types of PT and their operating modes [39]

PTs have four basic types by design. These are Rosen type, Radial mode, Thickness mode and Thickness-shear mode [11]. Rosen type is already described above. The other three types, radial mode, Thickness mode and Thickness-shear mode can be used in Step-down applications.

Radial mode Consists of round discs layered on top of each other in a thickness polarization direction. Layers can be varied to get desired transformer performance. The primary section produces radial strains which in return produce output voltage at secondary layers. This design is named *Transoner Radial mode PT* invented by *Face Electronics* in 1996 in the USA. The power of Transoner PTs is above 100W. The resonance frequency and power densities are 50-250 KHz and 40W/cm3 respectively.

In Thickness Vibration mode there is a single input layer and multiple output layers separated by an insulation layer. The electric field applied to the input electrode is parallel to the direction of poling. The output capacitance and resonance frequency of this design are high because the thickness dimension is smaller than the length and width dimension. One problem with this design is spurious vibrations which increase losses and mechanical strain. In Thickness Shear Vibration mode PTs the electric field is orthogonal to the direction of poling. Input at the primary section produces shear strain in the device which in turn produces a voltage at the secondary section. Thickness vibration mode PTs are discussed in [43], [44], [45], [46], [47]. In thickness-shear vibration mode, the direction of vibration of the transformer is in the poling direction whereas the field applied to it is perpendicular to the poling direction. Transformers operating in this mode has high power ratings and coupling coefficient.

In the 1980s Japanese companies started work on PTs for commercial use. The first main commercial application of PTs was the generation of high voltage for backlighting cold cathode fluorescent lamps (CCFL) of liquid crystal displays (LCDs) which reduced the size of LCDs. By the 2000s 25%-30% CCFL were made using PTs. Beyond the 2000s the research shifted towards power PTs and the main applications were AC- DC battery adapters and AC-DC LED drivers. In the 1990s thickness mode PTs for power applications were introduced by NEC in Japan but in the mid-1990s Face Electronics in the USA introduced a new PT called Transoner. In the late 1990s, a contour-extensional vibration mode PT was developed by NEC which used a similar approach like Transoner but with square geometry with internal radial electrode [12]. In Europe, universities of Spain and Denmark collaborated in ESPRIT IV project “TRAMST” to made a piezoelectric AC-DC converter for mobile phone battery charger by using a ring-shaped electrode operating in thickness vibration mode in which the primary and secondary of the device are separated by an insulation layer. After that research on radial mode and disk type piezoelectric transformers started in various countries. Jiri Erhart et al. [13] studied several types of ceramic disc piezoelectric transformers with the same ceramic body size operating in planar-extensional vibration mode. A. Cherif et al. [14] presented the radial mode piezoelectric transformer and analyzed the effects of thickness and radius on voltage gain and efficiency of the piezoelectric transformer. Results showed that the radial mode piezoelectric transformer operating in high frequency must have a small radius in order of 0 to 25×10^6 mm and PTs operating in low frequencies should have the same primary and secondary piezoelectric ceramic with the thickness of some hundred millimetres.

Shine-Tzong Ho [15] presented the electromechanical equations for disk-type PT. The equivalent circuit model of PT proposed in this research has the advantage of determining the PT's performance as a function of its designed parameters. Ghusoon Muhsin Ali et al. [16] developed a circular shape radial-mode piezoelectric transformer for a 220-V and 40-W electronic ballast that has an efficiency of 90% and zero voltage switching without using any external inductance. J-M Kissling et al. [17] simulated a disk-type piezoelectric transformer in COMSOL Multiphysics finding good clamping points for PT and also the various important electrical characteristics such as input impedance and efficiency at different operating points. Dae Jong Kim et al. [18] experimentally investigated the radial in-plane vibration characteristics of disk-shaped piezoelectric transducer polarized in the thickness direction by measuring natural frequencies and mode shapes. Bernardo Andres et al. [19] developed a procedure to obtain an improved model of the radial piezoelectric transformer by having primary and secondary of a transformer at the same piezoelectric surface. Recent research work is on inductor-less and bi-directional PT-based converters. Other applications of PTs developed in the 2000s were:

- Piezoelectric based electronic power conditioner for power supply of travelling wave tube (TWTs).
- Piezoelectric transformer-based discharge ignition system to discharge Pulse Plasma Thrusters used in small satellites using solid-state spark plugs.
- High voltage power supply for compact neutron generator.
- High voltage PT to monitor high voltage networks.
- PTs for Gate Driver and Isolation Feedback applications.

Some of the work done on the step down piezoelectric transformers in the 2000s is mention in the table below.

Table 1-1: A literature review of step-down PTs

Author	**Device type**	**Efficiency**	**Input Voltage**	**Output Voltage/Power**	**Resonance Frequency**
Sung-Jin Choi et al. (2005) [20]	Contour Vibration mode thickness polarization	85%	250V	18W	77.2kHz
Insung Kim et al. (2010) [21]	Radial mode disk type	100V	85 to 265V_{rms}	5W	70.25kHz
Monthakarn Peerasaksopholet al. (2011) [22]	Contour vibration mode	96%	-	36W	81.4kHz
Juhyun YOO et al. (2000) [23]	Contour vibration mode	>98%	210V	85.6V	74kHz
Yong-Wook park 2010	Ring/dot PT	85%	220V	30V_{dc}/27W	71kHz
Vo Viet Thang et al. (2011) [24]	Contour Vibration mode (Parallel Connection)	88%	60V	10W	69kHz
Insung Kim et al. (2012) [25]	Ring/dot PT	96%	115V	16W	72kHz
Chen-Yao Liu et al. (2006) [26]	Radial mode	_	21.16V_{pp}	2.16V_{pp}	50kHz

The performance of PTs can be limited by materials employed, electrical breakdown strength, mechanical strength and depolarization due to heating. Due to the transition from CCFL technology to LEDs for LCD backlighting, sales of high voltage PTs has declined. At present, the main area for piezoelectric transformers applications is in defence, security, power supplies and medical and sensitive measurement equipment.

1.2 Step-down Piezoelectric Transformer

As described above with the variations in designs it is possible to make a step-up or step down piezoelectric transformer. Major applications of a step down piezoelectric transformers are in adapters dc-dc converters and ac-dc converters. In the 1990s several companies started research for the development of piezoelectric transformers as shown in table 1.1 below:

Table 1-2: Different designs for step-down Piezoelectric Transformers

Transformer Design	**Country**
Thickness vibration mode Thickness polarization	Japan, NEC, 1992
Longitudinal vibration mode Longitudinal polarization	Japan, NEC, 1995
Contour vibration mode Thickness polarization	Korea
Radial vibration mode Thickness polarization	USA, Face, 1996
Thickness vibration mode Thickness polarization	Europe, Noliac, 1998

Due to the demand for reduced size power supplies for electrical appliances, the research on step-down piezoelectric transformers is active in Korea, Japan and the USA. As far as step-down applications are concerned Piezoelectric Transformers working in Radial vibration mode, longitudinal vibration mode, contour vibration mode and thickness vibration mode are convenient and are broadly studied in the Republic of Korea.

The focus of our research will be on Contour-shape radial-mode piezoelectric transformer with rectangular secondary layers. Contour-shape radial mode piezoelectric transformer operates in transverse mode. The contour shaped piezoelectric transformer can be called Ring Dot PT with the input electrode in the centre in a circular shape. To increase the step-down ratio of the transformer the number of secondary layers can be increased. There is only one input layer and the thickness and number of output layers can be different according to the particular design requirement. From different configurations of piezoelectric transformers, the radial vibration mode of the piezoelectric transformer can give high power applications such as in adapters.

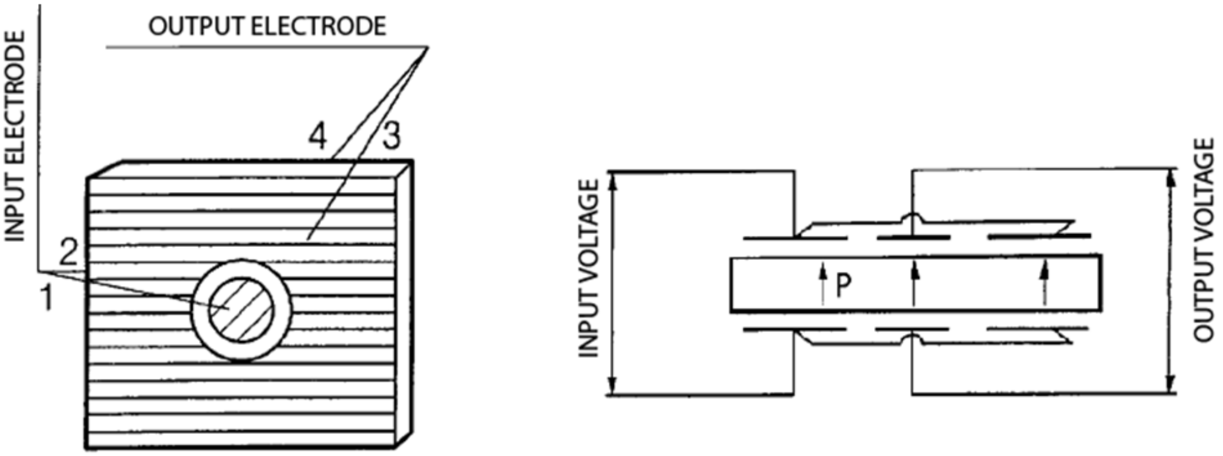


Figure 1.4: Korean PT type design [27]

1.3 Objective:

The thesis has the following objectives

- To design a software tool that calculates the characteristic parameters of a step-down piezoelectric transformer based on input and output electrical power parameters and dimensional constraints provided by the user.
- The software tool should be able to develop all parameters required for the analysis and manufacturing of the prototype piezoelectric transformer.
- Validation of the designed software by comparing the software tool parameters with a prototype. A prototype is provided by SEED Lab Hanyang University South Korea

1.4 Benchmarking Paper:

Though step-down piezoelectric transformer technology is discussed in many papers. For benchmarking, a research paper in which a piezoelectric transformer with different functions is designed and fabricated having multi-functionality is chosen [28]. It operates in a radial mode and is polled uni-directionally. It has a wide range of voltage gain operating at the resonant frequency. The efficiency of the designed PT is 65%. There is a good matching between the simulation and the experimental results of the PT. Software for simulations in MATLAB/SIMULINK.

CHAPTER 2: STEP-DOWN PIEZOELECTRIC TRANSFORMER DESIGN

The piezoelectric transformer used for this work is a contour shaped step-down piezoelectric transformer that operates in radial vibration mode. In this chapter, the design process of the step-down piezoelectric transformer will be discussed. The process of designing both the step-up and step-down piezoelectric transformer is similar, the only difference comes in the analytical solution that equations for the step-down piezoelectric transformer will be different.
The contour vibration mode piezoelectric transformer used in this work is shown in figure 2.1 below:

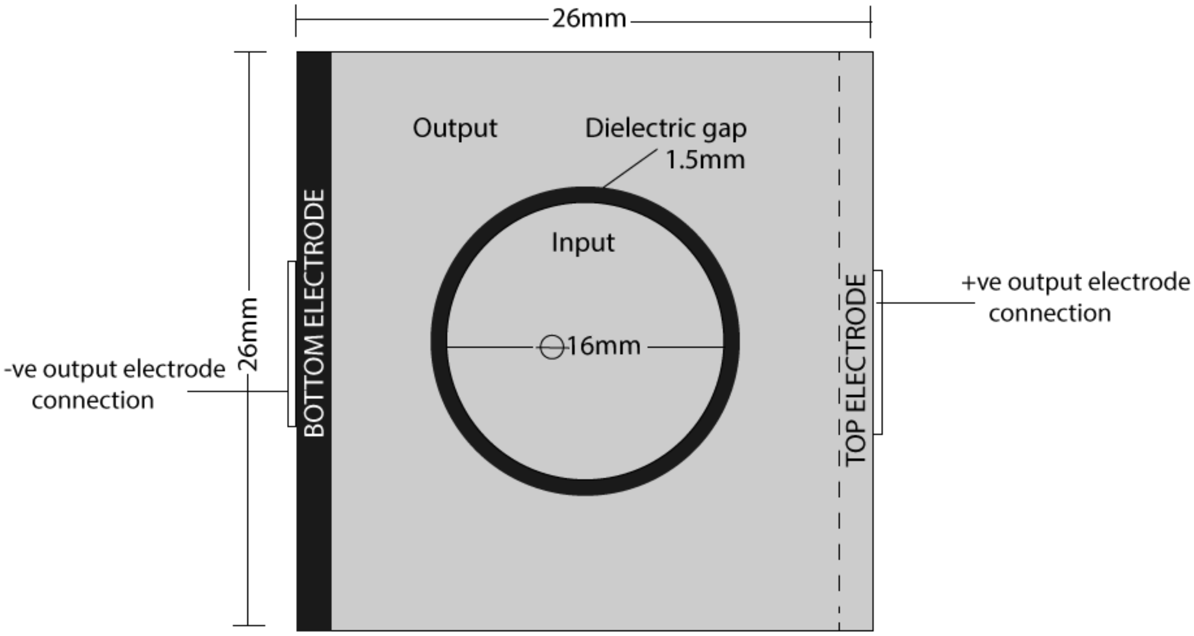
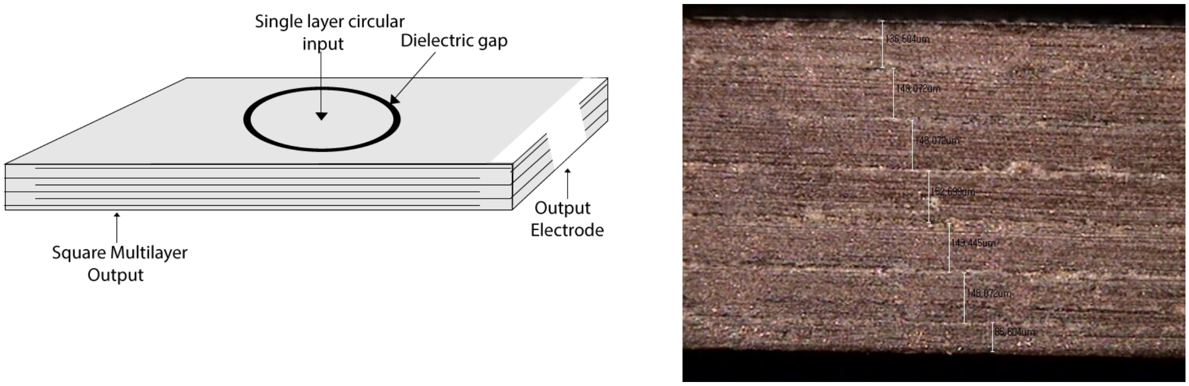


Figure 2.1: Contour shaped piezoelectric transformer shape and dimensions

Contour shaped transformer used in this research has a 16mm single layer circular input region and a seven-layered output region is in the form of a square shape. Both the input and output are separated by the dielectric region of 1.5mm. The length and width of this transformer are 26mm respectively having an overall thickness of 2mm. Both the input and output layers are covered with Ag-Pd electrodes of 10 µm thickness. A side view of PT is shown in figure 2.2 below:



(a) (b)

Figure 2.2: (a) Side view of piezoelectric transformer shape, (b) output layers under a microscope on PT non-electrode side

In the design section of this transformer, we will discuss fabrication, analytical equations and equivalent circuit parameters calculation.

2.1 Fabrication Process

The manufacturing process of piezoelectric transformers is application-specific and according to different applications, the size and the number of layers can be varied. Although PTs are application-specific the steps involved in the manufacturing process generally remain the same. PT used in this research is made with PZT (Lead-Zirconate-Titanate) material. The complete manufacturing process of Piezoelectric transformers as mentioned in [29], [30],[31], [32]. The steps involved in the manufacturing process of PT are shown in figure 2.3.

2.1.1 Slurry:

The first step involved in the manufacturing process is known as a slurry in which proper weightage and mixing of piezoelectric material powder and milling process are done.

- **Powder weightage and mixing:**

  PZT material has three different components as Lead, Zirconate and Titanate. These materials are available in the form of oxides such as lead oxide PbO, titanium dioxide TiO_2 and zirconium dioxide ZrO_2. These powders are first dried up and then their weightage is done thoroughly.

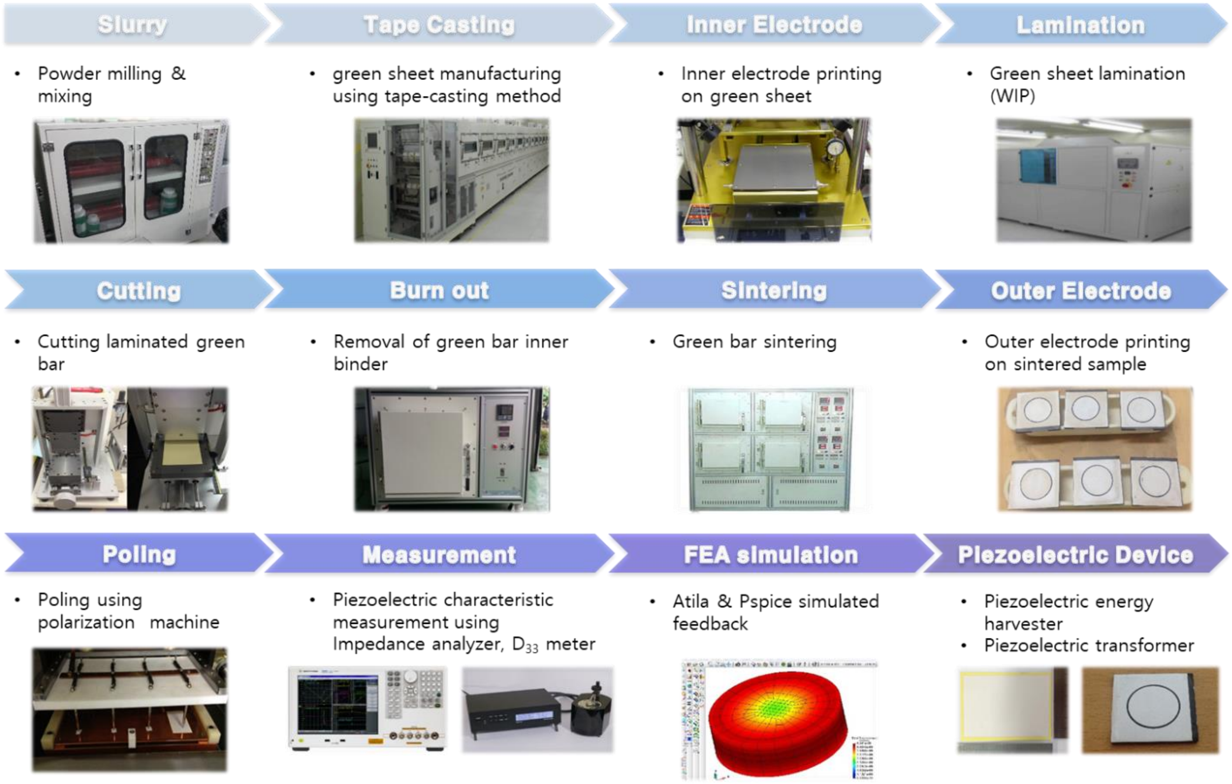


Figure 2.3: Manufacturing process of PT

- **Milling:** After proper weightage, these powders are milled together. The process of milling is of special attention in the manufacturing of technical ceramics such as the type of mill to be used and the time of grinding.

2.1.2 Calcination:

Calcination is the process of heating the powder material at a high temperature to remove any volatile substance or moisture. Calcination is the most important part as it greatly influences the characteristics of materials. The calcination temperature can be up to 900 ^{0}C. Calcination is done in four stages as follow:

- Decomposition of starting powder materials
- The reaction of Lead oxide and Titanium oxide
- The reaction of zirconium dioxide with the mixture obtained in the first reaction
- Homogenization of reaction

After the calcination process powders are grounded again to get fine and uniform powder. These powders are dried again and are mixed with some solution i.e poly-vinyl-alcohol (PVA). For bulk, thick and thin ceramic manufacturing this material is prepared in the form of green sheets. These sheets are then cut and converted into desired shapes and sizes. For piezoelectric transformer layers, these layers are stacked upon one another and pressed. The piezoelectric transformer manufacturing can be categorized in thin-layer ceramic manufacturing as green sheets with a thickness of 10μm are manufactured. Multiple green sheets can be stacked to develop a required thickness, one layer of the transformer. Then multiple layers can be stacked to develop a complete transformer with the required number of layers.

2.1.3 Tape Casting Process:

In the tape casting process, the sheets of piezoelectric material are manufactured, which are called green sheets. The required thickness to be achieved depends on the tape casting machines and their doctor-blade.

2.1.4 Pressure Pressing:

In pressure pressing the mixture of powders is pressed in a specifically designed steel dye to get the desired shape. The pressure applied can be up to 1 Gpa. This can be done using a hydraulic pressing machine or water pressure.

2.1.5 Inner electrode printing:

For multilayer PT, different layers are stacked together and every layer has electrodes connected to it. Silver-Palladium (Ag-Pd) electrodes are printed on the green sheets and then these sheets are stacked together through pressure pressing.

2.1.6 Cutting:

After inner electrode printing, the laminated green sheets are cut either manually or automatically.

2.1.7 Binder burnout:

In the mixing of piezoelectric material powder, a binder is used to hold the powder together to make a specific shape. Before sintering, it is necessary to remove the binder as it has completed its function to give a compact shape. Temperature ranging from 60° C to 350°C is applied (using a furnace or heating chambers with an exhauste) to volatilize the binder and moisture from the sheets. To avoid any pores or cracks this process is performed slowly.

2.1.8 Sintering:

Sintering is a phenomenon in which the material is heated at a temperature below the melting point. The sintering temperature can be up to 1000^0C or more depending upon the material. Sintering can help to obtain very complex shapes easily without using any complex machines. After sintering the mechanical strength of the material can also increase.

2.1.9 External/outer Electrode Deposition:

The Silver and Palladium (Ag-Pd) paste is used to make electrodes in manufacturing piezoelectric transformers. Silver and Palladium have the following two advantages:

a. It increases the melting point
b. Silver and palladium allow it to be co-fired at high temperatures.

As the cost of Silver and Palladium is high, cheaper electrode materials such as Copper (Cu) and Nickle (Ni) etc. are under study. After applying the paste to the material it is annealed in air at high temperature to remove the binder and also to provide bonding to the ceramic surface. The bonding between the electrode and the ceramic material is very important, as the columbic interaction between the electrode and dielectric material modifies the barrier height at the interface, which determines the transport of electrons injected during the poling process.

2.1.10 Poling:

Poling is a process in which a high DC electric field is applied to the ceramic material for a specific time duration while the material is heated inside a silicon oil bath. Typical applied DC voltages are in the range of some 2000 volts V/mm of component thickness. Poling aligns the dipoles of the piezoelectric materials in one direction. The direction of poling depends on the direction of the applied DC electric field. Polarization can be done in the thickness direction or the longitudinal direction depending upon the input and output requirements of the piezoelectric transformer.

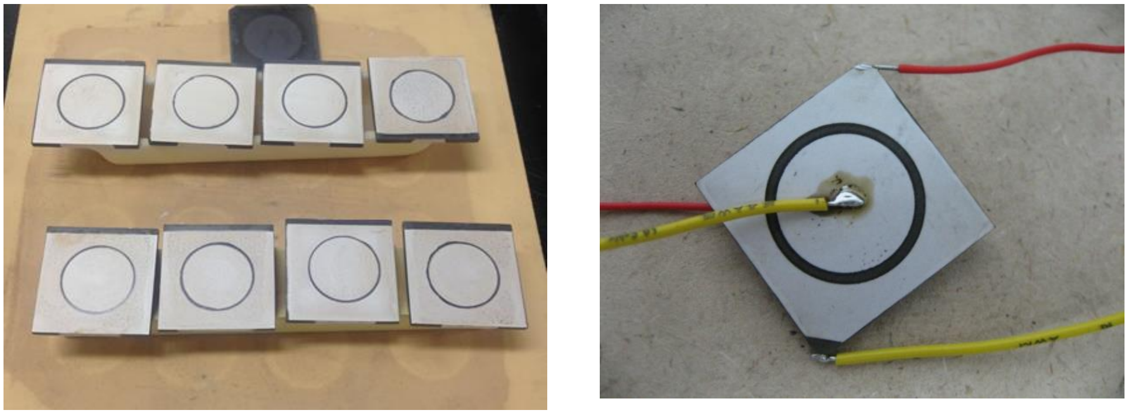
2.1.11 Measurements:

Following characteristics and properties of piezoelectric material and transformer are measured after manufacturing

- Dimensions after manufacturing (as the material will shrink on heating/sintering)
- Capacitance at 1000 Hz (either by d33 meter, LCR meter or impedance analyzer)
- Piezoelectric constant d_{33} (using d33 meter)
- Resonance and Anti-resonance frequency (LCR meter or impedance analyzer)
- Electromechanical coupling factor k_p
- Mechanical quality factor Q_m
- Vibration velocity (using a Vibrometer)
- Temperature rise at high voltage (change in temperature should be < 20°C at resonance frequency)

The d_{33} is measured by using a d_{33} meter and on the other hand k_p and Q_m can be measured using the data acquired through an impedance analyzer.

The circular input square shaped output piezoelectric transformer manufactured by following the above-mentioned manufacturing process is shown in figure 2.4 below:



(a) (b)

Figure 2.4: (a) The manufactured shape of PT, (b) A different electrode shape PT, not used in this thesis

2.2 Analytical Solution:

A piezoelectric transformer utilizes both converse and direct piezoelectric effects. As we are dealing with the step-down piezoelectric transformer working in contour vibration mode so the equations for mechanical strain S and charge density D in cylindrical coordinates as mentioned in [33], [34], [35], [36] are written as follow:

$$S = \frac{T}{Y} + d^t E \ = S^E T + \ d^t E \quad \text{(Converse effect)} \tag{2.1}$$

$$D = \frac{Q}{A} + \mathcal{E} E \ = \mathrm{d} T + \ \mathcal{E}^t E \quad \text{(Direct effect)} \tag{2.2}$$

In the above two equations S represents the mechanical strain, T represents the mechanical stress, D represents the charge density and Y, E, $\mathcal{E}^t$ represent Young’s modulus, electric field and permittivity under constant stress. D is the proportionality constant which is the same for both converse and direct piezoelectric effects.

Now applying cylindrical coordinates these equations can be written as:

$$\mathrm{S_{rr}} = \mathrm{S_{11}^E T_{rr}} + \mathrm{S_{12}^E T}_{\theta\theta} + \mathrm{d_{31} E_Z} \tag{2.3}$$

$$\mathrm{S}_{\theta\theta} = \mathrm{S_{12}^E T_{rr}} + \mathrm{S_{11}^E T}_{\theta\theta} + \mathrm{d_{31} E_Z} \tag{2.4}$$

$$\mathrm{D_z} = \mathrm{d_{31}}(\mathrm{T_{rr}} + \mathrm{T}_{\theta\theta}) + \varepsilon_{33}^{\mathrm{T}} \mathrm{E_Z} \tag{2.5}$$

The coupling coefficient is represented as follow:

$$\mathrm{K_{eff}^2} = \frac{\frac{1}{2}\varepsilon^{\mathrm{T}}\mathrm{E}^2 - \frac{1}{2}\varepsilon^{\mathrm{S}}\mathrm{E}^2}{\frac{1}{2}\varepsilon^{\mathrm{T}}\mathrm{E}^2} \tag{2.6}$$

In piezoelectric materials, both mechanical and electrical fields are coupled for energy conversion. The coupling coefficient for specific directions is represented with a different subscript. In our case, the input of PT is contour or circular so the planar coupling factor k_p will be used. It is also called the radial coupling factor.

2.3 The output of PT:

The output of PT has ‘n’ number of layers connected in parallel and are of the same dimensions. All the layers are manufactured with the same material. The total thickness of output and input layers is assumed to be the same. For simplification, we have considered the output of the piezoelectric transformer as circular and the radial stress on the edges is considered to be zero [37].

PT output current equation can be represented as follow:

$$I_{\mathrm{out}} = \frac{\mathrm{dQ}}{\mathrm{dT}} = j\omega \mathrm{Q} = j\omega \int_{\mathrm{r}_1}^{\mathrm{T}_2} \mathrm{D}_3^{\mathrm{out}}\, 2\pi \mathrm{r} dr \tag{2.7}$$

$$I_{out} = \frac{2\pi j\omega n d_{31}}{s_{11}^{\mathrm{E}}\left(1-\sigma_{\mathrm{c}}^{\mathrm{E}}\right)} \int_{\mathrm{r}_1}^{\mathrm{r}_2} (\mathrm{S}_{\mathrm{r}} + \mathrm{S}_{\theta}) r dr + \mathrm{V}_{\mathrm{out}} \left[\frac{j\omega 2\pi(\mathrm{r}_2{}^2 - \mathrm{r}_1^2)\mathrm{n}^2 \mathrm{d}_{31}{}^2}{\mathrm{s}_{11}^{\mathrm{E}}\left(\sigma_{\mathrm{c}}^{\mathrm{E}} - 1\right)\mathrm{t}_{\mathrm{in}}} + \frac{\mathrm{j}\omega\pi(\mathrm{r}_2{}^2 - \mathrm{r}_1{}^2)\mathrm{n}^2 \varepsilon_{33}^{\mathrm{T}}}{\mathrm{t}_{\mathrm{in}}}\right] \tag{2.8}$$

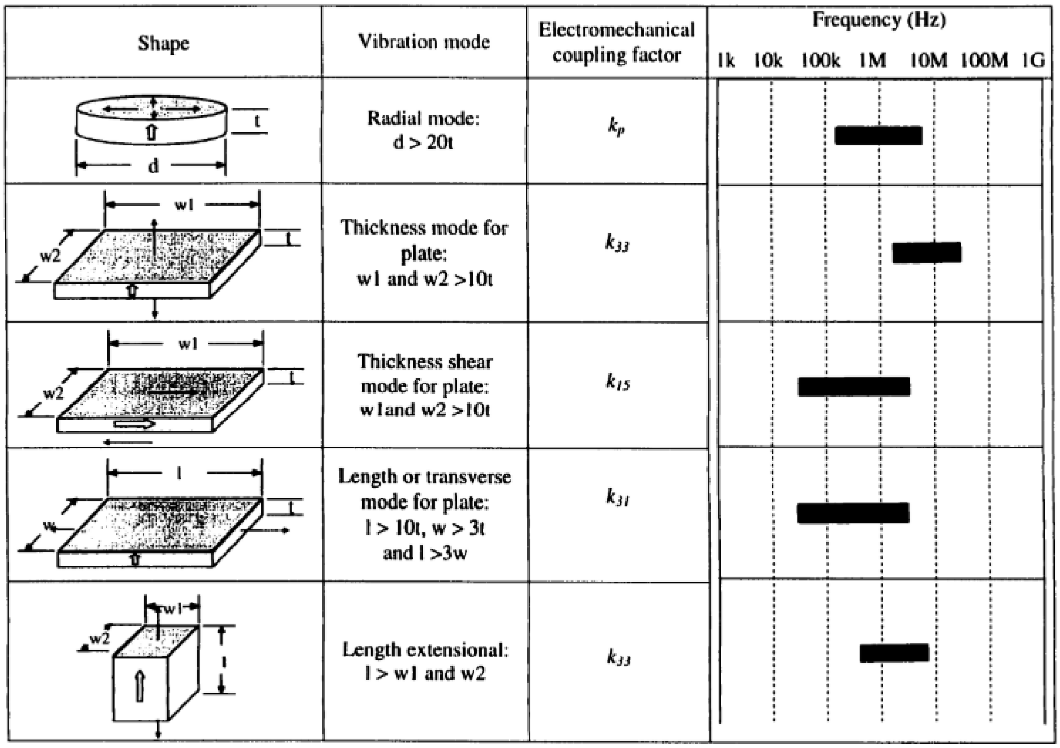
$$\frac{\mathrm{V}_{\mathrm{out}}}{\mathrm{V}_{\mathrm{in}}} = \frac{1}{\mathrm{n}^2[\mathrm{m}-1]} \left(\frac{\mathrm{I}_{\mathrm{out}} + \frac{2\pi j_{\mathrm{in}}}{\mathrm{s}_{11}^{\mathrm{E}}\left(1-\sigma_{\mathrm{c}}^{\mathrm{E}}\right)} \cdot \frac{j r_1 v_{\mathrm{r}_1}}{\omega}}{\mathrm{I}_{\mathrm{in}} - \frac{2\pi j\omega \mathrm{d}_{31}}{\mathrm{s}_{11}^{\mathrm{E}}\left(1-\sigma_{\mathrm{e}}^{\mathrm{E}}\right)} \cdot \frac{j r_1 v_{\mathrm{r}_1}}{\omega}} \right) \tag{2.9}$$

In the above equations the piezoelectric material parameters $\mathrm{d}_{31}^{\mathrm{out}} = \mathrm{d}_{31}^{\mathrm{in}}$ whereas $\varepsilon_{33}^{\mathrm{in}} = \mathrm{E}_{33}^{\mathrm{out}}$.

2.4 Vibrational modes of PT:

Piezoelectric transformers have three common vibration modes and are classified according to these modes. These are longitudinal vibration, thickness vibration, planar and shear vibration. In longitudinal vibration modes, the input is polarized in the length direction while the output is in the length direction. This forms the basic Rosen type step up piezoelectric transformer. Thickness vibration mode PT has both input and outputs polarized in the thickness direction and has different layers. These are step-down piezoelectric transformers. The transformation ratio in this mode is related to the input and output impedance ratio. The piezoelectric transformer in planar shear vibration mode is operated at the first radial mode of resonance frequency as these are designed in circular form and utilize both the shear and planar vibration modes [38].

Table 2-1: Five common vibration modes of Piezoelectric material [48]



Shape	Vibration mode	Electromechanical coupling factor	Frequency (Hz) 1k 10k 100k 1M 10M 100M 1G
d, t	Radial mode: d > 20t	k_p	
w1, w2, t	Thickness mode for plate: w1 and w2 >10t	k_{33}	
w1, w2, t	Thickness shear mode for plate: w1and w2 >10t	k_{15}	
l, w, t	Length or transverse mode for plate: l > 10t, w > 3t and l >3w	k_{31}	
w1, w2, l	Length extensional: l > w1 and w2	k_{33}	

2.5 The input of PT:

As per the converse piezoelectric effect Piezoelectric transformer works as an actuator on its input side. Consider that a PT is fixed at its centre [32] and the voltage signal is applied. It will actuate the input of PT. Due to this voltage signal, the input layer will produce vibrations and there will be displacement in the disc in compression and tension. Mechanical Strain produced as a result of this vibration will be directly proportional to the applied voltage signal having the same frequency.

The current in the input layer can be written as:

$$I_{\mathrm{in}} = I_3 = \frac{\mathrm{dQ}}{\mathrm{dT}} = j\omega \mathrm{Q} = j\omega \int_0^{\mathrm{r}_1} \mathrm{D}_3 2\pi \mathrm{r} dr \tag{2.10}$$

Charge density D_3 can be written as:

$$\mathrm{D}_3 = \mathrm{d}_{31}(\mathrm{T}_\mathrm{r} + \mathrm{T}_\theta) + \varepsilon_{33}^{\mathrm{T}} \mathrm{E}_3 \tag{2.11}$$

Constitutive equations for T_r and T_θ are as follow:

$$\mathrm{T}_\mathrm{r} = \frac{1}{\mathrm{s}_{11}^{\mathrm{E}}\left(1-\sigma_c^{\mathrm{E}^2}\right)}\left(\mathrm{S}_\mathrm{r} + \sigma_c^{\mathrm{E}} \mathrm{S}_\theta - \mathrm{d}_{31}\mathrm{E}_3\left(1+\sigma_c^{\mathrm{E}}\right)\right) \tag{2.12}$$

$$\mathrm{T}_\theta = \frac{1}{\mathrm{s}_{11}^{\mathrm{E}}\left(1-\sigma_{\mathrm{c}}^{\mathrm{E}^2}\right)}\left(\mathrm{S}_\theta + \sigma_{\mathrm{c}}^{\mathrm{E}}\mathrm{S}_{\mathrm{r}} - \mathrm{d}_{31}\mathrm{E}_3(1+\sigma_{\mathrm{c}}^{\mathrm{E}})\right) \tag{2.13}$$

T_{r} and T_θ are the radial and azimuthal stress. Now considering these equations the equation for input current becomes as:

$$I_{in} = \frac{2\pi j\omega \mathrm{d}_{31}}{\mathrm{s}_{11}^{\mathrm{E}}(1-\sigma_{\mathrm{c}}^{\mathrm{E}})} \cdot \frac{jr_1 v_{\mathrm{r}_1}}{\omega} + \frac{j\omega 2\pi r_1^2 d_{31}{}^2 E_3}{\mathrm{s}_{11}^{\mathrm{E}}(\sigma_{\mathrm{c}}^{\mathrm{E}}-1)} + j\omega\pi r_1^2 \varepsilon_{33}^{\mathrm{T}}\mathrm{E}_3 \tag{2.14}$$

And

$$\mathrm{E}_3 = \frac{\mathrm{V}_{\mathrm{in}}}{t_{\mathrm{in}}} = \frac{V_{\mathrm{in-dc}}\mathrm{E}^{j\omega t}}{t_{\mathrm{in}}} \tag{2.15}$$

2.6 Equivalent circuit of PT:

There are two types of an equivalent electrical circuit model for piezoelectric transformer, Type-1 and Type-2. In literature mostly type-2 PT equivalent circuit is shown but this circuit is independent of the transformer design type and its function whereas from a design point of view the type-1 circuit serves better. The results of the Type-1 equivalent circuit can be converted into a Type-2 equivalent circuit with the help of the procedure presented in [39], [40], [41]. In this thesis, a Type-1 equivalent circuit model is used and is shown below.

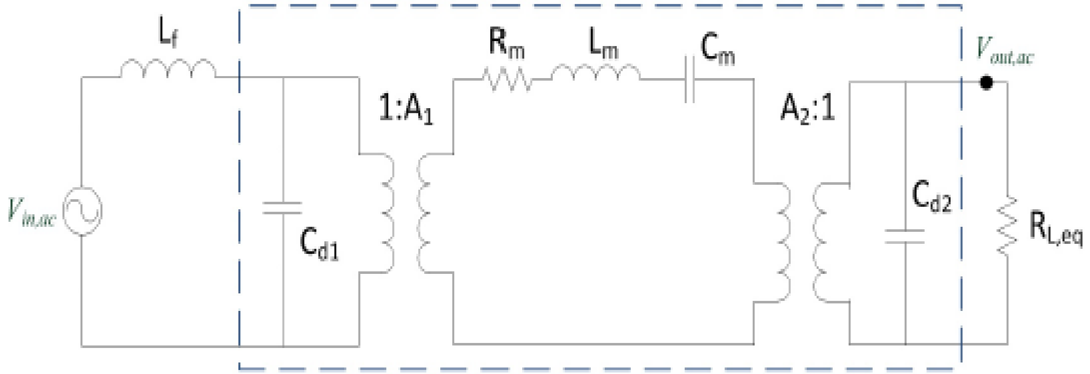


Figure 2.5: Type-1 Equivalent Electrical Circuit

The detail of equivalent electrical circuit model parameters is shown in table 2.1 below:

Table 2-2: Equivalent electrical circuit model parameters

L_f	Input Filtering
C_{d1}	Input Capacitance
C_{d2}	Output Capacitance
R_m, L_m, C_m	Motional Arm
A_1	Input Transformation Ratio
A_2	Output Transformation Ratio
$R_{L,eq}$	Load Resistance

Inductor L_f is used in the circuit to perform input filtering. R_m, L_m, C_m form the motional branch of the circuit where L_m and C_m form the mechanical resonance frequency of the circuit and R_m is the loss in the circuit. The losses will increase with an increase in output current, as all the current will flow through the motional branch. The losses are generally in the form of heat, and there is a restriction on how much the temperature of a working PT can increase. The temperature of the PT should not increase greater than 20°C during operation in the resonance frequency range, as this will start to affect the polarization and continuous heating can result in depolarization of material and loss in piezoelectricity and performance of the PT.

2.7 Input/Output Voltage and Power:

The output power of piezoelectric transformer at load can be calculated by using simple Ohm’s law relation as:

$$R = \frac{V^2}{P} \tag{2.16}$$

To drive the PT at its resonance frequency half-bridge driving circuit technique is used and the input AC voltage to drive this half-bridge circuit can be calculated as follow:

$$V_{in,ac}(t) = \frac{2}{\pi} V_{in,dc} \sin(\pi D) \sin(\omega t) \tag{2.17}$$

2.8 Resonance Frequency:

The resonance frequency of the PT can be calculated by the following relation:

$$\omega_{\text{res}} = \frac{\mathrm{N_r}}{2\mathrm{D}} \tag{2.18}$$

Where $\mathrm{N_r}$ is the radial frequency constant having its unit in m/s and D is the diameter of PT.

2.9 Type-1 Equivalent Circuit Parameters Calculation:

Depending upon the input and output voltage and power provided by the user and also the material properties available the equivalent circuit parameters can be approximated by using the following equations [40] [42]:

Output capacitance $\mathrm{C_{d2}}$ can be calculated as shown below:

$$\mathrm{C_{d2}} \simeq \frac{1}{\omega_{\text{res}}\mathrm{R_{eq,ac}}} \tag{2.19}$$

Where ω_{res} is the resonance frequency.

$\mathrm{C_{d1}}$ is calculated as shown below:

$$\mathrm{C_{d1}} = \frac{\mathrm{n_1}\varepsilon_{33}^{\mathrm{T}}\left(1-\mathrm{k_{p,in}^2}\right)\mathrm{A}}{\mathrm{t_{1,\ one\text{-}layer}}} \tag{2.20}$$

Where A is the area and $\mathrm{k_{p,in}^2}$ is input coupling coefficient.

Transformation ratio A_1 can be calculated as:

$$A1 = \frac{n1\pi D d_{31,in}}{0.70 S_{11}^{E}} \tag{2.21}$$

Transformation ratio A_2 can be calculated as:

$$A2 = \frac{\sqrt{p_{\text{out, }ac}}2w_{\text{res}}\, c_{d_2}}{v_{vv,max}} \tag{2.22}$$

Lm can be calculated as shown below:

$$\mathrm{Lm} = \ \mathrm{Mass}\ \times \alpha = 0{:}835\ \mathrm{Mass} \tag{2.23}$$

$$\mathrm{Mass}\ =\ \mathrm{Volume}\ \times\ \mathrm{Density}\ = \pi\pi\left(\frac{D}{2}\right)^2 t_{\text{total}}\,\rho_{PZT} \tag{2.24}$$

t_{total} is the thickness of all the layers of the piezoelectric transformer. Typically the density of PZT material is 7600 ${}^{Kg}/_{m^3}$.

Now R_m and C_m can be calculated with the following formula:

$$Cm = \frac{1}{w_{res}^{3} L_m} \tag{2.25}$$

$$Rm = \frac{w_{\mathrm{res}} L_m}{Q_m} \tag{2.26}$$

2.10 Type-2 Equivalent Circuit of PT:

In the type-2 equivalent circuit, the motional arm section (RLC network) is transferred to the input side of the PT and only one transformation ratio (N) is used. Type-2 equivalent circuit is shown in the figure below:

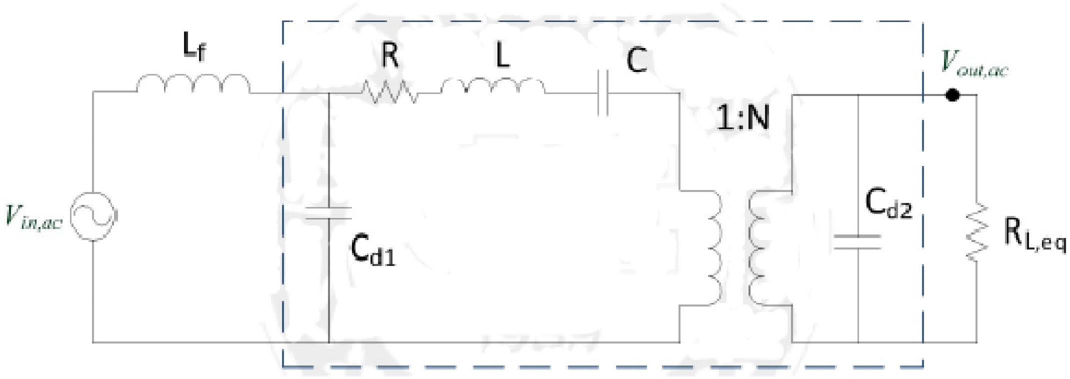


Figure 2.6: Type-2 Equivalent Electrical Circuit

R, L, C and N in the above circuit can be calculated by the following approximations:

$$\mathrm{N} = \frac{\mathrm{A}_1}{\mathrm{A}_2} \tag{2.27}$$

$$\mathrm{R} = \frac{\mathrm{R_m}}{\mathrm{A}_1{}^{2}} \tag{2.28}$$

$$\mathrm{L} = \frac{\mathrm{L_m}}{\mathrm{A}_1^{2}} \tag{2.29}$$

$$C = C_m A_1^2 \tag{2.30}$$

2.11 Piezoelectric Materials:

To solve the above analytical equations in the equivalent circuit, Piezoelectric material properties are required. These piezoelectric material properties are provided by the companies supplying the piezoelectric powder. The companies generate the piezoelectric material data after developing certain shapes and testing them from the powder as mentioned in [49].

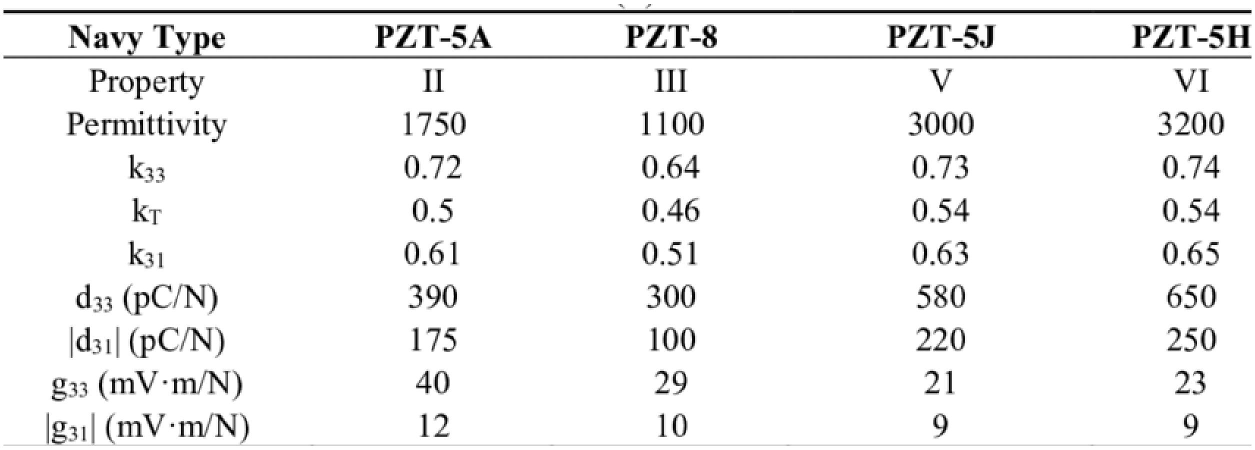
There are many types of Piezoelectric materials as mentioned below:

1. Crystal (Quartz)
2. Ceramic
    - Lead-based
    - Lead-Free
3. MEMS Scale

    Aluminum Nitride (AlN)

The most famous type of Piezoelectric ceramic material is Lead-Zirconate-Titanate (PZT), which is widely used in piezoelectric transformer development. PZT has further types based on precursor material composition and properties. Research is ongoing on lead-free materials but it is not commercialized yet. Ceramic materials can be manufactured as per required material properties by changing the precursor powder material composition.

Various navy types of piezoelectric materials developed by the U.S. Navy are available and are shown in the figure below. Many US and European companies use these naming conventions.



Navy Type	PZT-5A	PZT-8	PZT-5J	PZT-5H
Property	II	III	V	VI
Permittivity	1750	1100	3000	3200
k_{33}	0.72	0.64	0.73	0.74
k_T	0.5	0.46	0.54	0.54
k_{31}	0.61	0.51	0.63	0.65
d_{33} (pC/N)	390	300	580	650
$\lvert d_{31}\rvert$ (pC/N)	175	100	220	250
g_{33} (mV·m/N)	40	29	21	23
$\lvert g_{31}\rvert$ (mV·m/N)	12	10	9	9

Figure 2.7: Various Piezoelectric Ceramic Materials

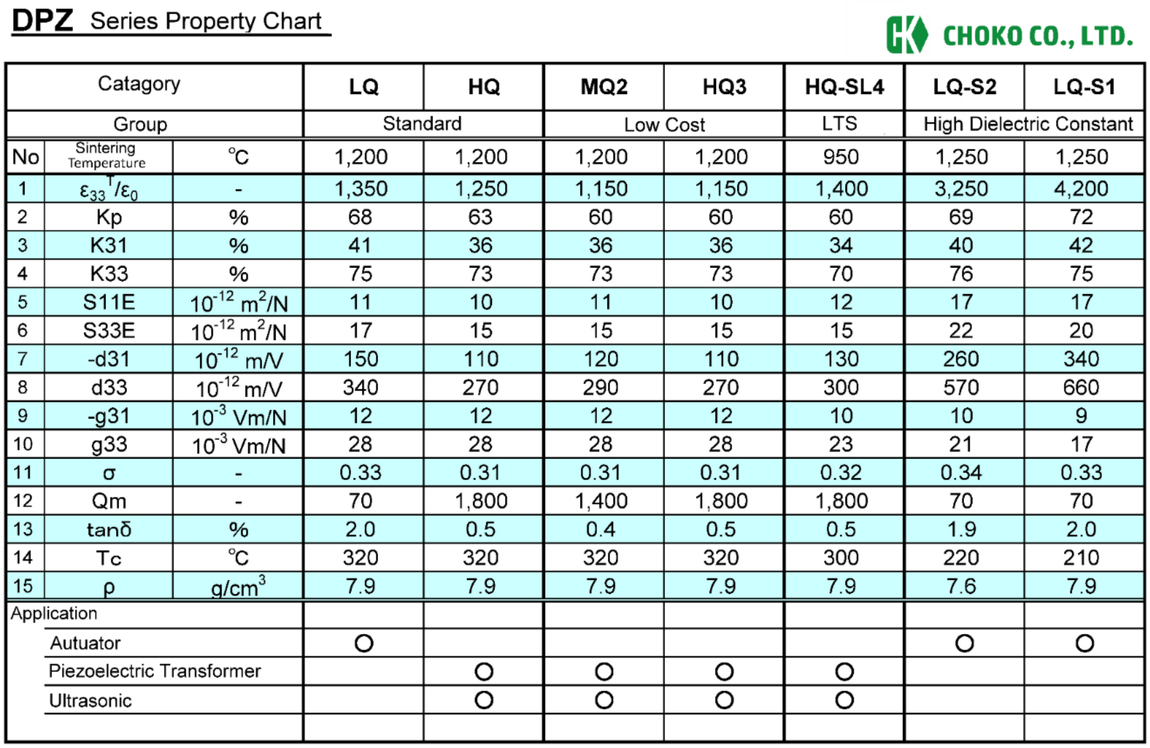
- **PZT-5A**

  This material is suitable for those applications that require high or varying temperatures.
- **PZT-5H**

  Although it has a slightly low-temperature range and can be affected by temperature, still it has the best piezoelectric material properties.
- **PZT-5J**

  Properties of this material are in between the properties of 5H and 5A.

There are other material types such as PZT-4, PZT-8 etc. Other countries have different naming conventions, as an example, a Chinese company PZT powder properties are given below.



DPZ Series Property Chart

CHOKO CO., LTD.

Catagory			LQ	HQ	MQ2	HQ3	HQ-SL4	LQ-S2	LQ-S1
Group			Standard		Low Cost		LTS	High Dielectric Constant	
No	Sintering Temperature	°C	1,200	1,200	1,200	1,200	950	1,250	1,250
1	$\varepsilon_{33}^{T}/\varepsilon_0$	-	1,350	1,250	1,150	1,150	1,400	3,250	4,200
2	Kp	%	68	63	60	60	60	69	72
3	K31	%	41	36	36	36	34	40	42
4	K33	%	75	73	73	73	70	76	75
5	S11E	10^{-12} m^2/N	11	10	11	10	12	17	17
6	S33E	10^{-12} m^2/N	17	15	15	15	15	22	20
7	-d31	10^{-12} m/V	150	110	120	110	130	260	340
8	d33	10^{-12} m/V	340	270	290	270	300	570	660
9	-g31	10^{-3} Vm/N	12	12	12	12	10	10	9
10	g33	10^{-3} Vm/N	28	28	28	28	23	21	17
11	σ	-	0.33	0.31	0.31	0.31	0.32	0.34	0.33
12	Qm	-	70	1,800	1,400	1,800	1,800	70	70
13	tanδ	%	2.0	0.5	0.4	0.5	0.5	1.9	2.0
14	Tc	°C	320	320	320	320	300	220	210
15	ρ	g/cm^3	7.9	7.9	7.9	7.9	7.9	7.6	7.9
Application									
Autuator			○					○	○
Piezoelectric Transformer				○	○	○	○		
Ultrasonic				○	○	○	○		

Figure 2.8: CHOKO CO. LTD, PZT powder properties

2.12: Design Process of PT:

PT design and development is an iterative process. It includes multiple steps and iteration between steps and cycles. The complete development cycle of PT with design and simulation details is shown in the figure below.

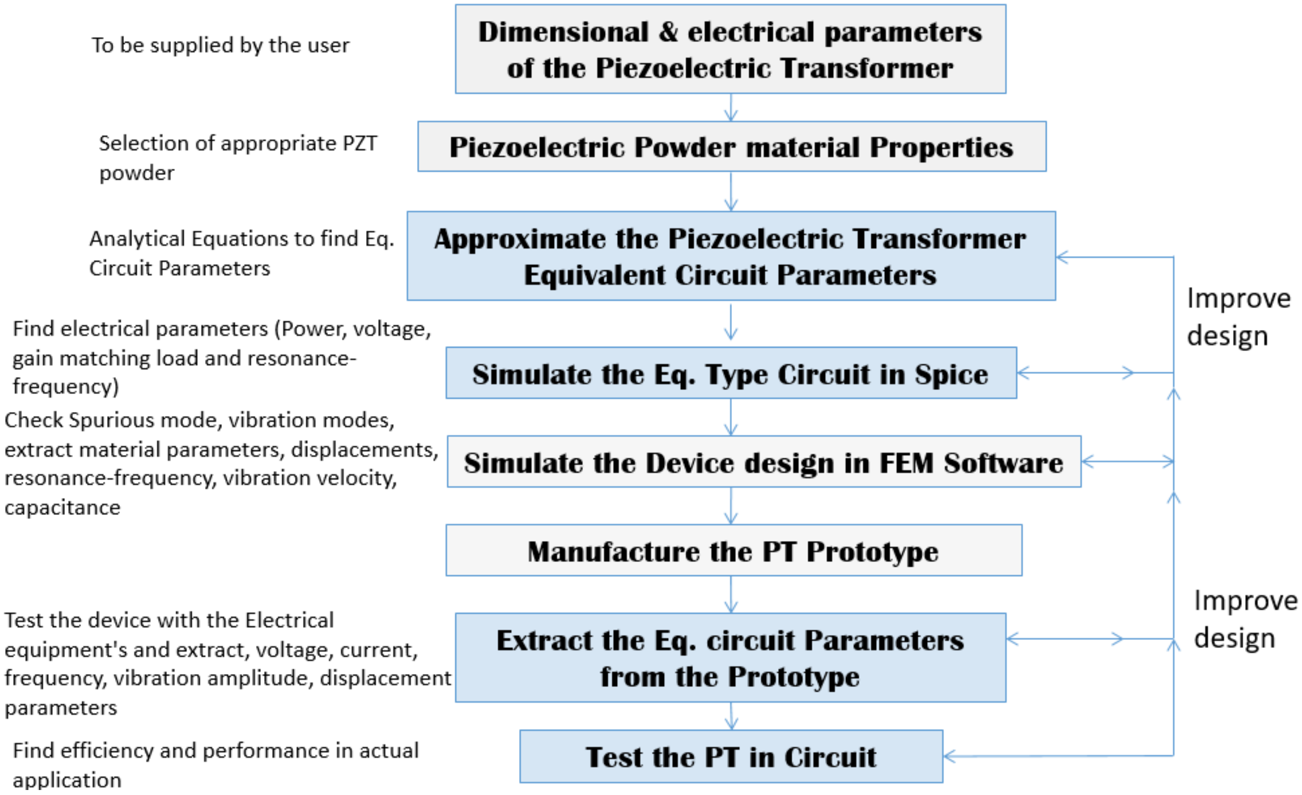


Figure 2.9: Development cycle of PT [39]

First, the user provides its parameter for PT design. Generally, these parameters include the resonance frequency value, dimensional constraints, output power, output voltage, matching impedance, input voltage etc.

The PZT powder properties are selected by the designer, the company providing the powder gives all the material properties (density, piezoelectric constants, coupling coefficients, dielectric etc.) and recommends the specific powders for each application. So, for initial analysis, these piezoelectric powder properties are used in analytical equations.

Based on these constraints provided by the user and material properties given by the PZT company, analytical equations are solved to find (approximate) the electrical and mechanical parameters of the PT. These parameters include the resonance frequency, input and output layers, dimensions, capacitances and transformation ratio. From these values, the PT equivalent circuit parameters (electrical components values) are generated. The equivalent circuit can be simulated in any SPICE based software. After iterations and achieving the required output voltage, matching load and efficiency values, the next step is to simulate the PT in FEM.

For FEM simulations, the mechanical dimensions are achieved after iteration processes are used. The main purpose of FEM simulation is to find the spurious mode (unwanted mode near the resonance frequency). Also, more realistic values of impedance, resonance frequency, capacitance, Qm, vibration velocity can be extracted to further improve the equivalent circuit and design process through iteration.

After the FEM and SPICE iteration, the design becomes ready for prototyping, multiple prototypes (in multiple iterations) can be required in a single design cycle. The prototype is then experimentally tested to find all parameters through standard equipment to further improve the design and its validation.

The key guidelines for designing the power supply in which PT will be used (also known as the driving circuit of the PT), the global regulatory electrical efficiency and no-load power requirements have to be met. For these requirements; California Energy Commission (CEC), EU's Ecodesign 2019/1782, Energy Star, international efficiency marking protocol system guidelines and specifications should be followed. As an example, the California Energy Commission Appliance Efficiency Regulations, large battery charger systems manufactured on or after January 1, 2014, shall meet the performance limits mentioned in the standards in which power conversion efficiency of the product (including PT and Circuit) should be ≥ 89 %.

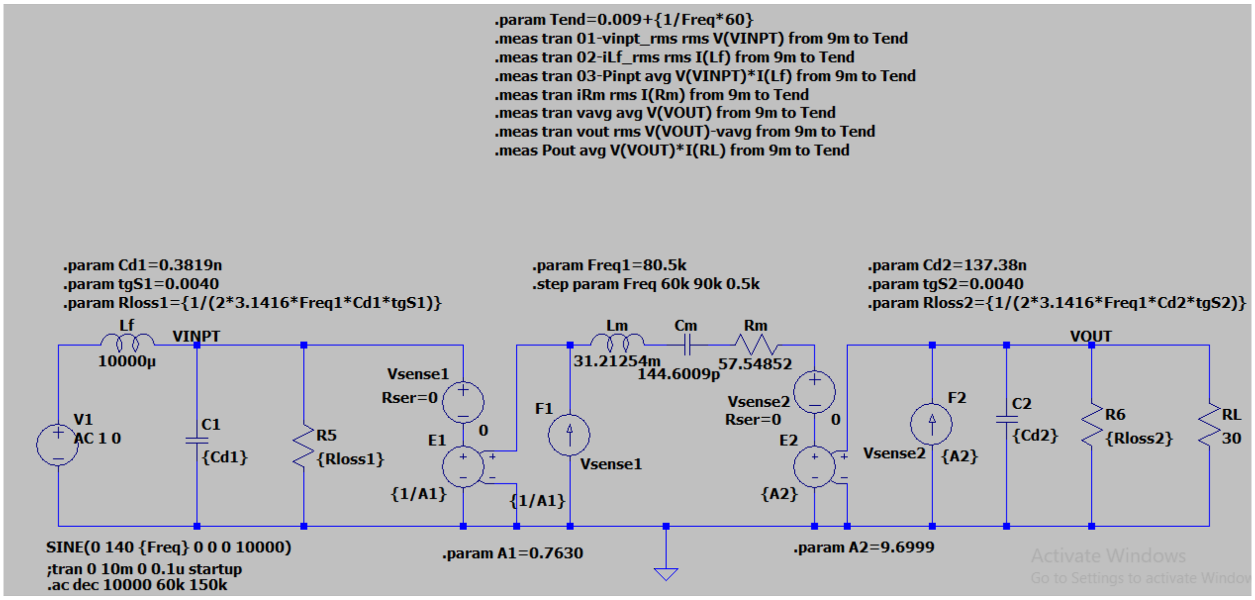
CHAPTER 3: LTSPICE SIMULATION

The analytical equations presented in the previous chapter are used to find the Type-1 equivalent circuit parameters. This equivalent circuit is then simulated to find the PT electrical parameters (input and output power, output voltage, voltage transformation ratio, power transfer efficiency, matching load, frequency).

LTspice is an analogue circuit simulator software based on the SPICE circuit simulator produced by Linear Technologies. It is a high-performance software that provides fast simulations of electrical circuits with enhanced waveform viewer and schematics. The software version used for LTspice simulations in this work is LTspiceXVII which is the latest version of this software. In LTspice the frequency response and time-domain analysis of the Type-1 Equivalent electrical circuit model of the piezoelectric transformer are done.

3.1 Frequency Response Analysis:

The circuit implemented in LTspice for frequency response analysis is shown in the figure below:



```
.param Tend=0.009+{1/Freq*60}
.meas tran 01-vinpt_rms rms V(VINPT) from 9m to Tend
.meas tran 02-iLf_rms rms I(Lf) from 9m to Tend
.meas tran 03-Pinpt avg V(VINPT)*I(Lf) from 9m to Tend
.meas tran iRm rms I(Rm) from 9m to Tend
.meas tran vavg avg V(VOUT) from 9m to Tend
.meas tran vout rms V(VOUT)-vavg from 9m to Tend
.meas Pout avg V(VOUT)*I(RL) from 9m to Tend
```

```
.param Cd1=0.3819n
.param tgS1=0.0040
.param Rloss1={1/(2*3.1416*Freq1*Cd1*tgS1)}
```

```
.param Freq1=80.5k
.step param Freq 60k 90k 0.5k
```

```
.param Cd2=137.38n
.param tgS2=0.0040
.param Rloss2={1/(2*3.1416*Freq1*Cd2*tgS2)}
```

```
SINE(0 140 {Freq} 0 0 0 10000)
;tran 0 10m 0 0.1u startup
.ac dec 10000 60k 150k
```

```
.param A1=0.7630
```

```
.param A2=9.6999
```

Figure 3.1: Type-1 Equivalent Electrical Circuit implemented in LtspiceXVII

The values of electrical circuit parameters are calculated from the equations described above and are given in Table 3.1 below:

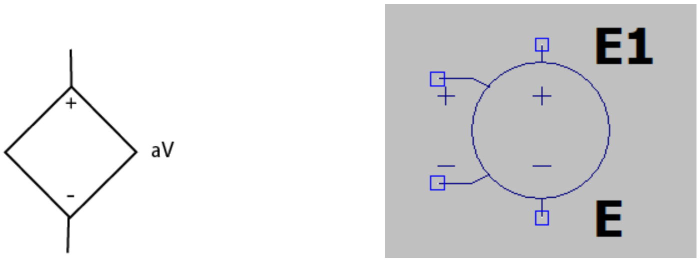
Table 3-1: Values for equivalent electrical circuit model parameters

L_f	10000u
C_{d1}	1.24nF
C_{d2}	83.60nF
R_m	57.54852 Ω
A_1	0.7630
A_2	9.6999
$R_{L,eq}$	30 Ω
C_m	144.6009 pF
L_m	31.21254 mH
R_{loss1}	448K Ohm
R_{loss2}	6.656K Ohm

In Ltspice the voltage transformation ratio is presented by using voltage control voltage sources (VCVS) and current-controlled current sources (CCCS). The output of these control sources is the product of input and the particular gain that we set as the transformation ratio [50].

3.1.1 VCVS:

Two voltage dependant sources are used in the circuit represented as E1 and E2 for input and output voltage transformation ratios. The input and output voltage transformation ratios will be set as the gain for these sources and it will multiply this gain value with the respective input voltage signal coming into the source. The symbol for the VCVS is shown below:

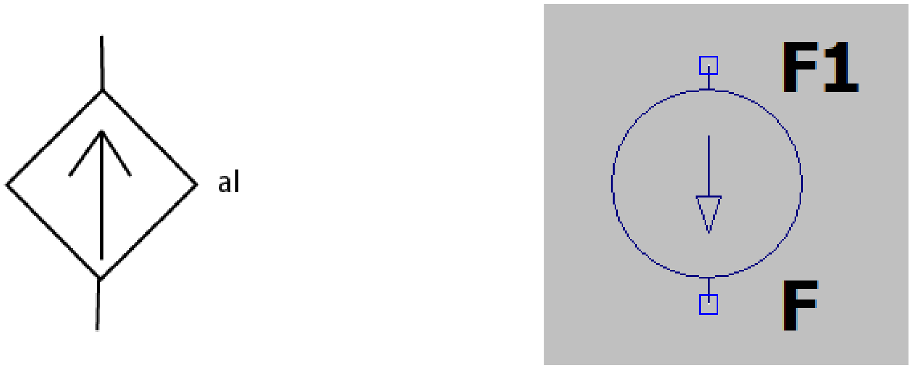


(a) **(b)**

Figure 3.2: (a) Symbol for VCVS (b) Symbol in LTspice

3.1.2 CCCS:

Two current dependant sources are used in the circuit represented as F1 and F2. The operating principle of CCCS is similar to VCVS as it multiplies the particular set gain value to the input current of the source. The symbol for CCCS is shown below:



(a) **(b)**

Figure 3.3: (a) Symbol for CCCS (b) Symmbol in Ltspice

The frequency response of this circuit is measured in LTspice in the form of a Bode plot which is a combination of magnitude plot and phase plot. In this plot, the input voltage phase angle switches to +90 between the resonance and anti-resonance frequency of the circuit and after resonance frequency, it turns again to -90. This phase angle of +90° shows the inductive behaviour of PT during resonance frequency, which is the desired parameter as PT is used to replace the electromagnetic transformer. Outside the resonance frequency range the PT behaves as a capacitor with -90° phase. This inductive behaviour can also be observed through impedance graph in LTSPICE, FEM and by using Impedance Analyzer equipment. The resonance frequency of the circuit is 71.5kHz. The bode plot is shown below:

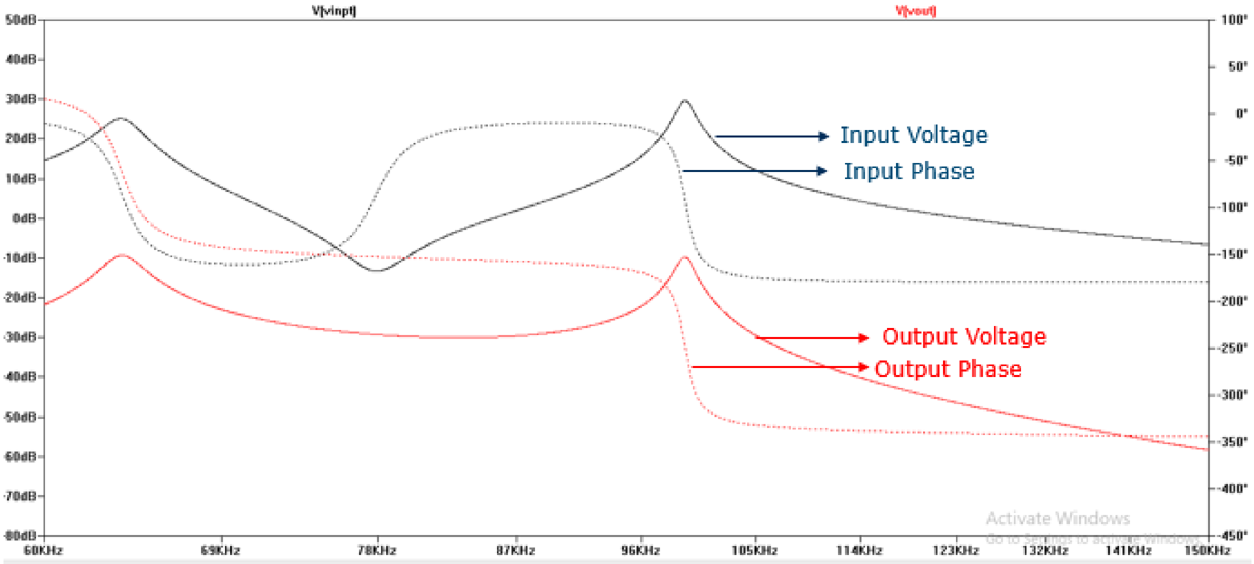


Figure 3.4: Bode Plot of Equivalent Circuit

In this plot blue lines represent input and red lines represent the output. Solid lines represent the magnitude of voltage gain in decibels while the dotted lines represent the phase in degrees. The first peak in solid lines represents the resonance frequency while the second peak represents the anti-resonance frequency. Output voltage Gain is maximum in the resonance frequency range at a specified load resistance.

3.2 Equivalent Circuit for Time Domain Analysis

For experimental validation of the sample piezoelectric transformer with the simulations, the equivalent circuit is designed in LTspice for time-domain analysis. Different load resistances are attached and output voltage response at different frequencies is measured. The results of these measurements will be shown in the results section. The circuit diagram for time-domain analysis is shown below:

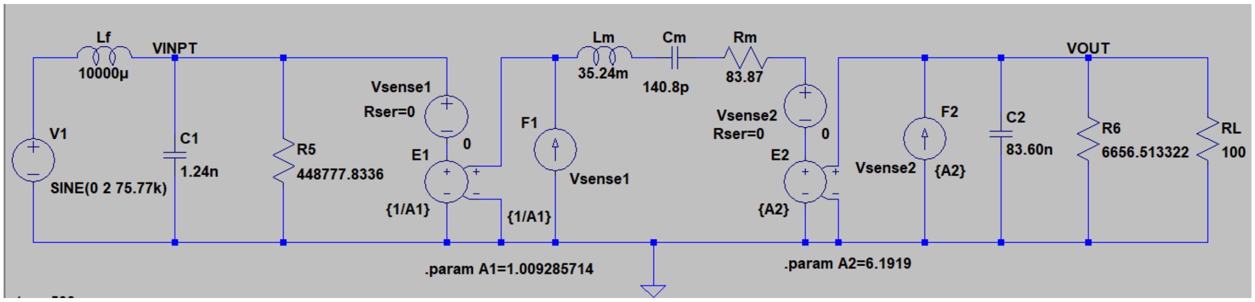


Figure 3.5: Equivalent Circuit for Time-Domain Analysis

CHAPTER 4: MATLAB/SIMULINK SIMULATION

As the purpose of this project is to design a PT design software tool, in which a parameters calculator for step-down piezoelectric transformer is the first part. A graphical user interface is developed in MATLAB which acquires the electrical and dimensional parameters from the user. Based on these user given parameters and PZT powder material properties, the PT equivalent circuit parameters are calculated.

The implementation of circuit parameters equations is done in MATLAB also. This user interface will have five windows for input Electrical properties, material properties, Testing and Simulation, output Electrical Properties and the Size of the Piezoelectric transformer. Upon pressing the calculate button the new figure window will open having the results for all the required parameters of the step-down piezoelectric transformer. These results are calculated from the same equations which are described in the previous chapter.

Matlab Graphical User Interface for implementing equations is discussed below:

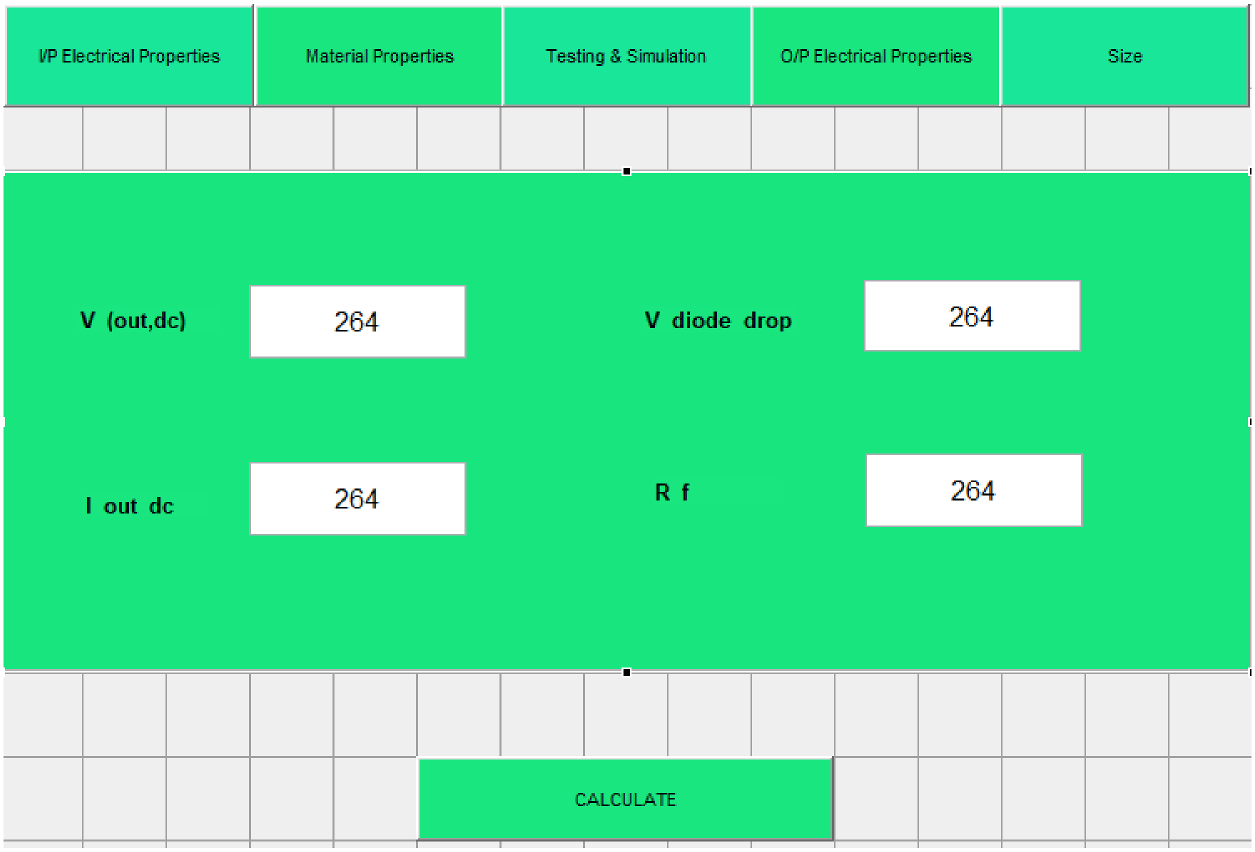
4.1 Tab for Input Electrical Properties:

As the application of PTs is in adapters and AC-DC converters etc. So the input signal for that is the AC main voltage and then the PT is driven by the driving circuitry typically the half-bridge driving circuit. This tab will include the parameters provided by the user which will include maximum input mains voltage, maximum and typical input mains frequency. It will also include duty cycle of half-bridge driving circuit.

Figure 4.1: Input electrical properties provided by the user.

4.2 Tab for Output Electrical Properties:

Output electrical properties include output dc voltage, output current, the diode voltage drop in case of the rectifier and the forward resistance of the full-bridge diode rectifier. Input, Output electrical properties and some dimensional parameters are provided by the user.



V (out,dc) 264

V diode drop 264

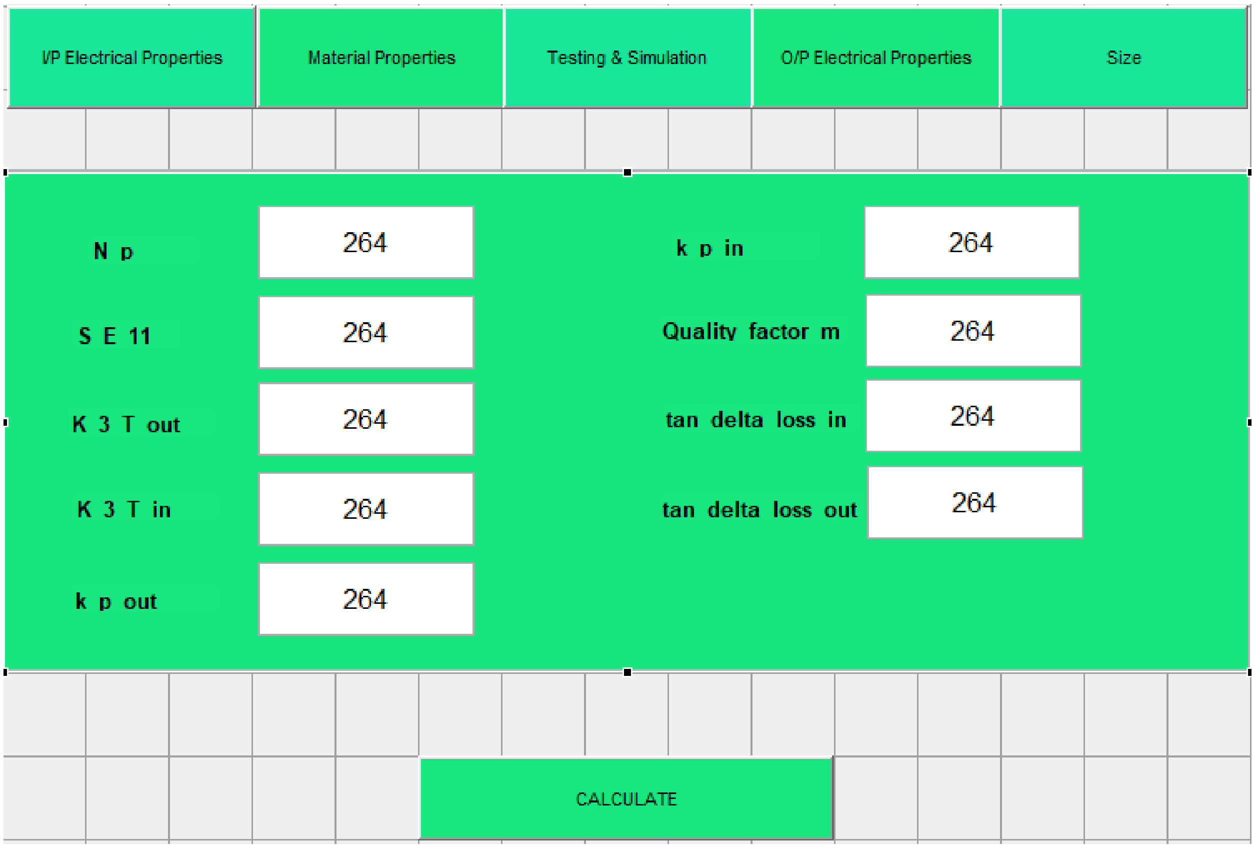
I out dc 264

R f 264

Figure 4.2: Tab for Output Electrical Properties.

4.3 Tab for PZT Material Properties:

These are the PZT powder material properties that are given by the manufacturers for particular materials. N_p is the planar frequency constant. K_p is the coupling coefficient of piezoelectric material. $K_{3T(out)}$ and $K_{3T(in)}$ are the output and input relative dielectric constants respectively. Tan_delta_loss is the dielectric loss factor for output and input of the PT. Quality_factor_m is the mechanical quality factor of the PT which is represented in literature as Q_m.



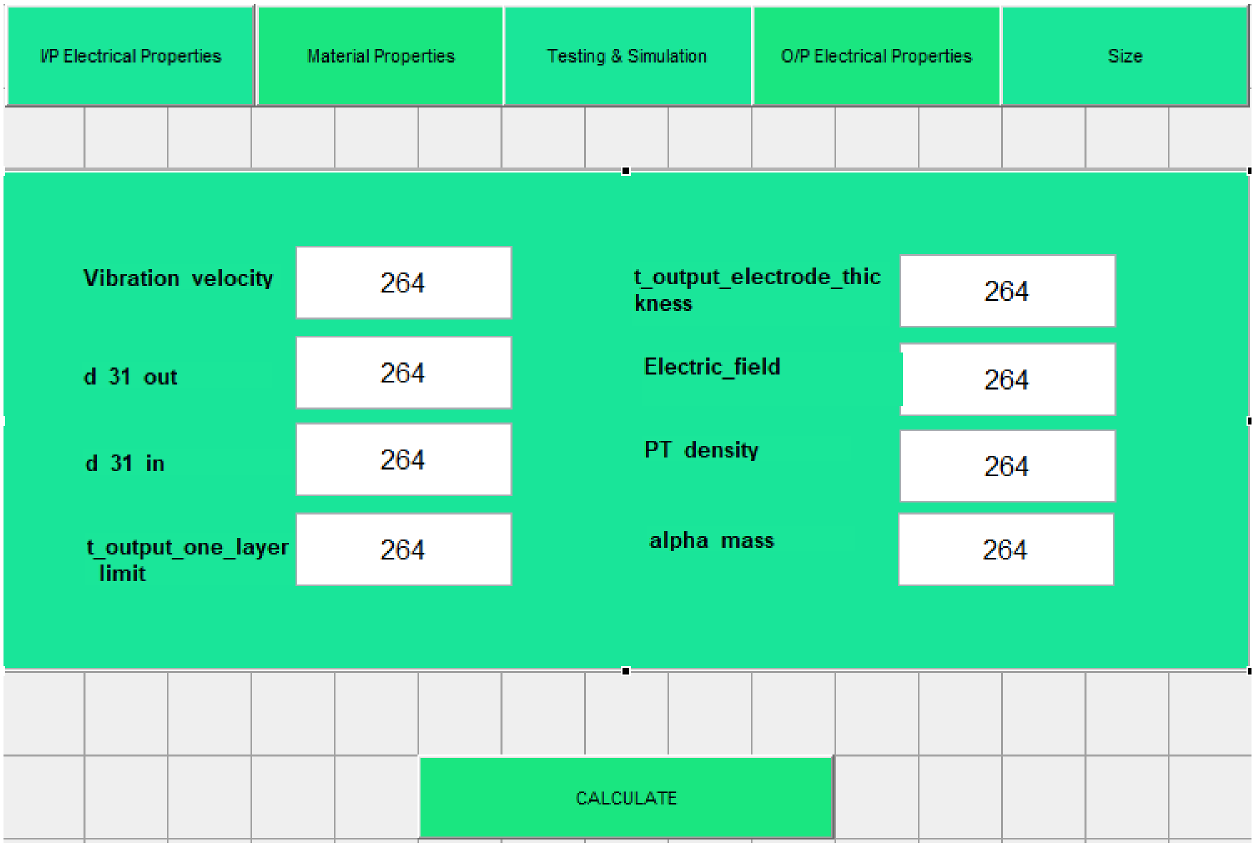
N p	264	k p in	264
S E 11	264	Quality factor m	264
K 3 T out	264	tan delta loss in	264
K 3 T in	264	tan delta loss out	264
k p out	264		

Figure 4.3: Tab for PZT material properties

4.4 Tab for Material Testing Values:

Piezoelectric coefficients $d_{31(out)}$ and $d_{31(in)}$ are the output and input piezoelectric charge constants of the PT. Alpha mass is required while calculation the inductance L_m of the PT which is normally 0.835. This tab will also have the parameter of vibration velocity. As PTs step up or step down electrical energy by using mechanical vibrations at the resonance frequency. It is important to the velocity of these vibrations. Materials have their limits of vibration velocities. Current flowing through the motional arm branch of the PT circuit makes the vibration velocity. We can find it by using FEM simulations or through experiments [51]. First vibration velocity can be approximated by the output power value given by the user using the following equation [39].

$$v_{vv,max} = \frac{\sqrt{P_{out,ac}2\omega_{res}C_{d2}}}{A_2} \tag{4.1}$$



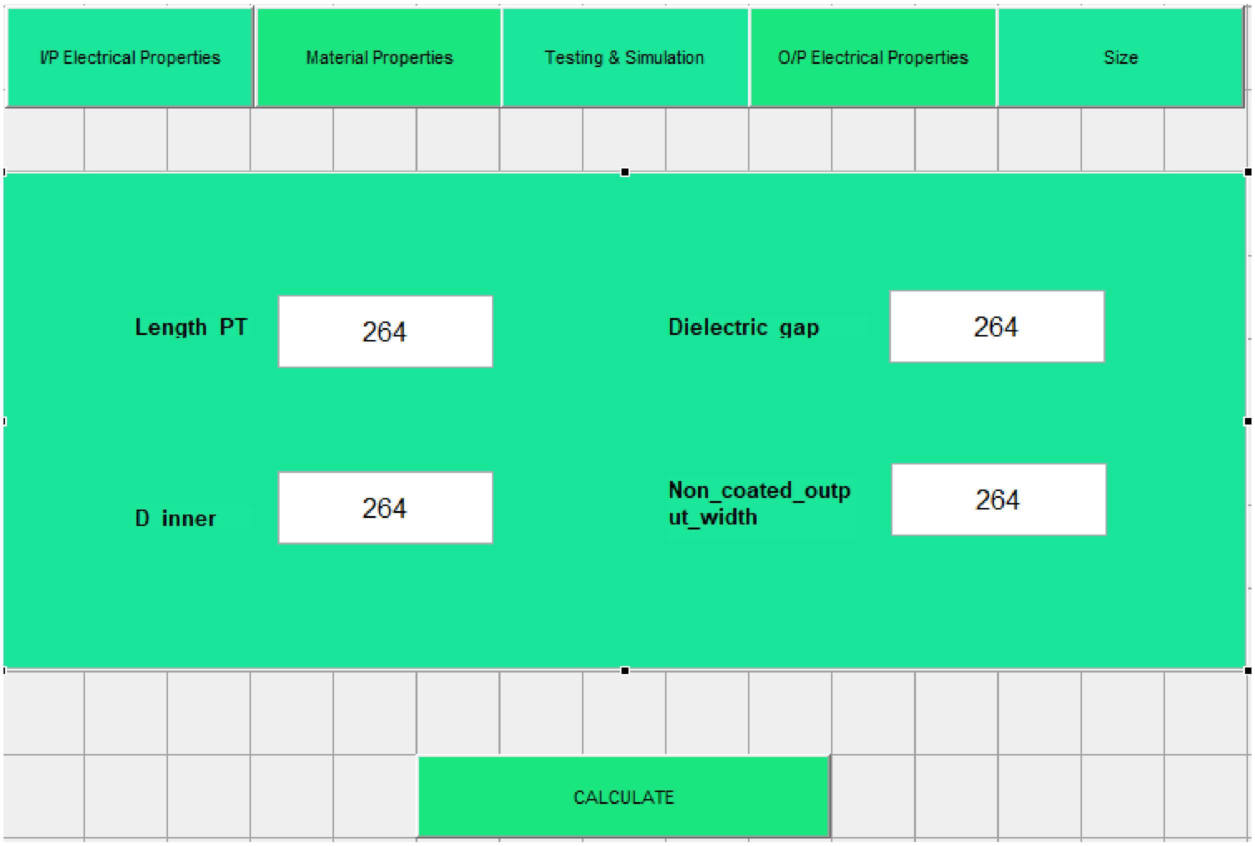
Vibration velocity	264	t_output_electrode_thickness	264
d 31 out	264	Electric_field	264
d 31 in	264	PT density	264
t_output_one_layer limit	264	alpha mass	264

Figure 4.4: Tab for Material Testing Values

4.5 Tab for Dimensional Values:

The size tab includes the overall length of the PT, the inner diameter of the input circular layer, the dielectric gap between input and output. Length of the PT and thickness of the layers is required while calculating transformation ratios A1 and A2 and input, output capacitances.

The length and width of the transformer are to be provided by the user. As our PT design is square, length and width values are the same. Dielectric gap, input electrode diameter, Non-Coated-output width are selected by the designer.



Length PT 264

Dielectric gap 264

D inner 264

Non_coated_output_width 264

Figure 4.5: Tab for Dimensional Values

4.6 Simulink Simulation:

As the equations for equivalent circuit parameter calculation are calculated in MATLAB so the equivalent electrical circuit which is implemented in LtspiceXVII software is again implemented in MATLAB/Simulink for comparison purposes to see whether the results of the bode plot match in both cases or not. After implementation of the circuit in Simulink, the bode plot results in both software were found similar.

The next step in our PT design software Tool is to implement the PT equivalent circuit inside the MATLAB/SIMULINK environment, this saves the hassle of importing the LTSPICE data in MATLAB. Input and Output transformation ratios are presented by using the ideal transformer in Simulink instead of using a voltage-controlled voltage source (VCVS). The functioning of the ideal transformer is similar to the voltage-controlled voltage source (VCVS) as it also multiplies the input of the transformer with the particular ratio that we will set as transformation ratio. The Simulink circuit implemented is shown below:

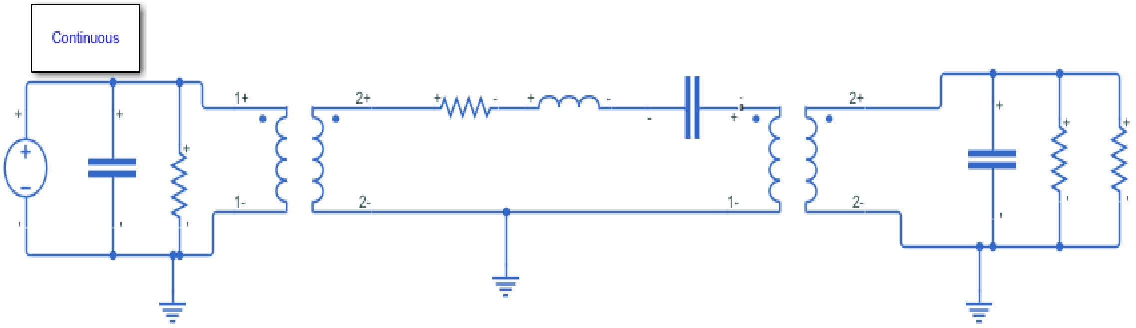


Figure 4.6: Equivalent Circuit in MATLAB/SIMULINK

Bode plot results for this circuit are similar to the Ltspice simulation results and are shown below:

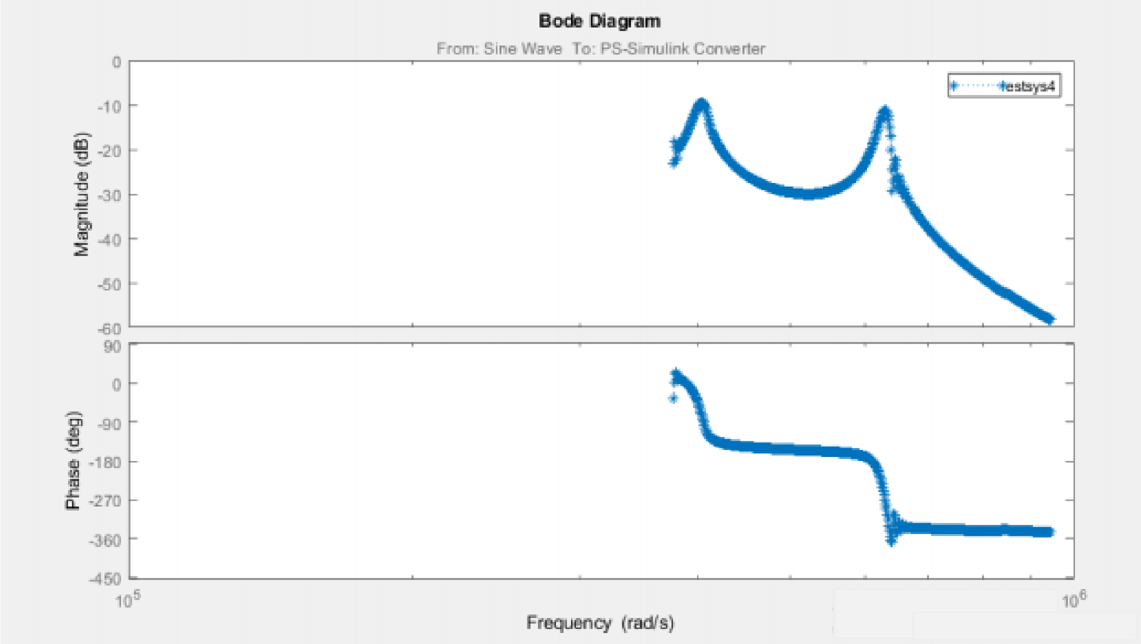


Figure 4.7: Bode Plot of Equivalent Circuit in MATLAB/SIMULINK

CHAPTER 5: COMSOL SIMULATION

After calculating the equivalent electrical circuit parameters and experimental verification it is followed by finite element method (FEM) modelling simulations. FEM analyses are conducted in Comsol on the structure of the proposed piezoelectric transformer to find frequency response and impedance magnitude and phase. PZT-5A material is assigned to the geometry. The prepared geometry of the piezoelectric transformer with the dimensions specified in chapter 2 is given below:

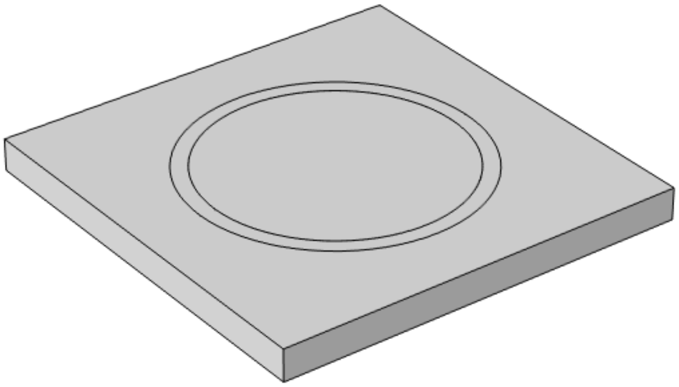


Figure 5.1: PT geometry in Comsol

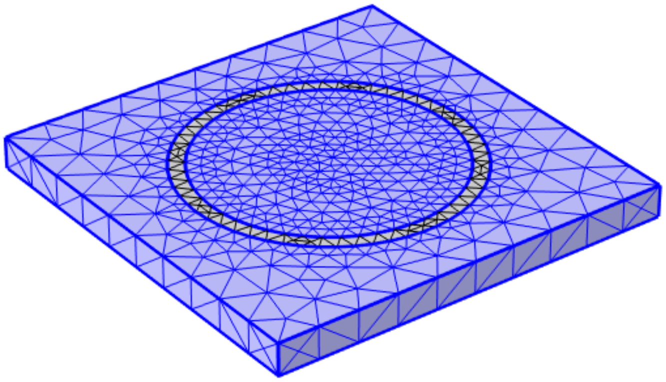


Figure 5.2: Mesh Model in Comsol

Meshing is a very important process in FEM analysis. The software divides the prepared geometry into small pieces for analysis. We have applied the normal solid model mesh with tetrahedral element size to optimize the simulation time. The obtained impedance magnitude and phase plots of the structure are given below:

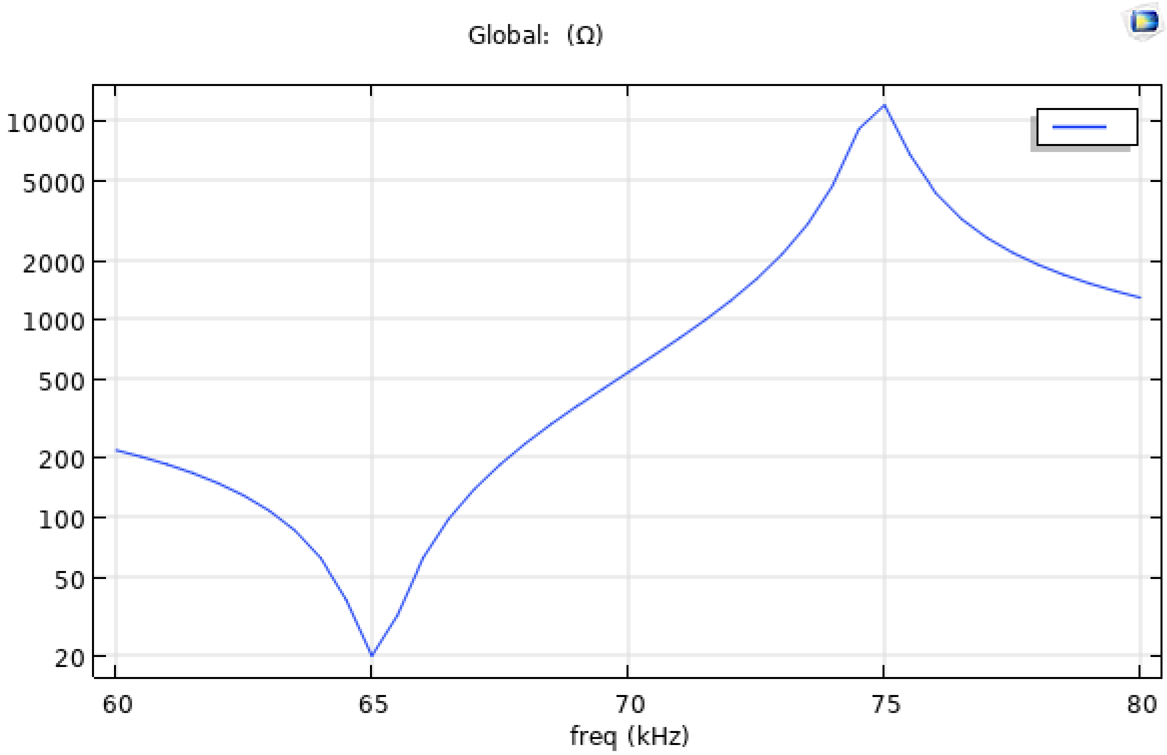


Figure 5.3: Impedance magnitude plot

For frequency response analysis the frequency range for simulating the model is 60kHz to 80kHz as shown on the x-axis. On the y-axis, it is the impedance magnitude in ohms. As far as the impedance plot is concerned the resonance frequency range has come out to be 65kHz to 75kHz. The phase plot is shown in figure 5.4 below. The phase starts changing to -90 degrees at 65kHz and then again comes to +90 degrees at 75kHz as it goes out of the resonance frequency range. This range between 65kHz and 75kHz is the maximum output operational range of the PT. The phase plot is shown below:

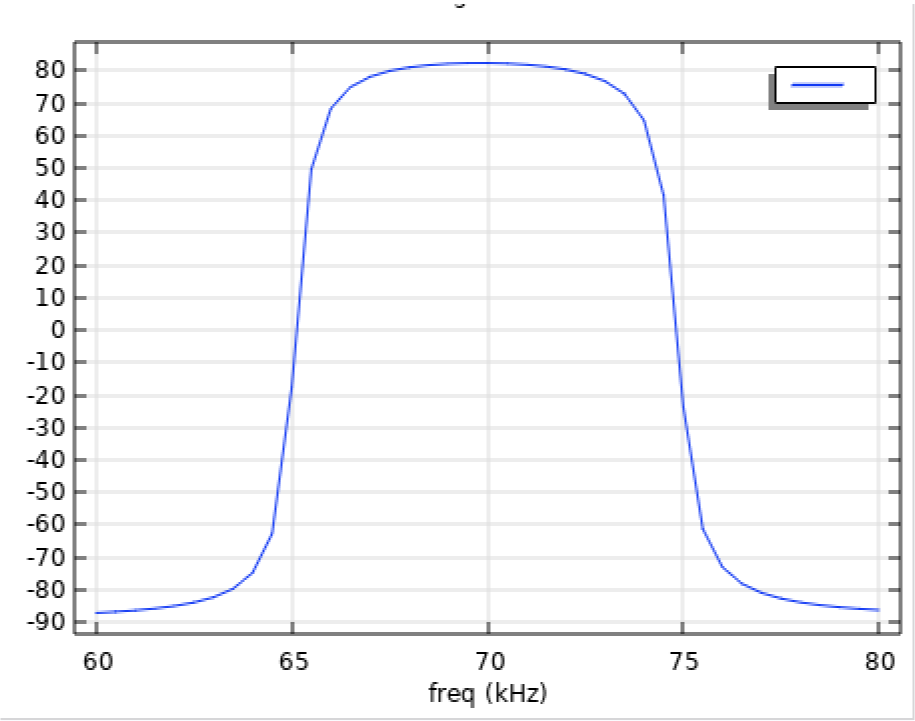


Figure 5.4: Phase plot of PT

As the material properties that we measured from analytical equations were approximation so with the help of FEM simulation we have checked for the spurious modes and extracted the material parameters. We find the impedance graph, displacement and vibration velocity. With the help of resonance and anti-resonance frequency we find the value coupling coefficient 'k' with the following formula:

$$K = \sqrt{\frac{f_a^2 - f_r^2}{f_a^2}}$$

CHAPTER 6: PIEZOELECTRIC TRANSFORMER TESTING

For experimental verification frequency signal is applied from UNI-T UTG9005C function generator. Output response is measured using Hantek DSO5102P oscilloscope as shown in figure 6.1

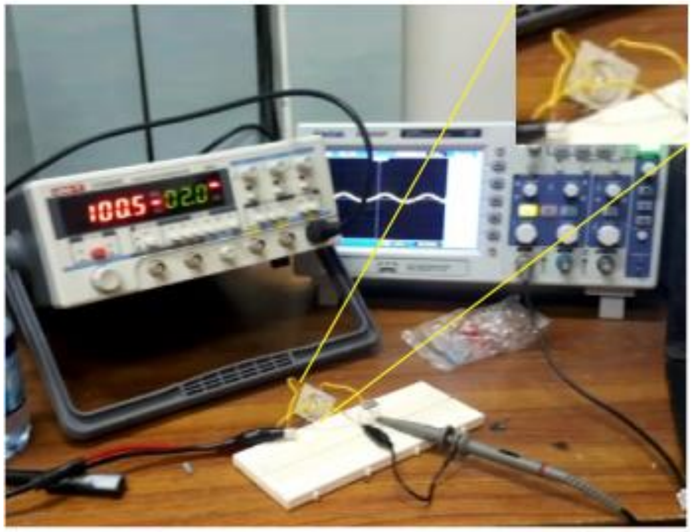


Figure 6.1: Experimental Setup

Two samples are used for experimental verification in our experiment. Both the samples are provided by SEED Lab Hanyang University South Korea. These are contour vibration mode PTs with one input layer and one output layer. Complete data of both the samples are given below:

Table 6-1: Data for testing samples

Parameters	**Sample # 1**	**Sample # 2**
PT Type	1:1 PT	1:1 PT
Length	26.64 mm	26mm
Inner Diameter	16 mm	16mm
Width	26.64 mm	26.66mm
Dielectric Gap	0.5 mm	1.5mm
Material	PZT-4	PZT-8
Resonance Frequency	76.09899 kHz	74 kHz
Anti-Resonance Frequency	82.10226 kHz	82 kHz
Coupling Coefficient $\boldsymbol{K = \sqrt{\frac{f_a{}^2 - f_r{}^2}{f_a{}^2}}}$	0.375356	0.430

Output voltage at different loads is measured. A sinusoidal voltage of 20 V is applied to sample #2 constantly with a load resistance of 22.23 ohm and only the frequency of the PT is varied from a function generator. Voltage peak is higher at high load and it decreases as the load is decreased from 100 ohms to 20 ohms. Similarly, 100 V_{rms} is applied to sample #1 and the frequency is varied and output is measured. The measured data and plots of experimental values from sample #1 and sample # 2 are shown below.

Table 6-2: Experimental and simulated values for sample # 2

Frequency kHz	**O/P V_{p-p} Experimental**	**Output Power**
70	436mV	296 mV
71	480 mV	318 mV
72	572 mV	338 mV
73	768 mV	374 mV
74	1.53 mV	420 mV
75	2.08 mV	476 mV
76	280 mV	560 mV
77	328 mV	692 mV
78	128 mV	960 mV
79	96 mV	1.04 mV
80	88 mV	3.1 V

Table 6-3: Experimental and simulated values for sample # 1

Pin	Vin (rms)	Pout	Vout(rms)
0.372457	100.746	0.327363	10.7041
0.523136	100.903	0.47115	12.8414
0.792686	101.115	0.729418	15.978
1.34756	101.431	1.26082	21.0068
2.76041	101.957	2.6159	30.2583
7.94586	102.927	7.58795	51.5343
28.9285	101.688	27.712	98.4845
11.697	97.6428	11.1888	62.5785
3.6727	98.587	3.49006	34.9502
1.70975	99.2071	1.6063	23.7108
0.989238	99.5613	0.914736	17.8929
0.651424	99.7985	0.590234	14.373
0.467066	99.9731	0.412924	12.0218
0.355683	100.111	0.305616	10.3424
0.283338	100.226	0.235748	9.08359
0.233736	100.326	0.187696	8.10515
0.198276	100.416	0.153211	7.32283
0.172071	100.498	0.127608	6.68301
0.152191	100.574	0.108063	6.14995
0.136767	100.646	0.092794	5.69893
0.124575	100.716	0.080631	5.31232

Data plots of both the samples are shown below:

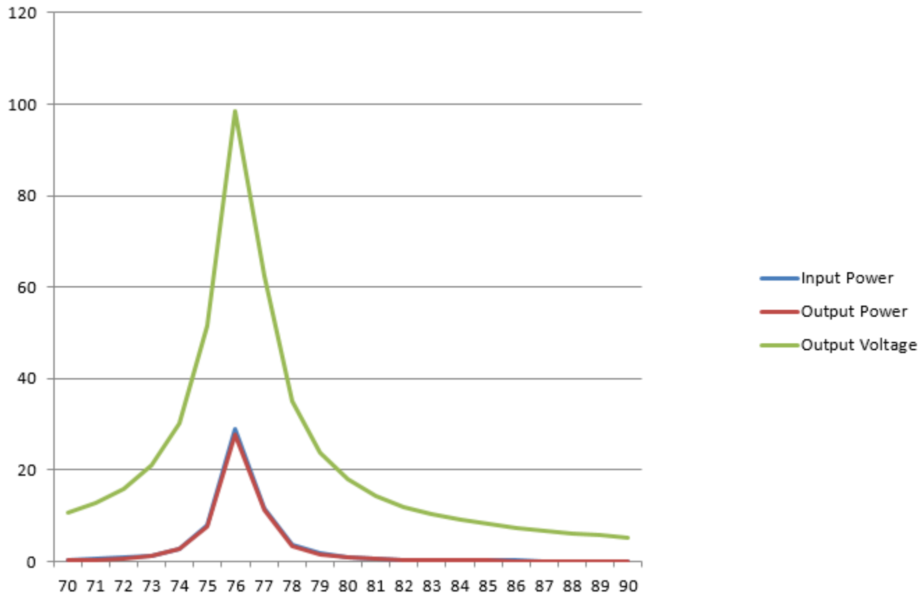


Figure 6.2: Data Plot for sample #1

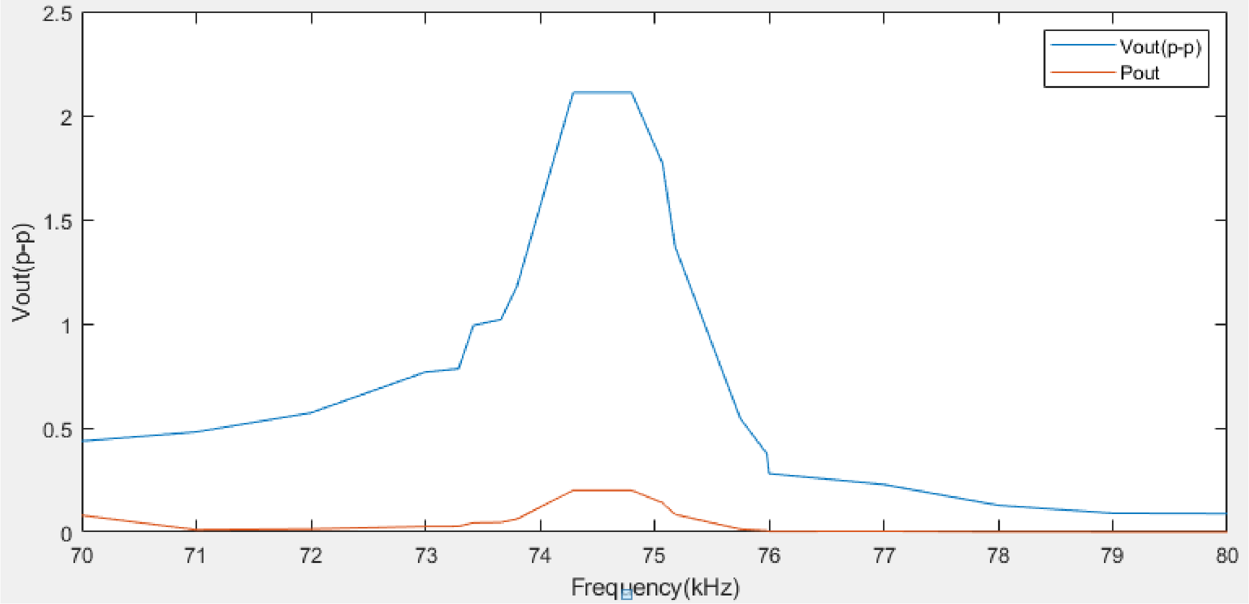


Figure 6.3: Data Plot for sample #2

CHAPTER 7: RESULTS AND DISCUSSION

The design of a piezoelectric transformer starts with the dimensional values and input and output electrical parameters values provided by the user. Dimensional parameters of the piezoelectric transformer include length and thickness whereas the electrical parameters include the input and output voltage. The next step is to choose the material powder for the manufacturing process. Normally the chosen material is Lead Zirconate Titanate (PZT) as it is studied widely in the literature. Manufacturers give the powder material properties and by using these properties we can find the approximate equivalent electrical circuit parameters.

We have approximated these parameters first in Ltspice and then in Matlab/Simulink. By approximating the equivalent electrical circuit parameters we can find the power, matching load and output voltage range across different frequencies of the PT. With the equivalent electrical circuit parameters, design and simulation next step are to design the piezoelectric transformer in Comsol for Finite Element Modelling (FEM) analysis. In these analyses we find different mode shapes samples across different frequencies, output voltage response and bode plot (impedance magnitude and phase plot) of the designed piezoelectric transformer.

The next step is to manufacture the piezoelectric transformer based on the calculated equivalent electrical circuit parameters and then extracting the equivalent circuit parameters by open and short circuit tests. With impedance analyzer following parameters were tested experimentally:

- Input capacitance Cd1 at 1kHz
- Output capacitance Cd2 at 1kHz
- Short circuit the output terminals of the PT and find the input equivalent circuit parameters with an impedance analyzer.
- Short circuit the input terminals of the piezoelectric transformer and measure the output equivalent circuit parameters.

The above data was acquired through FEM simulations as well. Based on these steps we can improve our piezoelectric design by repeating these steps and eliminating the errors.

In our case, we have not manufactured the piezoelectric transformer but tested our results with the single-layer circular input and single-layer square shaped output piezoelectric transformer provided by the SEED Lab Hanyang University South Korea.

CONCLUSION

This research work aimed to make a graphical user interface that can calculate the characteristic equivalent electrical circuit parameters based on some values that are provided by the user. These approximated results would then be used to make an equivalent electrical circuit simulation in Ltspice and Matlab/Simulink. FEM analysis would be done to find the frequency response of the material at the resonance frequency of the piezoelectric transformer.

Following are the capabilities of the design software tool

1. Parameters input from the user
2. Designer selectable PZT powder parameters
3. Calculation of Analytical Equations to generate a PT equivalent circuit model.
4. Simulation of Equivalent circuit model in SIMULINK (and LTSpice) for PT output voltage, matching load, power efficiency calculations.
5. The PT dimensional parameters calculated in step-3 were used to develop a model for FEM simulation in COMSOL. These simulations provided a better approximation of Step-3 values. Also, we can analyze the spurious (unwanted modes) in the PT.
6. Based on previous steps, the Prototype can be developed. Prototype testing data are shown, which shows the 99% transformer efficiency in the resonance frequency range and with a matching load resistor. The transformer was designed for a maximum of 100 Vrms sine signal input.
7. The software tool can list the Analytical, SPICE, FEM and Experimental PT data in a table for comparison and design iterations.

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Completion Certificate

It is certified that the contents of the thesis document titled "*Design calculator and performance analyzer software tool for step-down piezoelectric transformer*" submitted by NS Muhammad Abbas, Registration No. 00000238342 have been found satisfactory in all respects as per the requirements of Main Office, NUST (Exam branch).

Supervisor:
Dr. Hamid Jabbar
Date: