iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 **Issue:** V **Month of publication:** May 2018

DOI: http://doi.org/10.22214/ijraset.2018.5295

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 6 Issue V, May 2018- Available at www.ijraset.com

Energy Harvesting From the Piezoelectric Transformer

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***Abstract:** The piezoelectric transformer is a combination of piezoelectric actuators as the primary side and piezoelectric transducers as the secondary side, both of which work in longitudinal or transverse vibration mode. These actuators and transducers are both made of piezoelectric elements, which are composed of electrode plates and piezoelectric ceramic materials. Instead of the magnetic field coupling between the primary and secondary windings in a conventional magnetic core transformer, piezoelectric transformers transfer electrical energy via electro-mechanical coupling that occurs between the primary and secondary piezoelectric elements for isolation and step-up or step-down voltage conversion. Currently, there are three major types of piezoelectric transformers: Rosen, thickness vibration mode, and radial vibration mode, all three of which are used in DC/DC converters or in electronic ballasts for fluorescent Lamps. Unlike the other 2 transformers, the characterization and modeling of the radial vibration mode piezoelectric transformer have not been studied and developed prior to this work.*

***Keywords:** Piezoelectric Crystal, Transformer, Vibrations, Conversion, Actuators.*

I. INTRODUCTION

The transformer is one of the largest and heaviest components in the conventional circuits operating at mains frequency .it is well known that size of the transformer can be greatly reduced by increasing circuit frequency. Electrical power application using field are continuously advancing ,particularly in the domain of the miniaturization of both electrical and electro mechanical devices .This has led to the development of very compact systems such as microcomputers, micro systems, cellular transformer, telephones ,etc. The miniaturizations of classical electromagnetic transformers raisers certain problems pertaining to manufacturing of both the coils and the magnetic core, increase in magnetic leaker, degradation of performances and electromagnetic pollution of the environment .The interesting solution for the above problems is to use a piezoelectric transformer ,which would insure an electrical, mechanical-electrical double conversion of energy with a transformation ratio that allows PZT accomplishes the supply ,storage and transformation of electrical power adapting the output voltage being used .This transformer is more compact and lends itself better to miniaturization in addition to displaying the attractive characteristics of immunity to the magnetic field and a high galvanic insulation .They are inflammable ,easily driven at high frequencies and do not require magnetic shielding .

II. LITERATURE SURVEY

Most of the works related to the energy and power harvesting have been done in the recent past of whose some of the paper works have been mentioned below.

Comparison and conversion of energy from piezoelectric crystal, EM free noise and miniaturization characteristics, its conversion gain, frequency and impedance, principle of transforming voltage. This paper reviews the general modeling method of the piezoelectric transformers and its working.[1]. Low voltage driven dielectric electro active polymer actuator with integrated piezoelectric type of transformer based driver. This kind of piezoelectric transformer is used in the power conversion purposes and their design is being discussed over here.[2] This paper starts from modeling a piezoelectric transformer connected to a full wave rectifier in order to discuss the design constraints and configuration of the transformer. The optimization method adopted here use the MOPSO algorithm (Multiple Objective Particle Swarm Optimization). We start with the formulation of the objective function and constraints; then the results give different sizes of the transformer and the characteristics. In other word, this method is looking for a best size of the transformer for optimal efficiency condition that is suitable for variable load [3]. Ivensky detailed the voltage doublers rectifier by the waveform analysis of the rectifier and using a variable resister and a variable capacitor to serve as an equivalent rectifier[4]. In addition, Ivensky also made the comparisons between the voltage doublers rectifier and the current doublers rectifier[5]. However, Yaakov focused his research on the characteristic variations for the cases that PT was connected to different rectifiers and did not consider the PT design itself in detail. On the other hand, it is known that the PT can have the maximum efficiency when the PT output capacitance matches the load impedance. This condition is called the optimal (efficient) loading condition [6, 5]. The load variations prevent the PT from operating at the optimal loading condition under fixed frequency control such that variable frequency control is widely used in PT based converters [6, 7, 8]. However, variable frequency control may be too sensitive and also too complicated and costly. In fact, PT can operate at fixed frequency with good efficiency if we can be more careful in choosing a proper PT to fulfill all requirements related to the specification. To overcome this difficulty, the physical design constraints including the minimum input voltage, vibration velocity, and the dimensional constraints of the PT configuration must be examined. Especially, vibration velocity is one of the significant physical parameters[9] of PTs. Nevertheless, most papers related to PT optimize design[10] did not introduce this parameter and focused on the numerical prediction [11, 12]. Y.P. Liu proposed a design method of PT in a DC/DC converter based on analyze of the vibration velocity [13-15].

III. WORKING

Many materials such as quartz, niobate and lead titanate (PZT), exhibit some form of the piezoelectric effect. The piezoelectric transformer uses PZT, hence it is a PZT transformer. Two piezoelectric effects exist : the direct effect & inverse effect.

A. Direct Effect

If force or vibration (stress) on the piezoelectric element, then it generates a charge. The polarity of this change depends on the orientation of the stress compared with the direction of polarization. This polarization direction can be let during the manufacture process.

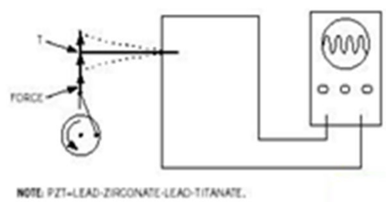

Fig 1. Result of a Vibration or Applied Force

B. Inverse Piezoelectric Effect

The principle is exactly opposite to direct effect i.e if the electric field or voltage applied to the piezoelectric element. Then it results in dimension change or strain. The direction of change is linked to the polarization direction .Applying a field at the same polarity of the element results in a dimensional increase and fields at opposite polarity results in a decrease. This phenomenon is an important factor in the operation of the transformer. The inverse or motor effect. The vibration couples through the structure to the output to generate an output voltage which is the direct or generator effect.

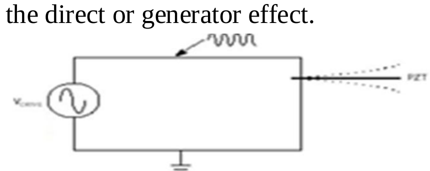

Fig 2. Inverse Piezoelectric Effect

C. Piezoelectric Transformer

The piezoelectric transformer that is discussed here is built in the hard piezoelectric material which is more suitable for this type application .The left part polarized in thickness ,represent the primary ,where as the right part polarized in length represents the secondary .all external faces are free. As a consequence we performed the transformer behavior in full wave length longitudinal vibration mode as represented in Fig 3 below.

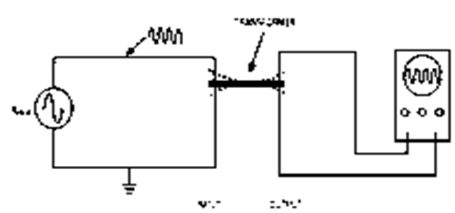

Fig 3. Longitudinal Vibration Mode of PT

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D. Operating Principle

The piezoelectric transformer uses both direct & inverse effect to create high voltage step up ratios. A sine wave voltage drives the input position of the transformer which causes it to vibrate. This operation is the inverse or motor effect. The vibration couples through the structure to the output to generate an output voltage which is the direct or generator effect.

The piezoelectric transformer forms an electrode on a piezoelectric ceramic element in a perpendicular & longitudinal direction, which has a structure polarized in both directions. If the voltage of frequency determined according to the longitudinal direction is applied in the perpendicular direction of this element , a strong mechanical oscillation occurs due to electrostriction effect in the longitudinal direction , whereby the voltage generated due to electrostriction effect is output from the electrode in the longitudinal direction , in other words the input voltage generates mechanical oscillations, which is then converted again to electricity at the secondary side by its amplitude & the voltage is to be increased according to the impedance ratio between primary & secondary .

The circuit diagram of the proposed piezoelectric converter is as shown in the Figure 5. The input voltage source Vi and the series resistance Rt denote the TEG harvester's open-circuit voltage and internal impedance. C1 and C2 are two electrode capacitances present in the piezoelectric transformer, the RLC circuit series branch represents the mechanical vibration and the ideal transformer. The converter works on the principle of Armstrong oscillator in which the replacement of the magnetic transformer is done by a piezoelectric transformer. The active component of the circuit is a depletion-mode MOSFET which is always in the normally-on mode. The circuit works as a resonant oscillator. The noise in the converter circuit is amplified and filtered by the Piezoelectric Transformer. This signal is inturn applied to the transistor and thus an AC current at the selected frequency appears at the primary branch of the converter circuit. Under particular and certain specific conditions, the signal oscillates and its amplitude increases. This signal rectification is done by the diode as soon as the threshold voltage is reached. When the loss and amplification of the signal are balanced, the circuit is said to be in the in steady-state. Initially, the transistor acts as a trans-conductance to amplify the feedback voltage applied at its gate. However, the two primary side branches of the piezoelectric transformer contain a capacitive part that prevent any DC current to flow through the transistor. Once the converter circuit is stabilized, the transistor stops exhibiting trans-conductance and thus cannot amplify the gate voltage and the oscillations disappear in the circuit. In order to resolve this issue, a biasing inductance Lin is added in parallel with C1 in order to let a DC current flow through the FET during the initial stage.

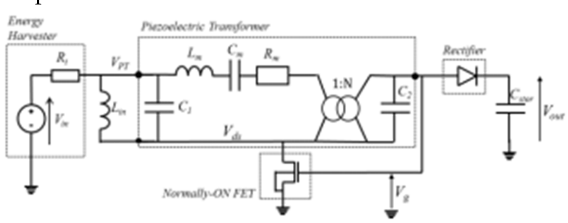

Fig 5. Circuit Schematic[16]

A small-signal analysis of the Figure 5 is as shown in the fig 6. This is combined with the application of the Barkhausen criterion which allows to find the free oscillation condition. The open-loop gain (G_{OL}) of the converter is determined by opening the loop at the gate of the transistor. The Barkhausen criterion states that oscillation appears if the following conditions are respected:

$$|G_{OL}| > 1 \text{ and } \arg(G_{OL}) = 0\ [2\pi]$$

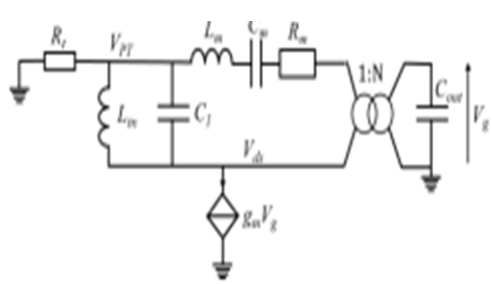

Fig 6. Small Signal Analysis of Circuit Schematic [16]

The open-loop gain of the oscillator is characterized by the trans-conductance of the transistor, the input impedance of the piezoelectric transformer and its voltage gain.

E. The Amazing One

The equivalent circuit model for the piezoelectric transformer looks identical to the that of its series resonance magnetic counterpart (Fig4). The differences however extend past the nominal values to the physical representation of the various component.

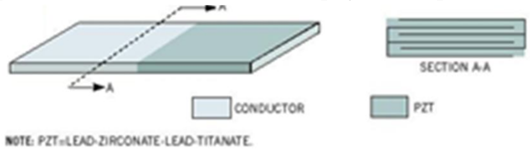

Fig 4 (a) Multilayer PZT

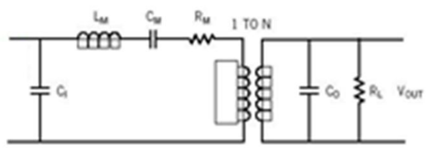

Fig 4 (b) Equivalent Circuit Model

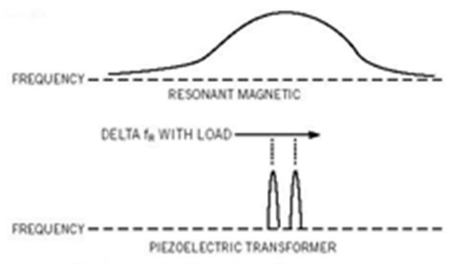

Fig 4 (c) Bandwidth of PZT

The input & output capacitance are simply the result of having a dielectric between the two metallic plates. The effective dielectric constant of the PZT material is 400 to 5000, depending on the composition unfortunately basic electronic ends.

The resonant frequency on the compliance of the material , which inturn is a function of the Young's modulus. An unusual property of piezoelectric material is that Young's modulus changes with electrical load. In most cases the shift in resonant frequency over rated load is greater than usable bandwidth

F. Features of Piezoelectric Transformer

1) Structure is very simple, thin & light.
2) Since no electromagnetic wave noise is produced ,magnetic shielding is not required.
3) Highly Safe.
4) No firing.
5) High efficiency is ensured.
6) Provide excellent coupling with low stray fields.
7) Simple to install & made with a rugged construction.

IV. MERITS

Some of the merits of the piezoelectric transformer are mentioned as follows:

A. Small size & less weight.
B. No winding & no short circuit capability between the windings.
C. It can operate at high frequency.
D. It can generate wide range of high voltage ac/dc.
E. No contribution to electromagnetic pollution as electromagnetic wave noise is produced

V. RESULTS

Following table below represents the data for piezoelectric characteristics vs frequency and load.

Load Value	Gain	Frequency (KHz)
50K	25	64
75K	38	67
100K	50	68
200K	72	69.5
250K	90	70
400K	185	70.5
500K	225	71.5
600K	235	72
750K	250	72.5
600K	230	72.9
500K	220	74
400K	180	75
250K	95	76.5
200K	70	77
100K	55	77.8
75K	35	78.5
50K	22	80

Table 1. Piezoelectric Characteristics vs Freq and Load

A Graph shown in fig 7 below depicts a bell shaped curve and the decrease in the gain for the above values.

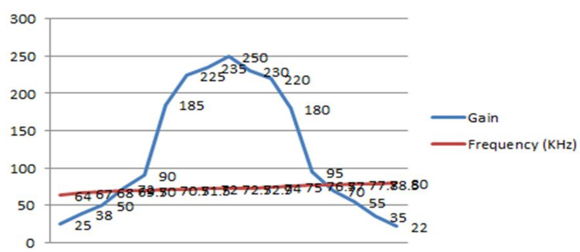

Fig 7. Piezoelectric Characteristics vs Freq and Load

The efficiency of the Piezo-Electric Transformer is much higher than the normal transformer.

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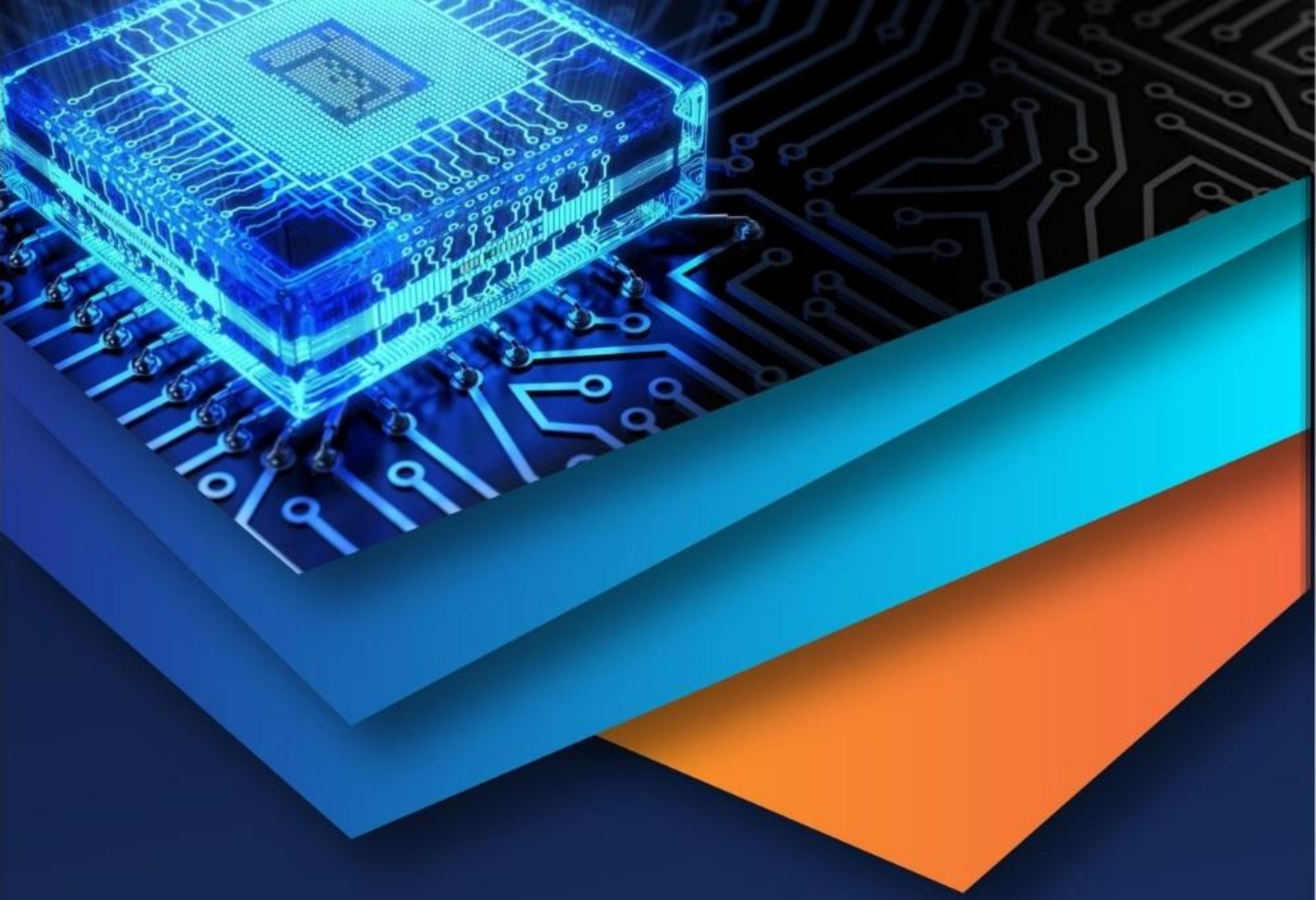

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