TELKOMNIKA Telecommunication, Computing, Electronics and Control
Vol. 18, No. 3, June 2020, pp. 1567~1572
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v18i3.14334

Comparison between piezoelectric transformer and electromagnetic transformer used in electronic circuits

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Article Info

Article history:

Received Oct 15, 2019
Revised Mar 3, 2019
Accepted Mar 12, 2019

Keywords:

Piezoelectric material
Piezoelectric transformer
PZT

ABSTRACT

This paper presents study, modeling and simulation of the piezoelectric material works as transformer (piezoelectric transformer (PT)) in power electronic circuits, comparisons are made with the regular transformer (iron core) works in the same circuit, the tested circuit is the full bridge converter which used in the simulation as dc power supply circuit. As a result, a detailed simulation for both the piezoelectric transformer and traditional transformer are achieved, as well as the output voltage from the dc power supply is tested by varying the load resistance. The dc power supply circuit has been simulated using PSIM (V9.1) power electronic circuit simulation software.

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1. INTRODUCTION

Renewable resources are sources that produce clean, clear and cost effective energy without making any harm to environment (pollution), the most common renewable resources are sunlight, wind, tides, waves, geothermal heat and ambient vibrations. Renewable energy has high efficiency and reliability. The piezoelectric materials are materials that produce electrical energy when exposed to external ambient influence (vibrations), the piezoelectric materials are widely used these days due to their ability to production of renewable energy [1, 2].

The application possibilities of piezo's are almost endless, such as scanning probe microscope scanners, power supplies, stick-slip motors and ultrasonic cleaning etc. The first empirical manifestation of a relation between microscopic piezoelectric phenomenon and crystallographic body was released by Jacques Curie and Pierre in 1880 [3]. They prepared special crystals using (quartz, tourmaline, sugar-cane, topaz and Rochelle-salt) and measure the charges on the surface of the crystals when a mechanical stress subjected to it. There are many known materials that own piezoelectric features, such as materials made of ceramic (e.g. Lead zirconate titanate (PZT)) and crystal (e.g. Quartz) and [4-6].

The effect of piezoelectric outcome from the electro-mechanical interaction in the crystal materials, which happened between the electrical and mechanical states of the crystal [7]. The piezoelectric materials are materials that generate charge when they are squeezed or positioned under mechanistic strain. The operation of PZ materials is also reversible, so if an electric field is applied to these materials, they will start vibrating and their shape will change slightly (mechanical strain), PZ materials also known as electro-mechanical materials, which can simply define as a device converts mechanical energy to electrical energy [8, 9]. The inverse piezoelectric effect is used in the production of ultrasonic sound waves which have many applications used in these days like cleaning, rock breaking, cutting etc. [10, 11].

Figure 1 shows that the piezoelectric materials are composed of an arrangement of a polarized material that is in a neutral state due to a symmetrical distribution of charge. By deforming the material, a charge can be created from a realignment of the polarized structure. This produces a voltage across a separation distance which can also be described as an electric field. PZ materials shows very strong frequency reliance when the mechanical and electrical energy are coupled [12].

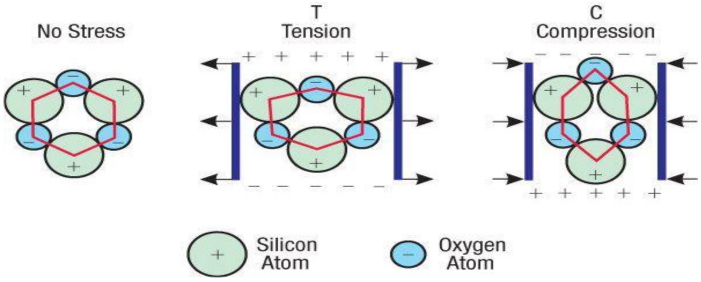

Figure 1. Piezoelectric effect in quartz

As previous state of art, authors in [13] discuss the essential boundaries on electro-mechanical energy transformation capability of piezoelectric transformers (PTs). In paper [14] authors proposed method in order to raise the power density of PTs by contact heat transfer structure to the PTs. In [15] the authors presented the behavior of the piezoelectric actuator in terms of mechanical displacement. The authors in [16] offers a design of a PZ filter module used for removing harmonic frequencies in PTs and compared the designed filter with a conventional inductor filter. In [17] authors use multiple-connected Piezoelectric Transformers in order to achieve higher output power and reduced the mechanical loss. This paper is organized as follows. Section 2 shows basic introduction and modelling of PTs. Section 3 presents the comparison and discussion for the developed power supply using PT and traditional transformer, which is verified through simulation results, followed by the conclusions and future work in section 4.

2. RESEARCH METHOD

2.1. Piezoelectric transformer basics

The piezoelectric influence is quite studied these days due to its huge applications in power conversion circuits [14]. PTs are solid-state devices that transform the electrical energy from one side to another by meaning of a mechanical vibration. These devices are fabricated using PZ materials that are working at resonance. By using suitable design and layout, it is conceivable to step-down and step-up the voltages between the input and output terminals of the PT, without using any magnetic materials (like iron core transformer) and gaining very high transformation efficiency [18]. PTs are low weight, compact, not affected by electrical noise, and can produce high power densities [15] also the PTs has no electromagnetic interference (EMI) and it’s not contain any windings like traditional transformer [17]. These benefits make PT very helpful for a lot of applications including the DC and AC power supplies used in electronic devices [19, 20], step-up transformers, plasma sources [21], and in inverters for display back-lighting, dust cleaning collectors, printing machines and image machines. The first notion of a Rosen type PZ ceramic transformer was offered by Charles A. Rosen in 1956 [22]. Since then, the development of PTs through history has been linked to the pertinent work of some excellent investigators as well as to the growth in materials, industrialization practicability, and driving circuit mechanism.

Figure 2 shows the studied type of ceramic PTs, which consists of primary and secondary electrodes on the PZ ceramic. The primary side is polarized in the thickness direction and the secondary side in the direction of the length. When voltage signal (Vin) with resonance frequency (fr) is delivered on the PT primary side, a powerful mechanical vibration is produced by inverse PZ effect, and a high voltage (Vo) is appeared at the output from the PT secondary side, matching its vibration by direct PZ effect [13].

The PT primary side is excited by an electrical AC voltage, which makes a deformation of the PTs structure. The deformation of the secondary side generates an output voltage [23]. The electrical equivalent circuit of the piezoelectric transformer is shown in Figure 3, which It can be seen that it consists of an RLC branch (R1, L1, and C1) and capacitance at the primary side C01 and C02 is the output capacitance at the secondary side [24].

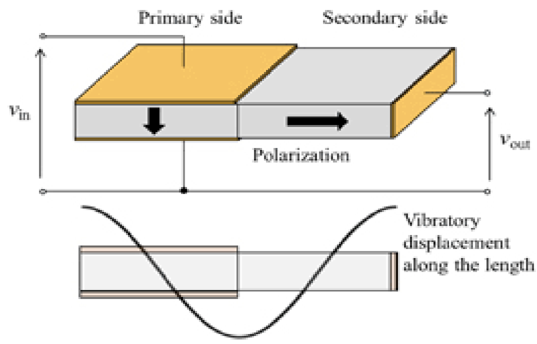

Figure 2. Ceramic type PT

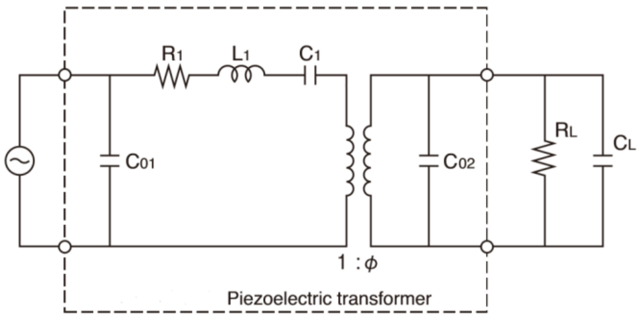

Figure 3. PTs equivalent circuit

2.2. Piezoelectric transformer modelling

A PT utilizes two interconnected piezoelectric elements. One is set into motion, by the inverse piezoelectric effect, and the other is harvesting the power from the motion by the direct PZ effect. By proper design the PT is capable of transferring energy. The conversion ratio is given by geometry, polarization and placement of electrodes. The PZ main equations in stress charge form is shown by the (1) and (2). The two equations characterize the connection between the mechanical and the electrical states. Although various vibration mode and mechanical structure are in PTs, but still the relevance between different parts of PZT is same. According to the equations of PZ, boundary conditions and wave equation, the equations substantive the PZT is given below [21, 3]:

$$T = c^E \cdot S - e \cdot E \tag{1}$$

$$D = e \cdot S + \varepsilon^S \cdot E \tag{2}$$

where, the PZ material stress is represented by symbol (T) measured in [N/m^2], the strain in the PZ material is represented by the symbol (S), the electric field is represented by the symbol (E) measured in [V/m], the electric displacement is represented by symbol (D) measured in [C/m^2], the elastic stiffness tensor is represented by (cE) measured in [N/m^2], the PZ permittivity at constant strain is represented by (εS) and (e) is the piezoelectric constant [25].

3. RESULTS AND ANALYSIS

In this paper the PT is tested as step-up transformer in the DC/DC full bridge converter circuit, the modeling of PT converters by using Rosen type is shown in Figure 4. The parameters of the PT converters represented in Table 1. The values of PT circuit parameters are taken from the Specifications of the PT model AP-313TP. The simulation is made using PSIM software version 9.1, by using the values in Table 1 the simulation circuit diagram is shown in Figure 5, the simulation is done as two parts, the first part is use the PT as step-up transformer in the DC/DC converter circuit and the obtained results are shown in Table 2, the second part is use regular transformer (iron core) instead the PT in the same DC/DC converter circuit and the obtained results are shown in Table 3.

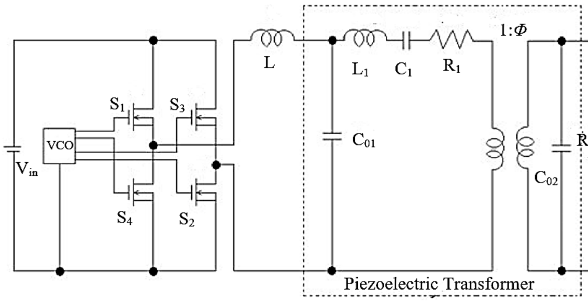

Table 1. Power supply parameters

Parameter	Value
V_{in}	12 (V)
C_{01}	400 (pF)
L_1	50 (mH)
C_1	20 (pF)
R_1	150 (Ω)
C_{02}	3 (pF)
Φ	5 (-)
f_S	50 (KHz)
C_F	1 (nF)
L	2.03 (mH)

Figure 4. Circuit diagram of full bridge converter using PT

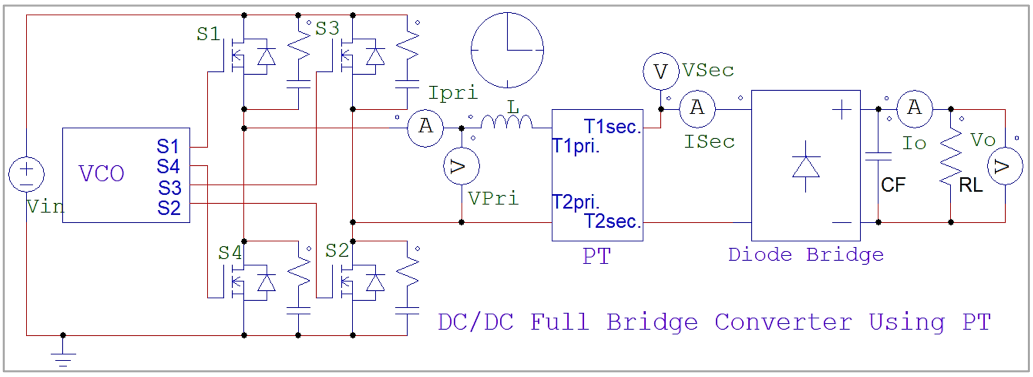

Figure 5. Simulation circuit diagram for DC/DC full bridge converter using Rosen type PT

Table 2. DC/DC power supply results using PT

Input Voltage (Volt)	Load Resistant (K Ω)	Output Voltage (Volt)	Output Current (Ampere)	Output Power (Watt)	THD (%)
12	300	54.53	0.0001733	0.00896003	1.20524
12	400	56.77	0.0001411	0.00786678	1.15634
12	500	59.45	0.0001189	0.00698858	1.13817
12	700	59.89	0.0000892	0.00519658	1.09394
12	1000	60.01	0.0000636	0.00402404	1.04899

Table 3. DC/DC power supply results using regular transformer

Input Voltage (Volt)	Load Resistant (K Ω)	Output Voltage (Volt)	Output Current (Ampere)	Output Power (Watt)	THD (%)
12	300	58.03	0.0001988	0.01186207	3.15394
12	400	59.02	0.0001489	0.00097471	2.13576
12	500	59.25	0.0011856	0.00710329	1.26831
12	700	59.46	0.0000849	0.00512556	1.13546
12	1000	59.75	0.0000596	0.00366717	1.03245

Comparison is made between the obtained results from the two circuits (power supply circuit) once by using PT and again by using iron core transformer, both works at switching frequency (f_S = 50KHz), which shows that for variable wide range load resistance (R_L) the output voltage (V_o) is almost constant for both circuits with transformation ratio (Φ=5), and although low power obtained at the power supply output but the PT works as perfect step-up transformer with low total harmonic distortion (THD) in the output current signal less than 1.3%, high conversion efficiency (about 94%), and high reliability. For all the benefits mentions, also the PT has no core losses appeared (iron losses and eddy current losses) no electromagnetic interference (EMI), and good input–output isolation Figure 6 shows the simulation results for DC/DC power supply based on PT with R_L = 700 KΩ. an output voltage of (V_o = 60 volt) is achieved and output current injected to the load by (I_o = 8.92*10^{-5} Amp.) with THD = 1.0939%, which results output power received (P_o = 5.195 mW).

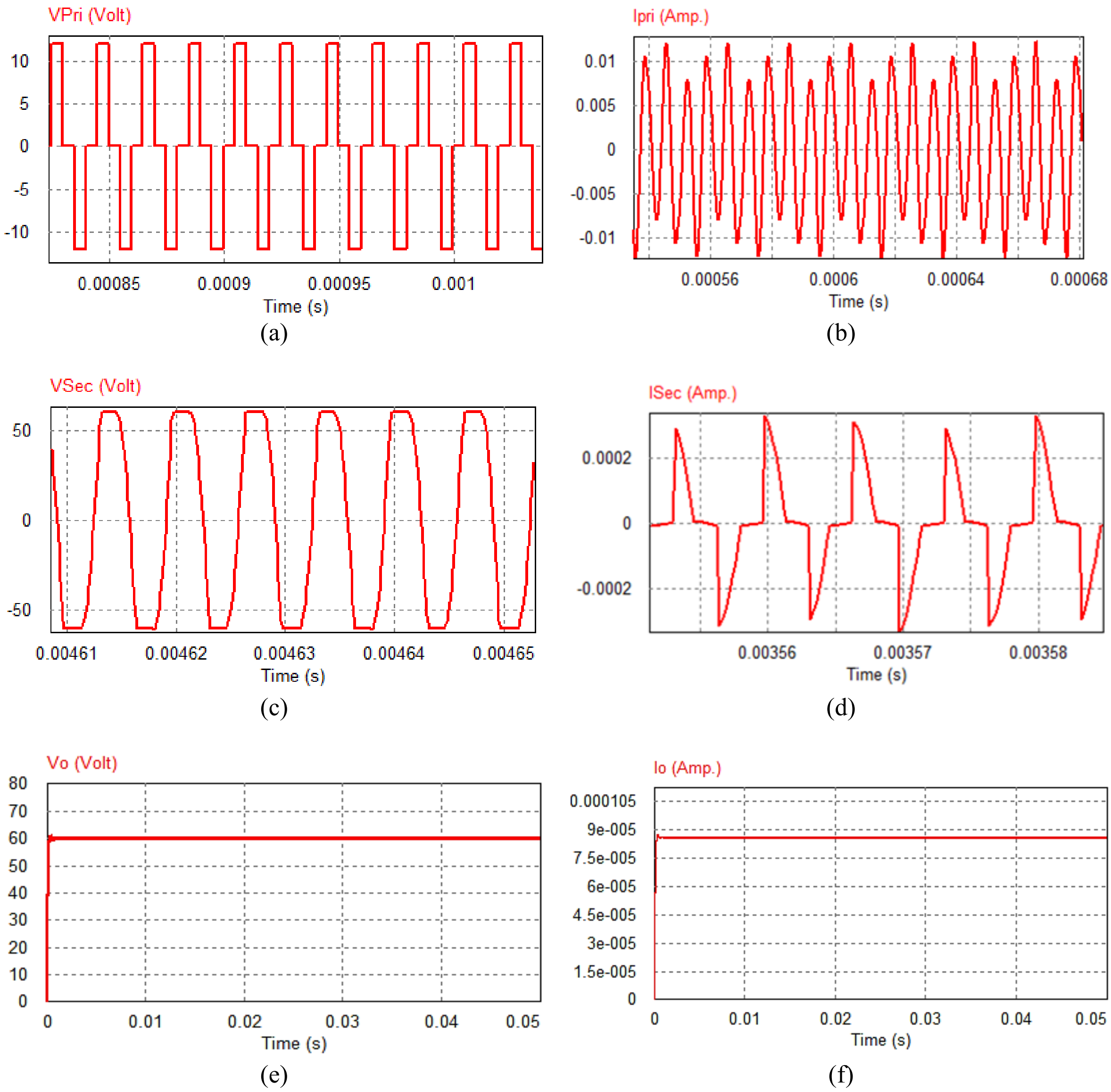

Figure 6. DC/DC power supply based on PT simulation results for RL=700 KΩ, (a) Voltage at the primary side of PT, (b) Current at the primary side of PT, (c) Voltage at the secondary side of PT, (d) Current at the secondary side of PT, (e) Output voltage, (f) Output current

4. CONCLUSION

In this paper, PT as step-up transformer works in DC/DC power supply is simulated using PSIM software, the results from simulation compared with traditional electromagnetic transformers (iron core transformer). The results show that PTs are promising because they have a very low THD, no core losses appeared, high efficiency (above 94%). Also they have many advantages on the regular transformer such inflammable, leakage flux not appears, high reliability, small size and thickness, flexible transforming ratio, electromagnetic immunity incombustibility, good isolation and low harmonic current noise. The industrialization process for PTs is much simpler than for iron core transformers as there is no windings or assembled cores are required also with reduced element size and weight. As future work a multiple PTs can be used in parallel in order to increase the power supply output power delivered at the load.

ACKNOWLEDGEMENTS

The authors would like to thank the Iraqi government represented by the ministry of higher education and scientific research, Mustansiriyah University (www.uomustansiriyah.edu.iq) Baghdad–Iraq for its support in the present work.

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