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Harmonics elimination for DC/DC power supply based on piezoelectric filters

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ABSTRACT

This research presents a study, modelling and simulation of the piezoelectric material work as filters (piezoelectric filter) used to eliminate the harmonics in power electronic circuits, high order harmonics are generating due to the high switching frequencies and circuit equipment, detailed simulation is achieved for the piezoelectric filter tested in full-bridge DC/DC converter circuit with resistive load works as dc power supply (12 to 48 volt). As a result, the uses of piezoelectric filters have a great impact on harmonics elimination, which leads to reduce the overall total harmonic distortion leads to increase the efficiency, as well as the output voltage from the dc power supply remain constant by varying the load resistance over a wide range. The dc power supply circuit including the piezoelectric filter has been simulated using PSIM (V9.1) power electronic circuit simulation software.

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1. INTRODUCTION

The piezoelectric materials (PZ) have been widely used for the last two decades in electronic applications, the possibilities of piezo's usage are almost endless, such in the communication field, sensors (ultrasonic sensors, knock sensors, shock sensors, acceleration sensors, scanning probe microscope scanners), power sources (electrical-mechanical transducers), stick-slip motors, ultrasonic cleaners piezoelectric actuators, piezoelectric fans, filters (ceramic resonators, ceramic filters, microforms, and surface acoustic wave filters). [1], [2]. The first empirical manifestation of a relationship between the microscopic piezoelectric phenomenon and the 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 mechanical stress subjected to it. Many known materials 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 a 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].

Figure 1 shows that the piezoelectric materials are composed of an arrangement of a polarized material that is in a neutral state due to the asymmetrical 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 show very strong frequency reliance when mechanical and electrical energy are coupled [10]-[12].

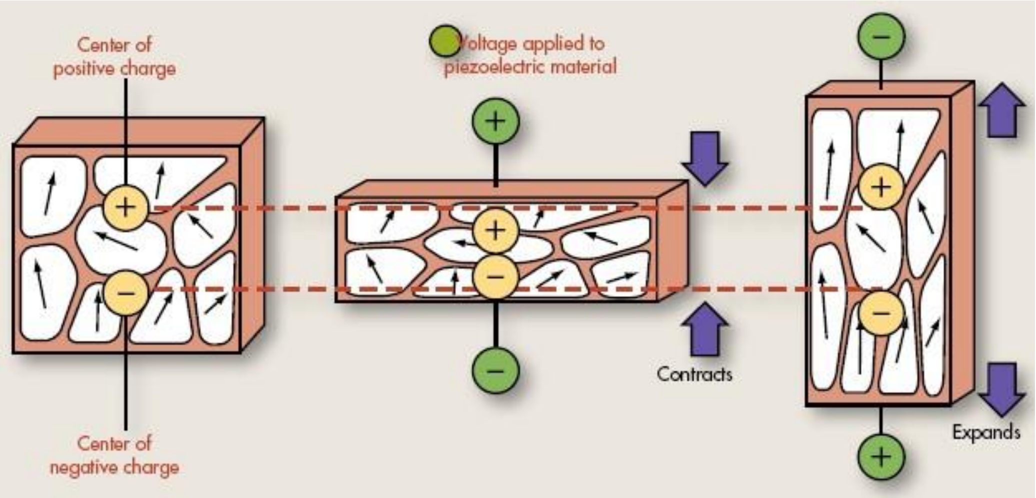


Figure 1. Piezoelectric effect in crystal materials.

As the previous state of art, authors in [13] discuss the essential boundaries of electro-mechanical energy transformation capability of piezoelectric transformers (PTs). In paper [14] authors proposed a method to raise the power density of PTs by contact heat transfer structure to the PTs. The author in [15] shows the applications of piezoelectric filters and resonators. The authors in [16] offer 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 to achieve higher output power and reduced mechanical loss.

This paper is organized as follows. Section 2 shows the basic introduction and modeling of the PFs. Section 3 presents the analysis and discussion for the developed power supply and eliminate harmonics using PF, which is verified through simulation results, followed by the conclusions and future work in Section 4.

2. RESEARCH METHOD

2.1. Piezoelectric filters basics

Harmonics appears on the electric system as abrupt short pulses in electric voltages and currents, which created by the electronic circuit equipment (wires, transformers, and inductors) and machinery can malfunction or fail in the presence of high harmonic voltage and/or current levels, the harmonic distortion that appears in the electronic circuits has become a growing concern, which degrades the level of power quality and its efficiency. Harmonics are especially prevalent when there are many personal computers, laser printers, fax machines, copiers, or medical test equipment, fluorescent lighting, uninterruptible power supplies (UPSs), and variable speed drives all on the same electrical system.

The piezoelectric influence is quite studied these days due to its huge applications in power conversion circuits [14]. For high frequencies filtering it’s more difficult to make mechanical filters, due to the dimensions of the mechanical resonator shrinks inversely to the resonant frequency [15] so PFs are very suitable for high-frequency filtering applications. The PFs are devices that transform electrical energy by the meaning of mechanical vibration. These devices are fabricated using PZ materials that are working at resonance. By using suitable design and layout, it is conceivable to eliminate the harmonics in the signals without using any elements like inductor or capacitor, which leads to gain very high electromechanical transformation efficiency, high stability, high machinability [18]. PFs are the best choice over the traditional filters due to PFs are low weight, low cost, small size and not affected by electrical noise [16]. These benefits make PF very helpful for a lot of applications including the DC and AC power supplies used in electronic devices [19], step-up transformers, plasma sources [20], and in inverters for display back-lighting, dust cleaning collectors, printing machines and image machines. Since then, the development of PFs 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 [21].

Figure 2 shows the type of ceramic PF, which consists of two electrodes are mounted at the top and bottom of the PZ ceramics. When there is a stress on the PZ, it produces polarization which is a linear function of the stress (piezoelectric effect), and when a piezoelectric substance has an electric field applied across its electrodes, it produces distortion which is a linear function of the electric field (reverse piezoelectric effect) an AC voltage signal with certain frequency is submitted on the terminals of the PF, a powerful mechanical vibration is produced by inverse PZ effect [13], [22]. The electrical equivalent circuit of the PF is shown below in Figure 3, which it can be seen that it consists of an RLC series branch (R_1, L_1, and C_1) represents the inertia, friction, and stiffness of the crystal connected in parallel to capacitance C_0, which represent the self-capacitor of the crystal [23].

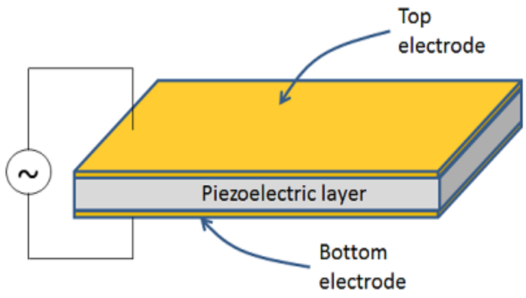


Figure 2. Ceramic type PF.

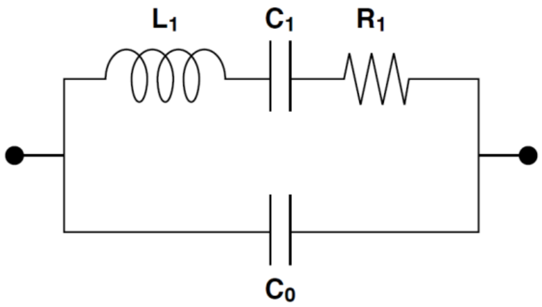


Figure 3. PFs equivalent circuit.

2.2. Piezoelectric filter modelling

As mention before the PF characteristics for the piezoelectric effect and reverse piezoelectric effect can be illustrated in the (1)(2) [20]:

$$P = d\,T \tag{1}$$

$$S = d\,E \tag{2}$$

where (P) is the polarization, (T) is the stress measured in [N/m^2], (S) distortion, (E) electric field measured in [V/m] and (d) piezoelectric strain constant. For an elastic material, the relationship of distortion S to the stress T is given by (3) and for a dielectric substance, the relationship of electrical displacement D with electric field strength E is given by (4) [24]:

$$S = s^E T \tag{3}$$

$$D = \varepsilon E \tag{4}$$

where (s^E) is the compliance, (ε) is the PZ permittivity at constant strain and (D) is the electric displacement measured in [C/m^2]. The PZ main equations in stress charge form are shown by (5) and (6). These equations called the basic piezoelectric equations, which characterize the connection between the mechanical and the electrical states. Although various vibration mode and mechanical structure [3]:

$$S = s^E \cdot T + d \cdot E \tag{5}$$

$$D = d \cdot T + \varepsilon^T \cdot E \tag{6}$$

All ceramic filters derive their basic frequency selectivity from a mechanical vibration resulting from a piezoelectric effect, the resonant and anti-resonant frequencies of PF shown in Figure 4 can be calculated by using (7) and (8) respectively;

$$f_r = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{7}$$

$$\mathrm{f_a} = \frac{1}{2\pi\sqrt{\mathrm{L_1}\frac{\mathrm{C_1 C_0}}{\mathrm{C_1+C_0}}}} \tag{8}$$

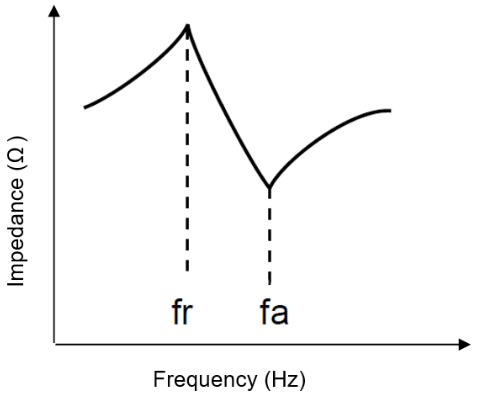


Figure 4. The typical response for PF.

3. RESULTS AND DISCUSSION

In this research, the piezoelectric ceramic materials are tested as a filter in DC/DC full-bridge converter circuit presented by 12 to 48 DC/DC power supply, the modeling of PF by using ceramic type as shown in Figure 5. The parameters of the PF represented in Table 1. The parameters are taken from the Specifications of the ceramic PF model CH-S42, which used to filter signals with 150KHz.

Table 1. PF parameters

Parameter	Nominal Value
L_1	50 mH
C_1	20 nF
R_1	150 Ω
C_o	400 nF

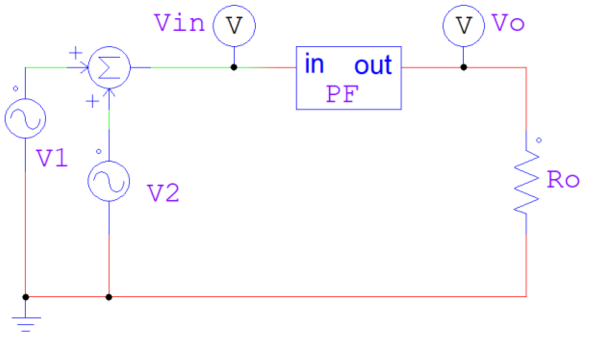


Figure 5. Test circuit for PF.

At first to check the harmonic elimination ability of the PF a simple test circuit shown in the Figure 5 is used, which is presented by an AC source generate a signal with 3rd harmonics V_{in} (9) and resistive load R_o;

$$V_{in} = V_1 + V_2 \tag{9}$$

where, $V_1 = V_m \sin \omega t \; and \; V_2 = (V_m/3)\sin(\omega \times 3)t,$
By substituting $V_m = 220V \; and \; \omega = 2\pi f, f = 150\text{kHz}$ in (9);

$$V_{in} = 220\sin(942 \times 10^3)t + 73.334\sin(2826 \times 10^3)t$$

Figure 6 shows the input and output signals to the PF, which is very clearly shows that the 3^{rd} harmonic has been eliminated from the input signal also Figure 7 the fast Fourier transform (FFT) show that.

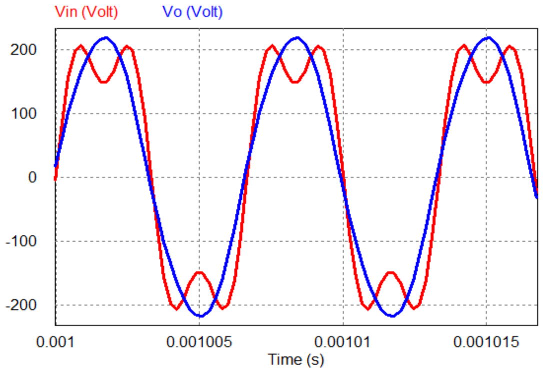


Figure 6. Input and output signals for PF

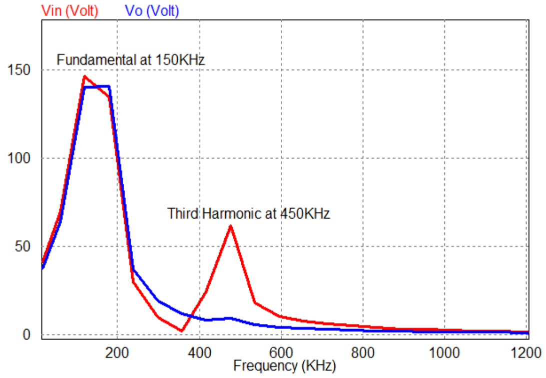


Figure 7. FFT for PF Input and output signals

Now after checking the PF filter performance, the PF filter is tested in full-bridge converter circuit, presented by 12-48 volt DC/DC power supply, which used to filter the outage signal from the transformer secondary side, Figure 8 shows the circuit diagram for the power supply [25] and Table 2 shows the system specifications.

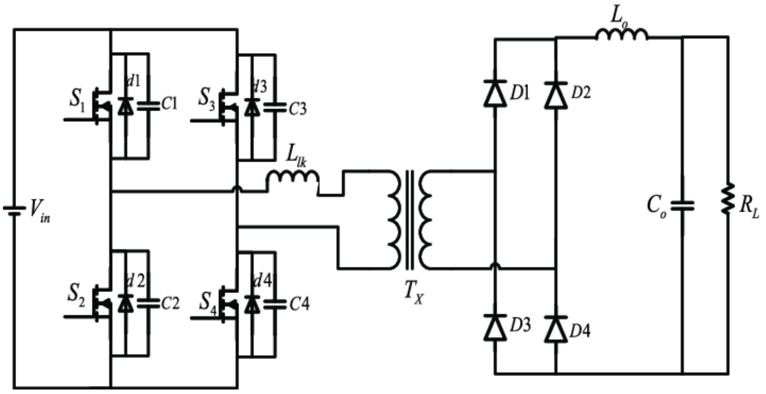


Figure 8. Full-bridge DC/DC converter topology [26].

For the in, the resonant (f_r) and anti-resonant (f_a) frequencies can be calculated mathematically by substituting the values of PF parameters in Table.1 into (7) and (8), which has been verified using simulation results as shown in Figure 9 with a slight difference between mathematical and simulation results.

$$f_r = \frac{1}{2 \times 3.14 \times \sqrt{50 \times 10^{-3} \times 20 \times 10^{-12}}} = 159.235\ KHz$$

$$f_a = \frac{1}{2 \times 3.14 \times \sqrt{50 \times 10^{-3} \times \frac{20 \times 10^{-12} \times 400 \times 10^{-12}}{20 \times 10^{-12} + 400 \times 10^{-12}}}} = 163.168\ KHz$$

Table 2. Power supply specifications

Parameter	Specification	Value
V_{in}	DC input voltage	12 V
V_o	DC output voltage (Desired)	48 V
f	Converter switching frequency	150 kHz

T	Transformer ratio	1:4
C	Filter capacitance	250 µF
R_o	Load resistance (minimum)	100 KΩ

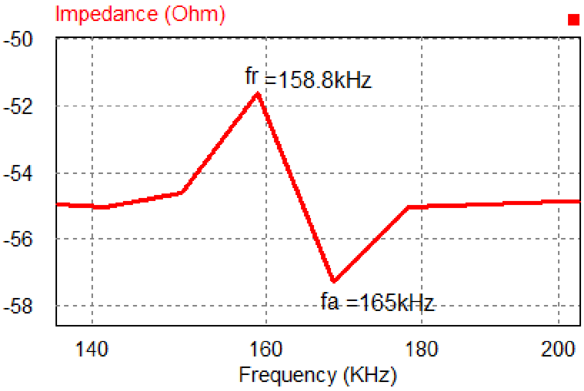


Figure 9. The typical response for PF

The simulation is made using PSIM software version 9.1, by using the values in Table 2 the simulation circuit diagram is shown in Figure 10, for the power supply the simulation results are obtained and shown in Table 3, Figure 11 shows the power supply output voltage remains constant at 48V by changing the load from 200K-1MΩ.

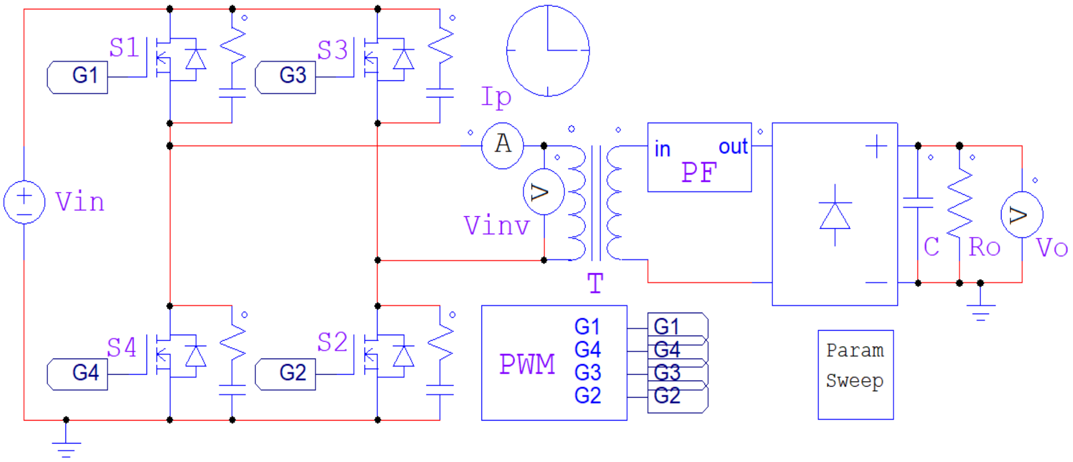
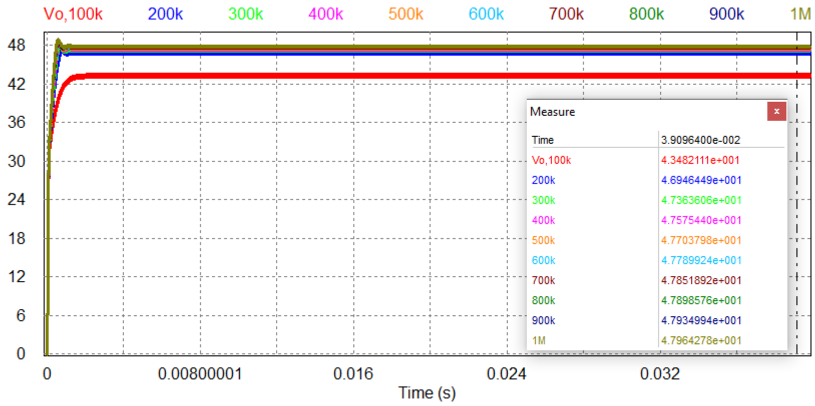


Figure 10. Simulation circuit diagram for DC/DC full-bridge converter using ceramic type PF



Time	3.9096400e-002
Vo,100k	4.3482111e+001
200k	4.6946449e+001
300k	4.7363606e+001
400k	4.7575440e+001
500k	4.7703798e+001
600k	4.7789924e+001
700k	4.7851892e+001
800k	4.7898576e+001
900k	4.7934994e+001
1M	4.7964278e+001

Figure 11. Output voltage signal for different loads

Table 3. Simulation results

R_o (KΩ)	V_o (Volt)
100	43.48
200	46.94
300	47.36
400	47.57
500	47.70
600	47.78
700	47.85
800	47.89
900	47.93
1000	47.96

Figure 12 and 13 shows the output signal at transformer secondary side before and after the PF, which shows the high PF performance for harmonics elimination 3rd and 5th, which has a great impact on the power supply performance and increase efficiency.

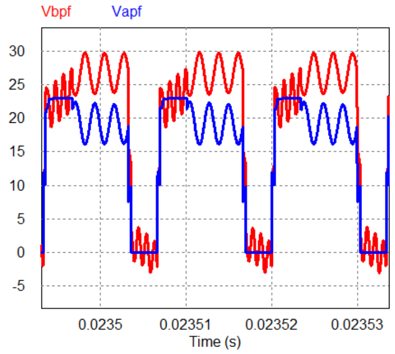


Figure 12. Transformer output voltage signal before and after PF.

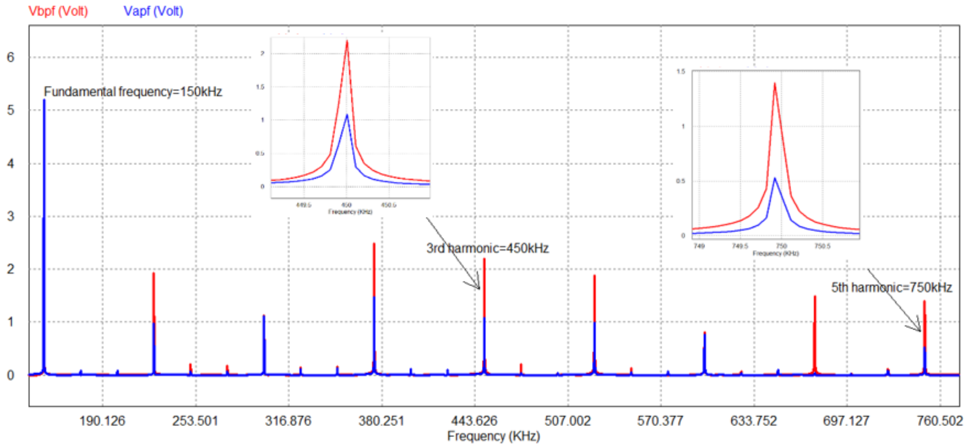


Figure 13. FFT for the output voltage signal from the transformer.

4. CONCLUSION

The present work investigated the performance of PF for harmonics elimination works in full-bridge DC/DC converter circuit by tuning the values of the PF as shown in Table 1 to filter the signals with 150KHz frequency, which increases the power supply efficiency, size and cost which no need for filter equipment (inductor. Regarding the simulation results obtained from the system of power supply (Table 3) confirmed that the power supply is robust and reliable against output load changes and it strongly less sensitive to disturbances for variations).

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