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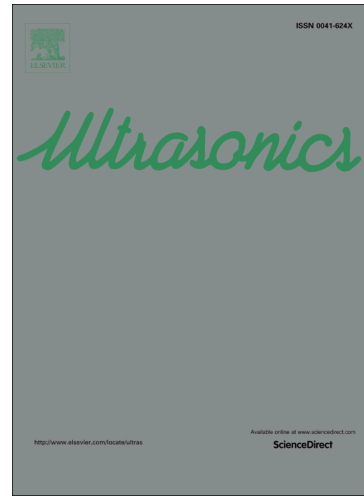

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Dissimilar trend of nonlinearity in ultrasound transducers and systems at resonance and non-resonance frequencies

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Abstract— Several factors can affect performance of an ultrasound system such as quality of excitation signal and ultrasound transducer behaviour. Nonlinearity of piezoelectric ultrasound transducers is a key determinant in designing a proper driving power supply. Although, the nonlinearity of piezoelectric transducer impedance has been discussed in different literatures, the trend of the nonlinearity at different frequencies with respect to excitation voltage variations has not been clearly investigated in practice. . In this paper, to demonstrate how the nonlinearity behaves, a sandwich piezoceramic transducer was excited at different frequencies. Different excitation signals were generated using a linear power amplifier and a multilevel converter within a range of 30 V- 200V. Empirical relation was developed to express the resistance of the piezoelectric transducer as a nonlinear function of both excitation voltage and resonance frequency. The impedance measurements revealed that at higher voltage ranges, the piezoelectric transducer can be easily saturated. Also, it was shown that for the developed ultrasound system composed of two transducers (one transmitter and one receiver), the output voltage measured across receiver is a function of a voltage across the resistor in the RLC branches and is related to the resonance frequencies of the ultrasound transducer.

Index Terms **—** High power ultrasound transducer, nonlinear behaviour, ultrasound system excitation, power electronic converters

1. INTRODUCTION

High power converters utilized in ultrasound systems play a significant role in different applications where an energy conversion at different ranges of voltage and frequency is required. In such a system, a high power ultrasound transducer converts electrical energy to mechanical energy (ultrasound wave) and vice versa [1-7]and the transducers can be employed as transmitters, receivers or both. As shown in Fig. 1, as a transmitter, the ultrasound transducer converts an electrical energy (v_{input}) to a mechanical energy (ultrasound waves) and as a receiver it converts a mechanical energy back to an electrical energy (v_{output}) [2].

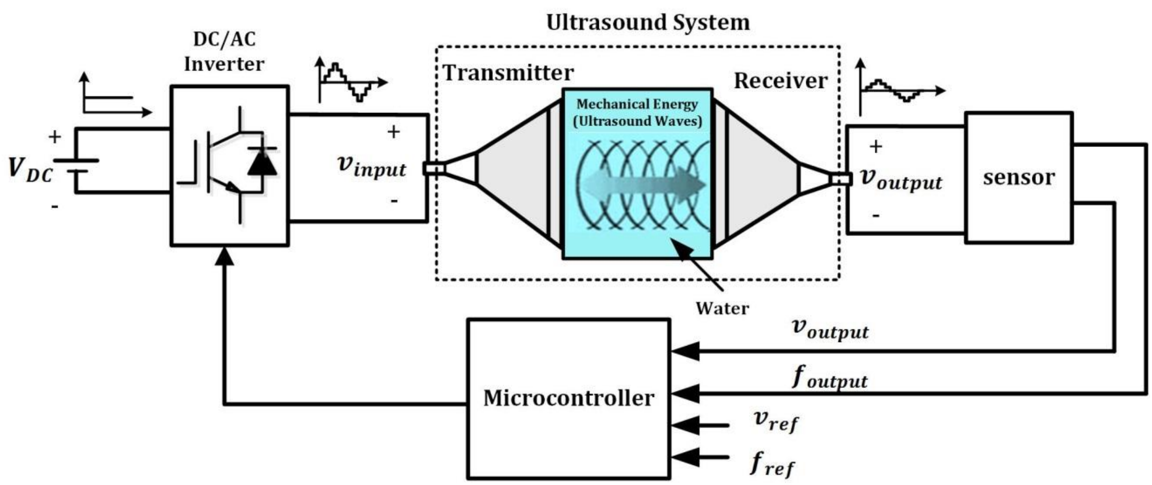


Fig. 1. Block diagram of the ultrasound system

To achieve a high power energy conversion, a transmitter should be excited by a high power signal tuned at a specific frequency. Power electronic converters are key technology to converter different power types – DC or AC ⇔ DC or AC – and generate a desirable voltage and/or frequency suitable for many applications including the ultrasound system. The associated control system generates a desired reference signal through an output feedback for which the accuracy of such a control system highly depends on the load behaviour. The nonlinearity of the load can affect the accuracy of the system and hence a proper control system needs to be developed based on the load and system characteristics [8]. A high power ultrasound system as a load for a power electronics converter can deteriorate the performance of the system and increase the power consumption if its nonlinear behaviour is not well understood. Thus, to attain a better control, the behaviour of the ultrasound system should be studied.

The system characteristic can be affected by the characteristic of the ultrasound transducer. The intensity of the generated ultrasound wave is highly related to the mechanical deformation of a material within the transducer which depends on the applied electrical energy across the ultrasound transducer. In this case, to have a better performance, an appropriate excitation signal with high quality (low distortion) is required [2, 3, 8].

In high power ultrasound systems used in industrial and biomedical applications [9, 10], a flexible power supply is required to convert an electrical energy into a desirable signal with adjustable amplitude and frequency in order to efficiently excite the high power transducer [11]. Thereby, investigating the ultrasound transducer behaviours at both device and system levels within different voltage and frequency ranges can give a better insight in maximizing the energy conversion performance.

An ultrasound transducer has several resonance frequencies in which its lowest electrical impedance results in a high efficient energy conversion compared to non-resonant frequencies (high impedances) [12-14]. Usually the resonant frequencies are represented and modelled by a parallel combination of RLC legs. Several electrical models of an ultrasound transducer are introduced in literature [12, 15-17]. Fig. 2 illustrates the most well-known models. The *Van Dyke model* is the basic model of the transducer which is a parallel connection of a series RLC leg and a capacitor [17]. The *Sherrit model* proposes a parallel combination of a series LC leg and a capacitor. The *Easy model* is another type of electrical model in which a resistor and a capacitor are in series with a parallel RLC leg [12]. An electrical model of the ultrasound transducer with multiple resonance frequencies is shown in Fig. 2(d) and is used for further analysis through this paper.

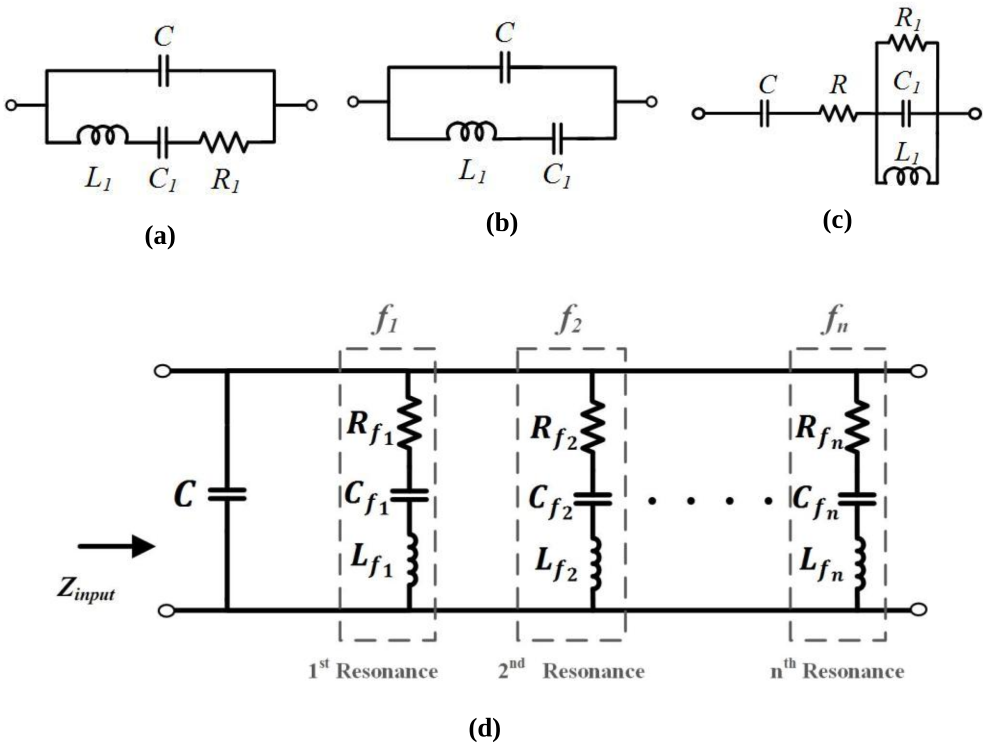


Fig. 2. Electrical model of an ultrasound transducer (a) Van Dyke model [12] (b) Sherrit model [12] (c) Easy model [17] and (d) extended Van Dyke model for a device with multiple resonance frequencies

According to Fig. 2 (d), (Z_{input}) is the total input impedance of the transducer which is given in (1).

$$Z_{input}(\omega) = Z_C(\omega) \| Z_{f_1}(\omega_1) \| Z_{f_2}(\omega_2) \dots \| Z_{f_i}(\omega_i) \quad \text{for } i = 1,2,\dots,n \tag{1}$$

$$Z_C(\omega) = {}^{1}/_{j\omega C}$$

$$Z_{f_i}(\omega_i) = R_i + Z_{L_i}(\omega_i) + Z_{C_i}(\omega_i) = R_i + j\left(\omega_i L_i - \frac{1}{\omega_i C_i}\right) \quad \text{for } i = 1,2,\dots,n$$

$$\omega_i = 2\pi f_i \qquad \text{for } i = 1,2,\dots,n$$

$$f_i = \frac{1}{(2\pi\sqrt{L_i C_i})} \quad \text{for } i = 1,2,\dots,n$$

where Z_{input} is the total impedance of piezoelectric transducer, Z_{f_i}, R_i, L_i and C_i are the equivalent impedance, resistance, inductance and capacitance of the transducer respectively at f_i and f_i is the i^{th} resonant frequency of the transducer.

Since at each resonance frequency of the transducer, the inductor and the capacitor reactance (X_L and X_C) of that particular leg are opposite and equal, hence they cancel each other. In this case, the resistor of that particular leg represents as an element to converter an electrical energy to a mechanical energy.

Thereby, as it is shown in Fig. 3, in an ultrasound system the resistor of the transmitter (R_{f_i}) is a function of the input voltage (v_{input}) and the resonant frequency (f_i) and it is given in (2). Also, it shown that the output voltage (v_{output}) across the second transducer (receiver), is directly related to the generated mechanical energy which in turn is a function of the resistor of the transmitter at the resonant frequency and it is given in (3).

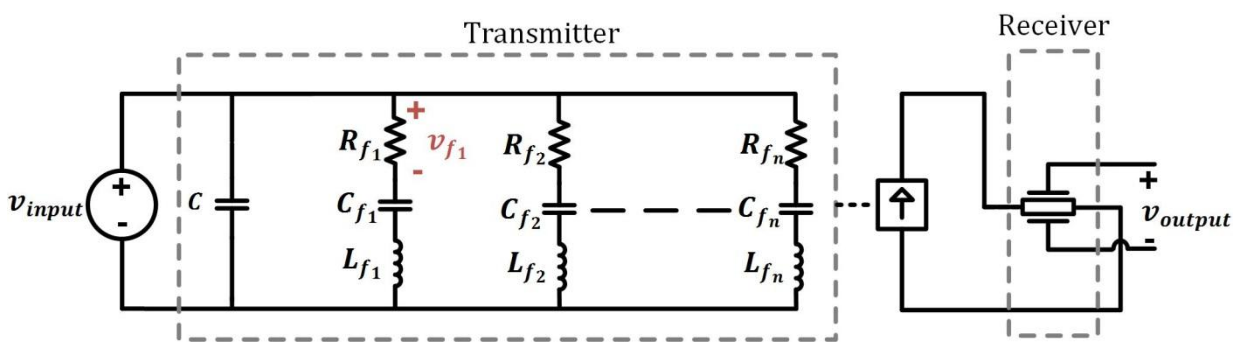


Fig. 3. Circuit diagram of the ultrasound system includes two ultrasound transducers

$$R_{f_i} = g(v_{input}, f_i) \quad (2)$$

$$v_{output} = g(R_{f_i}) \quad (3)$$

with R_{f_i} being the resistance of the ultrasound transducer at the i^{th} resonant frequency, f_i frequency of the i^{th} resonant frequency, v_{f_i} the voltage across R_{f_i} and v_{output} the output voltage of the ultrasound system.

If the input voltage is a sinusoidal signal with a fundamental frequency close to one of the resonant frequencies of the ultrasound transducer for instance i^{th} resonance frequency, v_{output} is proportional to v_{f_i}. However if it is excited by multiple frequency signal (such as a square wave), v_{output} is proportional to resistor voltage drops at multiple frequencies. Therefore, at each resonant frequency, the electrical impedance behaviour of the ultrasound transducer is related to the resistor characteristic at that frequency. One of the important factors that can affect the physical property of the transducer is the excitation voltage that can make the behaviour of the transducer even more nonlinear. This needs to be investigated based on different modelling and tests. In the ultrasound system, energy conversion can be affected by the system characteristics. In a real case, the system characteristics can be influenced by the ultrasound transducer characteristics, temperature, time etc [18-20].

In order to find out the resonant frequencies and the electrical impedance of an ultrasound transducer at different frequencies several tests are performed [21, 22]. Due to a constraint of a network analyzer which operates at low voltage, other methods are used to measure the electrical impedance of the ultrasound transducer at higher voltage ranges.

In this paper, a high power ultrasound system is developed in order to investigate its behaviour at both system and device levels. In this regard, the electrical impedance of the high power ultrasound transducer and the voltage ratio of the high power ultrasound system are measured. Since a high power ultrasound system can perform energy conversion in low and high voltage ranges based on different applications, the implemented high power ultrasound system is tested at different voltage ranges. Also, to study the behaviour of the ultrasound transducer at its resonant and non-resonant frequencies, the ultrasound transducer is excited within a wide range of frequencies. Different methods are used to evaluate the characteristics of the high power ultrasound transducer and the ultrasound system – with two ultrasound transducers – which are classified in Table I:

Table I. Excitation methods

Low voltage measurement ($\leq$ ***30 V***)		**High voltage measurement** (***> 30 V***)
Network Analyzer (electrical impedance measurement)	Function Generator	Switched-mode Power Converter

The rest of this paper is organized as follows. In section 2, different impedance measurement methods are applied for the purpose of studying the impedance characteristic of the ultrasound transducer. The behaviour of the ultrasound system in different voltage and frequency ranges is studied in section 3. Finally, conclusion is drawn in section 4.

2. IMPEDANCE CHARACTERISTIC OF THE ULTRASOUND TRANSDUCER

In order to find out the resonant frequencies of an ultrasound transducer and measure its electrical impedance, a sandwich piezoelectric transducer composed of two piezoelectric ceramic elements and a vector network analyzer (R&S ZVL3) are used. The transducer specifications are given in Table II.

Since the voltage range of network analyzer is limited ($< 2\ V$), another test is required to measure the electrical impedance of the ultrasound transducer in a higher voltage range ($2\ V < V \leq 30\ V$). In this regard, a sinusoidal signal is generated to drive the ultrasound transducer using an

EZ Digital FG 7020A function generator and a power amplifier (OPA549). Then the voltage and the current of the ultrasound transducer are measured to compute its electrical impedance. Due to the voltage limitation of the power amplifier, a switched-mode power converter is used to generate a high voltage signal (*30 V* $<V\leq$ *200 V*).

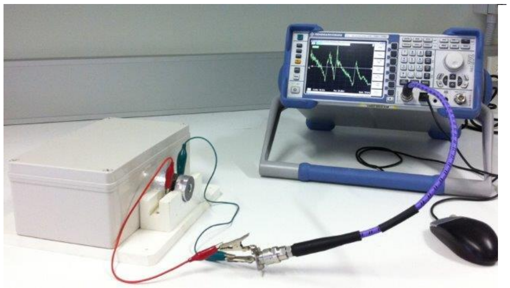
Table II. Transducer specifications

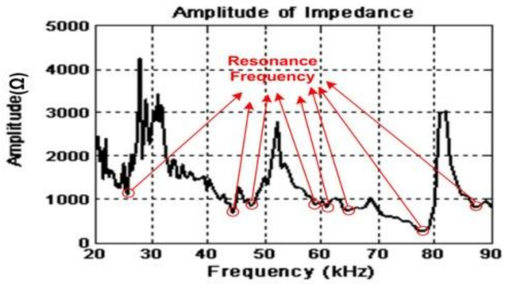
<table>
<tr><td rowspan="5"></td><td>Design: Sandwich piezoceramic transducer</td></tr>
<tr><td>Piezoceramics: PZT8</td></tr>
<tr><td>Piezoceramic Diameters: 35 mm</td></tr>
<tr><td>Piezoceramic thickness: 5.1 mm</td></tr>
<tr><td>Vibration mode: Thickness Vibration</td></tr>
</table>

2.1. Using a Vector Network Analyzer (R&S ZVL3)

A vector network analyzer drives the ultrasound transducer by applying an input signal then measures the voltage and the feedback current to obtain the electrical impedance of the ultrasound transducer. The experimental setup and the measured electrical impedance of the high power ultrasound transducer are shown in Fig. 4.

As it is clear in Fig. 4(b), the ultrasound transducer has several resonance frequencies in which its electrical impedance amplitude is minimum compared to non-resonance frequencies. Based on the minimum amplitudes of the electrical impedance, maximum values of the output power are attained at these resonance frequencies. Among these resonance frequencies, only at one frequency the lowest electrical impedance is achieved and this frequency is defined as the main resonance frequency of the ultrasound transducer. Table III presents the impedance amplitudes achieved at the resonance frequencies of the transducer.





(a) (b)

Fig. 4. Ultrasound transducer electrical impedance measurement (a) experimental test using network analyser (b) measured impedance amplitude

Table III. Transducer impedance at its resonant frequencies

Frequency (kHz)	24.43	25.61	44.41	47.24	59.6	67.25	74.11	78	87.13
Impedance Amplitude (Ω)	1132	1058	683.4	777.8	883.7	709.6	455.8	252.85	862.3

As shown in Fig. 4(b) and Table III, the transducer has several resonances and *78 kHz* is its main resonant frequency at which the transducer impedance has the lowest amplitude.

To achieve the electrical impedance of the ultrasound transducer at higher voltage ranges ($2\ V < V \leq 30\ V$) and investigate its nonlinearity, the same ultrasound transducer should be excited by a high voltage signal. This analysis is discussed in the next following section.

2.2.Using a Sinusoidal Signal

The ultrasound transducer performance is highly dependent on its excitation signal and therefore a proper excitation voltage should be generated since a distorted signal could degrade its performance. Among different excitation methods introduced in [23, 24], generating a sinusoidal signal with low distortion is an appropriate option.

Therefore, in this research work a sine-wave voltage is generated using an EZ Digital FG 7020A function generator and a linear power amplifier (OPA 549) to drive the ultrasound transducer as shown in Fig.5 (a). To measure the current through the first transducer, a small resistor (1Ω) is placed in series with the transducer. To study the characteristic of the ultrasound transducer and the electrical impedance at different frequencies, the frequency of the excitation signal is adjusted to *39 kHz* and *60 kHz*. The voltage across transducer (V_{trans}) and the current through it (i_{trans}) are measured to calculate its electrical impedance using (4).

$$Z(\omega_i) = \frac{V_{trans}(\omega_i)}{i_{trans}(\omega_i)} \quad (4)$$

$$\omega_i = 2\pi f_i \qquad \text{for } i = 1,2,\dots,n$$

where f_i is the i^{th} resonant frequency of the transducer.

Since the electrical impedance of the ultrasound transducer is computed based on the measured voltage and current at each frequency, it is expected that the electrical impedance variations remain the same regardless of the amplitude changes of the input voltage for a linear ultrasound transducer. To investigate its linear characteristic, the superposition law is used.

Principle of Superposition

According to the principle of the superposition, the sum of the responses of a linear system to the individual inputs is equal to the response of the system to the sum of the inputs [25]. This principle is shown by:

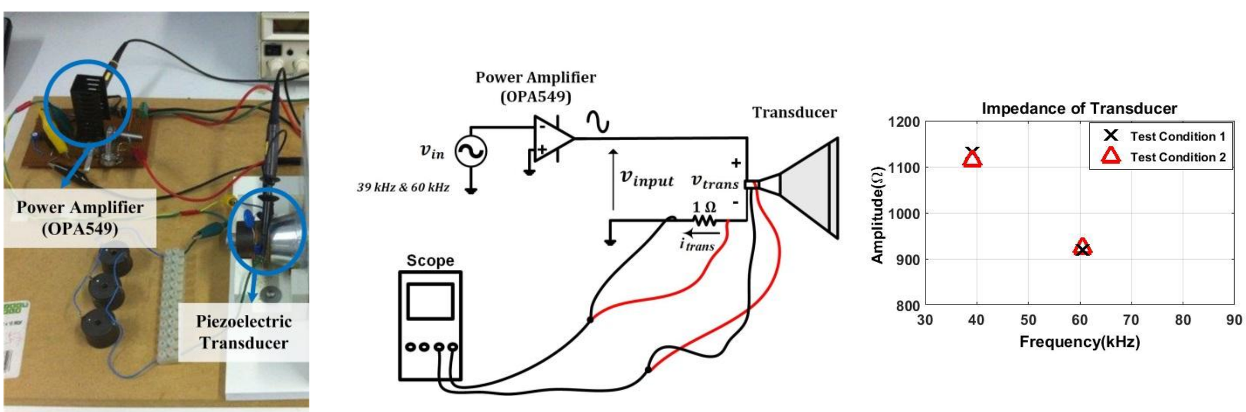
$$g\{V_1(f_1) + V_2(f_2) + \cdots\} = g\{V_1(f_1)\} + g\{V_2(f_2)\} + \cdots \quad (5)$$

This general pattern holds true for the ultrasound transducer electrical impedance if its measured values are the same for the following excitation conditions:

- **Test Condition 1:** Exciting by two separate input sinusoidal signals (*39 kHz, 60 kHz*)
- **Test Condition 2:** Exciting by two simultaneous input sinusoidal signals (*39 kHz* and *60 kHz*)

The experimental prototype developed for this test and the block diagram of this setup are depicted in Fig. 5(a) and (b). To meet the test condition 1, two input sinusoidal signals with different fundamental frequencies (*39 kHz and 60 kHz*) are generated to excite the ultrasound transducer individually. The amplitude of these signals are adjusted at *30 V* using the amplifier. The responses of the ultrasound transducer to these individual input signals are added together in the frequency domain.

In the next step, two sinusoidal signals at *39 kHz* and *60 kHz* are generated simultaneously using two function generators and then added together using the op-amp (OPA 549). The amplitudes of these signals are adjusted at *30 V* same as the previous case. The comparison between the calculated electrical impedances makes it clear whether the ultrasound transducer has a linear or a nonlinear characteristic. As shown in Fig. 5(c), the magnitudes of the ultrasound transducer impedances achieved for test conditions 1 and 2 are different at *39 kHz* while at *60 kHz*, the impedances are almost the same. At this stage due to the power amplifier limitations, it is not possible to increase the voltage and the power of the power supply in order to investigate the transducers performance at different voltage and power levels. However, these test results verify that the impedance of the ultrasound transducer can be a function of the excitation input signal (voltage and frequency) and the resonant frequencies of the transducer.



(a) (b) (c)

Fig. 5. Electrical impedance measurement of the ultrasound transducer (a) experimental prototype (b) block diagram of setup (c) test results.

2.3.Using a Two-Level Inverter

According to different applications, an ultrasound transducer could be used in different ranges of voltage and frequency. For instance, an ultrasound transducer is used in low voltage range in diagnostic applications, whereas it is also used at higher voltage and power ranges for therapeutic applications [1, 26]. To attain a better performance of the ultrasound transducer, studying its characteristic at higher voltage and power ranges is necessary.

As it was mentioned, the maximum sinusoidal signal voltage generated by the linear amplifier is limited to the electrical characteristic of the power amplifier. To overcome the voltage limitation of the excitation signal, a two-level inverter is implemented to generate an appropriate high voltage signal *(≤ 200 V*). The block diagram and a laboratory setup of this test are shown in Fig. 6(a) and Fig. 6(b) respectively. The square wave signal consists of a fundamental frequency and its harmonics and it cannot be considered as a pour sinusoidal signal.

Since the minimum electrical impedances and the maximum output powers of each ultrasound transducer are achieved at its resonance frequencies, the power converter is controlled in such a way to generate the square wave signal with the fundamental frequency, matching the resonant frequency of the ultrasound transducer which is depicted in Fig.6(c). The response of the ultrasound transducer is measured at different voltage and frequency ranges by changing the DC link voltage (V_{DC}) and the fundamental frequency of the inverter, respectively. The quality of the excitation signal is really important because a poor quality signal can affect the performance of the ultrasound transducer by increasing the harmonic contents and deliver power at undesired frequency ranges [27]. To investigate and analyse this issue, the fundamental frequency of the inverter output signal (f_{inv}) is adjusted at $f_{inv}=39\ kHz$ while the second harmonic of the signal is at $f_{inv}=78\ kHz$ which is exactly at the resonant frequency of the transducer. The DC link voltage values are changed (*50 V, 100 V* and *200 V*) in order to measure the impedance of the transducer at different voltage and power levels. In this test, two differential voltage probes are used to measure the voltage across transducer (V_{trans}) and the current through it (i_{trans}). Then the electrical impedance is computed using the measured voltage and current values in time domain from the laboratory test and then Fast Fourier transform (FFT) analysis by MATLAB software. The results of these tests are depicted in Fig. 6(d).

The analysis shows the nonlinearity of the ultrasound transducer as the impedance of the transducer is changed when the v_{input} is increased. The result also shows that the transducer has been excited by multi-input voltages whose magnitude and frequencies can be calculated by (6).

$$V_{\text{input}}(t)=\sum_{n=1}^{\infty}\frac{4V_{dc}}{n\pi}\sin(2n\pi f_{inv}t) \tag{6}$$

$$V_{\text{input}}(t)=\frac{4V_{dc}}{\pi}\sin(2\pi f_{inv}t)+\frac{4V_{dc}}{2\pi}\sin(4\pi f_{inv}t)+\cdots+\frac{4V_{dc}}{n\pi}\sin(2n\pi f_{inv}t)$$

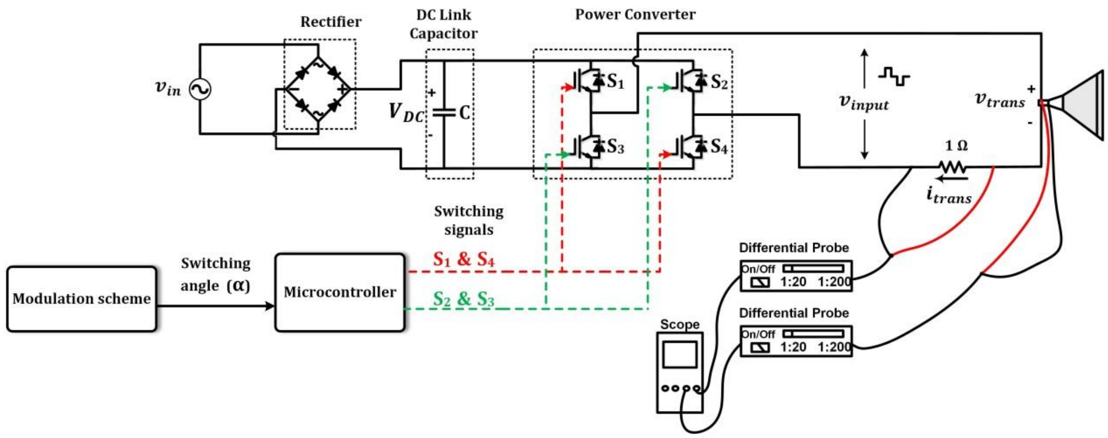
where V_{dc} is the DC voltage and f_{inv} is the fundamental frequency of the inverter and "n" is the order of the harmonic.

Thus, the test results verify that the electrical impedance amplitude is changed based on the amplitude variations of the input voltage signal. This has be described in Eq.(2) such a way that the resistors in each parallel branch can be affected by other resonant frequencies and energies which means each resistor in the RLC branch is a function of multi frequencies not a single frequency.

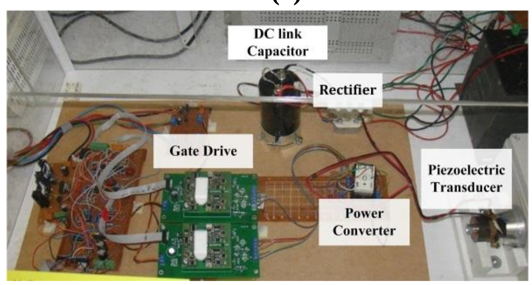
In Fig. 6(d), if the input voltage is changed from *50 V* to *100 V* and then to *200 V*, the electrical impedance amplitude of the ultrasound transducer at *39 kHz* is changed from *362.7 Ω* to *372* Ω and then to *351.5 Ω*. This variation is explained due to the nonlinearity of the ultrasound transducer; otherwise the electrical impedance amplitude should be the same for a linear system.

It is also important to measure and analysis the impedance of the transducer at *78 kHz* (the second harmonic of the applied signal) which is exactly at the main resonant frequency of the transducer. At *78 kHz,* if the input voltage is changed from *50 V* to *100 V* and then to *200 V* the transducer impedance is changed form *91.7* Ω to *97.29* Ω and then to *71.7* Ω. Although the fundamental frequency of the generated signal is adjusted to *39 kHz,* some higher harmonics are generated such as the third harmonics at *3x 39 kHz= 117 kHz*. The higher order harmonics are not within the main characteristic of the transducer and it cannot influence the transducer characteristic. In some applications such as therapeutic one, the performance of the ultrasound transducer should be controlled to achieve maximum energy conversion at desired frequency ranges so undesired effects of sidebands are not acceptable. For instance, as shown in Fig. 6(d), when the transducer is excited with a multi-frequency input signal, the energy conversion happens at *39 kHz* and *78 kHz* while the fundamental frequency of excitation signal is adjusted to *39 kHz* to achieve the energy conversion only at *39 kHz* not at *78 kHz*. In such case the sideband harmonics should be filtered to avoid undesired effects. According to these experimental results, it can be concluded that at higher voltage range, the ultrasound transducer could be saturated and will have a nonlinear behaviour. Overall, the nonlinearity of the ultrasound transducer is concluded from these test results.

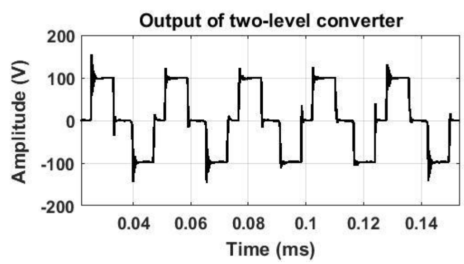
In addition, the hysteretic behaviour of the transducer is studied through an experimental test for which the piezoelectric transducer is excited at different voltage levels. In this test, the impedance of the transducer has been measured with respect to the change in the amplitude of the excitation signal. All measured impedances associated with the excitation signal changes are tabulated in Table IV and the transducer impedance behaviour is shown in Fig. 7.



(a)



(b)



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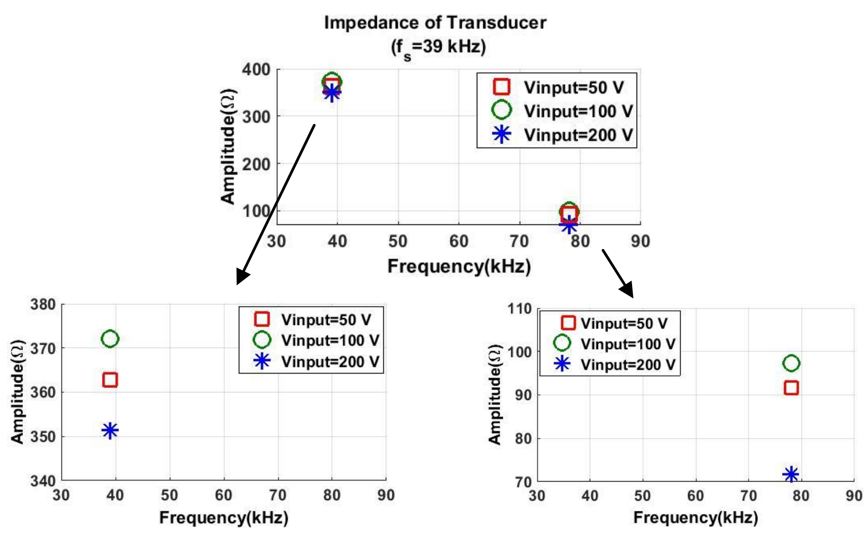


(d)

Fig. 6. Test with two-level converter (a) block diagram of setup (b) experimental setup (c) output of two-level converter (d) impedance of transducer for $f_{inv} = 39\ kHz$

Table IV. Transducer impedance with respect to excitation signal changes

Excitation Voltage (V)	300	600	200	50	600	300
Transducer Impedance (Ω)	1491	1486	1361	916.7	1471	1477

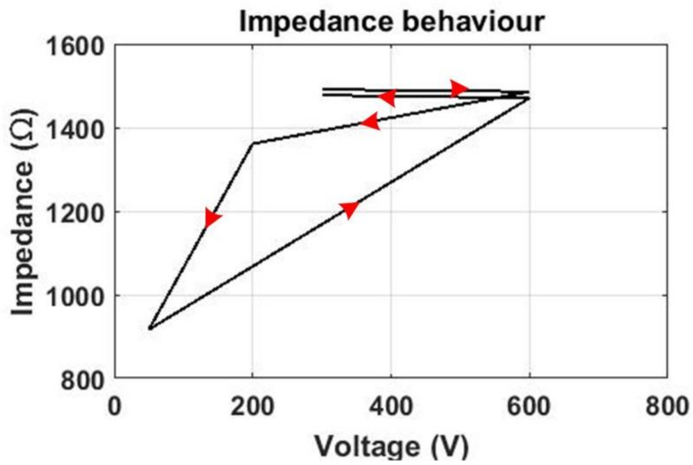


Fig.7. Impedance behaviour of the transducer with respect to excitation signal changes

3. Ultrasound System Characteristic

As shown in Fig. 1, in an ultrasound system, the transmitter generates ultrasound waves (mechanical energy) related to the applied electrical energy (input voltage) and then some parts of these ultrasound waves are converted to the electrical energy (output voltage) by the receiver. Other parts of the generated ultrasound wave which are not converted to the electrical energy might be absorbed or dispersed. Different mediums can be used to couple these two ultrasound transducers in the ultrasound system such as water, oil and etc [28]. The intensity of the generated mechanical energy (ultrasound wave) depends on the applied input voltage and can affect the generated output voltage. Therefore, the efficiency of the ultrasound system can be analyzed according to the comparison of the input and the output voltages of the system. In this regard, the voltage across transmitter is measured as an input voltage signal and the output voltage is measured across the receiver. Several tests are carried out to study the characteristic of the ultrasound system. The responses of the second ultrasound transducer to the input voltages with different amplitudes are measured to illustrate the characteristic of the system.

3.1. Using a Sinusoidal Signal

Undesired distortion (poor quality) of the excitation signal can deteriorate the performance of the ultrasound transducer, which can affect the performance of the ultrasound system as well. Therefore, a sinusoidal signal with lower distortion could be a proper option to drive the ultrasound transducer.

The block diagram of the ultrasound system with two transducers – transmitter and receiver – including a sinusoidal power supply is shown in Fig. 8(a). In this test, the transducer 1 plays a role of a transmitter and the transducer 2 is applied as a receiver. Two sinusoidal signals with different fundamental frequencies (*39 kHz* and *60 kHz*) are generated individually using the power amplifier (OPA 549). To study the quality of the input and the output signals and compare the performance of the ultrasound system at different frequencies, test results shown in Fig. 8(b) are illustrated in the frequency domain.

Based on (5), the ultrasound system is linear if its responses to the test condition 1 and the test condition 2 – mentioned in section 2.2 are the same. To meet the test condition 1, the ultrasound system is excited by two individual input signals with different frequencies (*39 kHz* and *60 kHz*). The responses of the system to these input signals are added together in frequency domain. Based on the test condition 2, two input sinusoidal signals with the amplitudes of *30 V* and the fundamental frequencies of *39 kHz* and *60 kHz* are added together in order to generate a new signal to drive the ultrasound system.

As a linear system, the output of the system should be a function of its input. Therefore, it is expected that the output voltage variations of the ultrasound system should be almost the same based on test conditions 1 & 2. As shown in Fig. 8(b), the amplitudes of the output signals at *39 kHz* are different while at *60 kHz* are almost the same when a single and a double sinusoidal excitation are applied to the system. For a linear system the output voltage amplitude should be related to the amplitude of the input voltage. The performance of the ultrasound transducer varies at different frequencies. Therefore, the responses of the system (including the ultrasound transducer) to the input signals verifies the nonlinear behaviour of the transducers and the system. The differences between test results verify that this system does not obey the superposition rule so it is a nonlinear system.

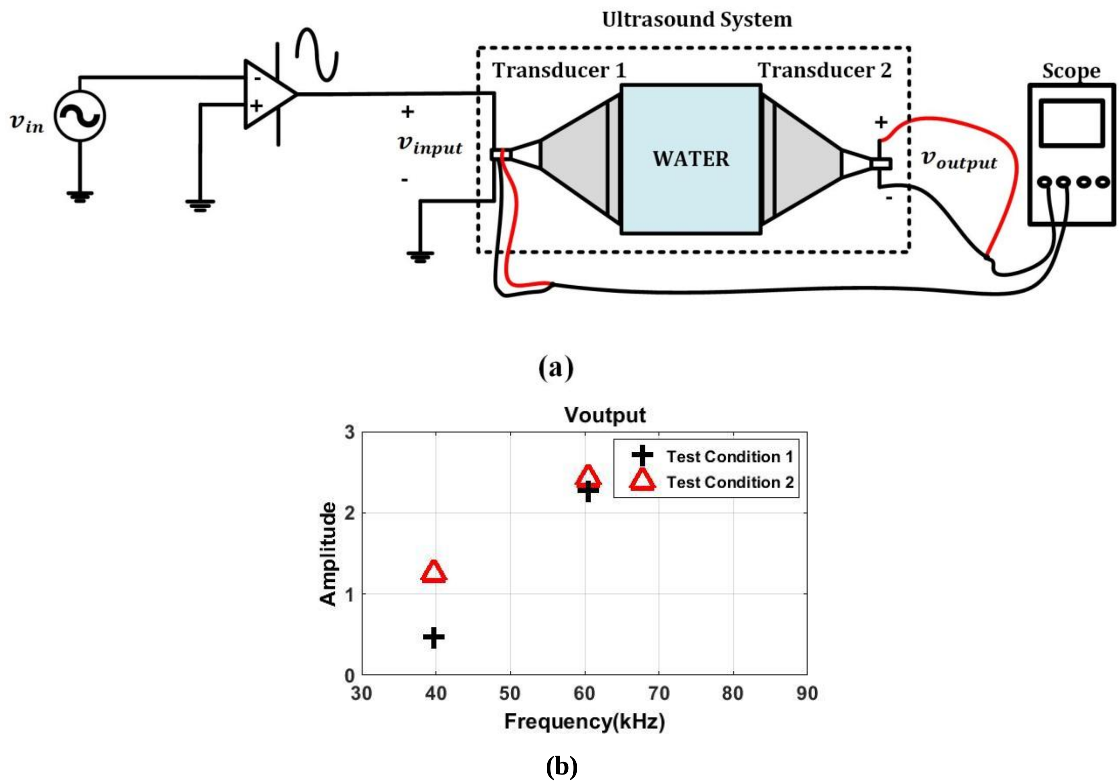


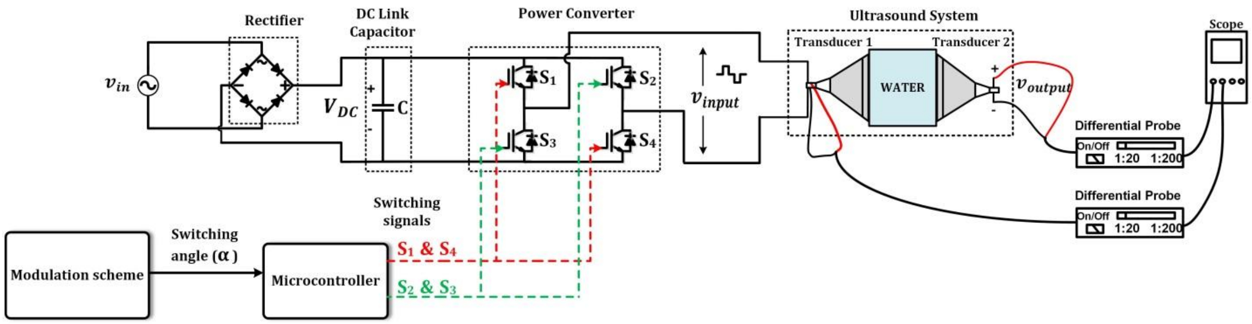
Fig. 8. Ultrasound system excitation using sinusoidal signal (a) a block diagram of the setup (b) experimental results

3.2. Using a Two-Level Inverter

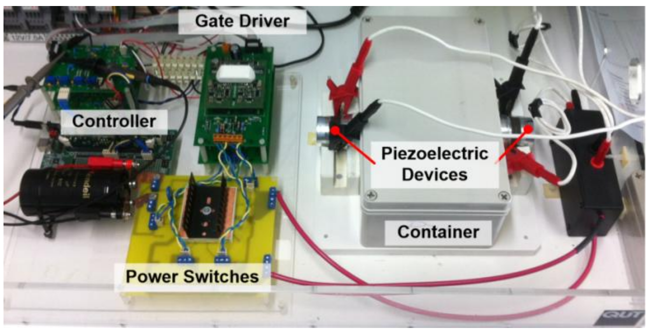
To study the characteristics of the ultrasound system at higher voltage ranges another test is required to generate a high voltage signal to excite the ultrasound system. In this regard, the power converter is used to generate a high voltage square wave signal which contains some harmonics and it is not a pure sinewave. The block diagram of the experimental test and developed experimental prototype are shown in Fig. 9(a) and (b) respectively.

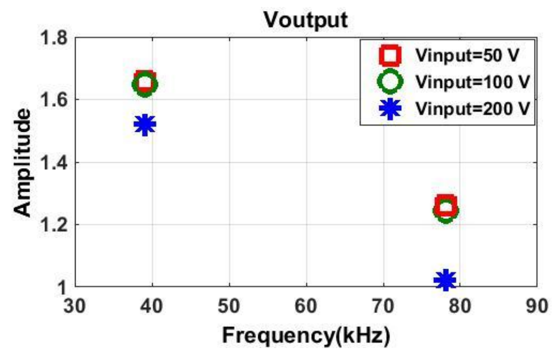
The voltages across the transducer 1 and the transducer 2 are measured as the input and the output voltages respectively using two differential voltage probes. The captured data of this test are analyzed in frequency domain using MATLAB. The generated signal has a fundamental component at *39 kHz* and some harmonics as it is not a pure sinusoidal signal. To study the effect of these harmonics on the performance of the ultrasound transducer, the fundamental frequency of the input signal is adjusted to *39 kHz*. Therefore, its second harmonic appears at *78 kHz* which is the main resonance frequency of the ultrasound transducer. In this test, the DC link voltage is adjusted to *50 V*, *100 V* and *200 V* therefore the responses of the ultrasound system to the input voltage signals with different amplitudes can be studied.

To have a better comparison, the amplitudes of the input and the output voltages are normalized at *50V* dividing by factors of 1, 2 and 4. Despite the input voltage signals, the normalized output voltages do not match each other and some differences can be seen in Fig. 9(c). For example, at *39 kHz* the response of the system to the input voltage signal with the amplitude of *200 V* is a factor 1.5 but the response to *100 V* input voltage signal is a factor of 1.7. If the ultrasound system under the test is linear, then the measured voltages across the second transducer should be consistent with the applied input voltages, but the results of this test show that this system does not obey this rule and has nonlinear behaviour.



(a)





(b) (c)

Fig. 9. Ultrasound system excitation using a two-level converter (a) block diagram (b) experimental prototype (c) experimental result

4. Conclusion

It is important to consider electrical characteristic of a high power ultrasound transducer in order to design an efficient high power converter to excite the ultrasound system. The characteristic of the high power ultrasound transducer and the ultrasound system in low and high voltages (*30 V- 200 V* peak) are investigated in this paper. In this regard, an ultrasound system including two high power ultrasound transducers (*78 kHz*) is developed and excited at different voltage and frequency ranges. According to the test results, it is concluded that at each resonant frequency of the transducer, the equivalent resistor of each RLC branch delivers the electromechanical power to the output side of the ultrasound system. Therefore, the behaviour of the ultrasound transducer at each resonance frequency is influenced by the characteristic of the equivalent resistor at that resonant frequency. A low voltage sinusoidal signal and a high voltage square wave signal are generated to excite the ultrasound transducer and system in different frequency ranges (*30 kHz – 90 kHz*). The test results present a nonlinear behaviour of the ultrasound transducer especially in high voltage ranges. This is due to the fact that the amplitude of the transducer electrical impedance changes by the amplitude variations of the input voltage signals. Also, the characteristic of the ultrasound system is analyzed in low and high voltage ranges based on the voltage ratio of the ultrasound system. The nonlinearity of the ultrasound system has been observed in the test results where the measured output voltage amplitudes of the system are not commensurate with the amplitude changes of the input voltage signals. According to the superposition law, the ultrasound system has different behaviours when it is excited by multi-sinusoidal signal. Thus, in order to improve the quality and the efficiency of the ultrasound system, it is recommended to investigate main resonant frequencies of the ultrasound transducer and design a proper power converter with high quality output signal and with low harmonic orders.

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Highlights

- At high voltage range (>100 V), the ultrasound transducer could be saturated.
- The impedance of the transducer is changed when the excitation signal is increased.
- Nonlinearity of the ultrasound transducer is concluded from experimental results.
- The ultrasound system is nonlinear because it does not obey the superposition rule.