Improving Ultrasound Excitation Systems Using a Flexible Power Supply with Adjustable Voltage and Frequency to Drive Piezoelectric Transducers

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Abstract

The ability of a piezoelectric transducer in energy conversion is rapidly expanding in several applications. Some of the industrial applications for which a high power ultrasound transducer can be used are surface cleaning, water treatment, plastic welding and food sterilization. Also, a high power ultrasound transducer plays a great role in biomedical applications such as diagnostic and therapeutic applications. An ultrasound transducer is usually applied to convert electrical energy to mechanical energy and vice versa. In some high power ultrasound system, ultrasound transducers are applied as a transmitter, as a receiver or both. As a transmitter, it converts electrical energy to mechanical energy while a receiver converts mechanical energy to electrical energy as a sensor for control system. Once a piezoelectric transducer is excited by electrical signal, piezoelectric material starts to vibrate and generates ultrasound waves. A portion of the ultrasound waves which passes through the medium will be sensed by the receiver and converted to electrical energy. To drive an ultrasound transducer, an excitation signal should be properly designed otherwise undesired signal (low quality) can deteriorate the performance of the transducer (energy conversion) and increase power consumption in the system. For instance, some portion of generated power may be delivered in unwanted frequency which is not acceptable for some applications especially for biomedical applications.

To achieve better performance of the transducer, along with the quality of the excitation signal, the characteristics of the high power ultrasound transducer should be taken into consideration as well. In this regard, several simulation and experimental tests are carried out in this research to model high power ultrasound transducers and systems. During these experiments, high power ultrasound transducers are excited by several excitation signals with different amplitudes and frequencies, using a network analyser, a signal generator, a high power amplifier and a multilevel converter. Also, to analyse the behaviour of the ultrasound system, the voltage ratio of the system is measured in different tests. The voltage across transmitter is measured as an input voltage then divided by the output voltage which is measured across receiver. The results of the transducer characteristics and the ultrasound system behaviour are discussed in chapter 4 and 5 of this thesis.

Each piezoelectric transducer has several resonance frequencies in which its impedance has lower magnitude as compared to non-resonance frequencies. Among
these resonance frequencies, just at one of those frequencies, the magnitude of the impedance is minimum. This resonance frequency is known as the main resonance frequency of the transducer. To attain higher efficiency and deliver more power to the ultrasound system, the transducer is usually excited at the main resonance frequency. Therefore, it is important to find out this frequency and other resonance frequencies. Hereof, a frequency detection method is proposed in this research which is discussed in chapter 2.

An extended electrical model of the ultrasound transducer with multiple resonance frequencies consists of several RLC legs in parallel with a capacitor. Each RLC leg represents one of the resonance frequencies of the ultrasound transducer. At resonance frequency the inductor reactance and capacitor reactance cancel out each other and the resistor of this leg represents power conversion of the system at that frequency. This concept is shown in simulation and test results presented in chapter 4.

To excite a high power ultrasound transducer, a high power signal is required. Multilevel converters are usually applied to generate a high power signal but the drawback of this signal is low quality in comparison with a sinusoidal signal. In some applications like ultrasound, it is extensively important to generate a high quality signal. Several control and modulation techniques are introduced in different papers to control the output voltage of the multilevel converters. One of those techniques is harmonic elimination technique. In this technique, switching angles are chosen in such way to reduce harmonic contents in the output side. It is undeniable that increasing the number of the switching angles results in more harmonic reduction. But to have more switching angles, more output voltage levels are required which increase the number of components and cost of the converter. To improve the quality of the output voltage signal with no more components, a new harmonic elimination technique is proposed in this research. Based on this new technique, more variables (DC voltage levels and switching angles) are chosen to eliminate more low order harmonics compared to conventional harmonic elimination techniques. In conventional harmonic elimination method, DC voltage levels are same and only switching angles are calculated to eliminate harmonics. Therefore, the number of eliminated harmonic is limited by the number of switching cycles. In the proposed modulation technique, the switching angles and the DC voltage levels are calculated off-line to eliminate more harmonics. Therefore, the DC voltage levels
are not equal and should be regulated. To achieve this aim, a DC/DC converter is applied to adjust the DC link voltages with several capacitors. The effect of the new harmonic elimination technique on the output quality of several single phase multilevel converters is explained in chapter 3 and 6 of this thesis.

According to the electrical model of high power ultrasound transducer, this device can be modelled as parallel combinations of RLC legs with a main capacitor. The impedance diagram of the transducer in frequency domain shows it has capacitive characteristics in almost all frequencies. Therefore, using a voltage source converter to drive a high power ultrasound transducer can create significant leakage current through the transducer. It happens due to significant voltage stress \( \frac{dv}{dt} \) across the transducer. To remedy this problem, LC filters are applied in some applications. For some applications such as ultrasound, using a LC filter can deteriorate the performance of the transducer by changing its characteristics and displacing the resonance frequency of the transducer. For such a case a current source converter could be a suitable choice to overcome this problem. In this regard, a current source converter is implemented and applied to excite the high power ultrasound transducer. To control the output current and voltage, a hysteresis control and unipolar modulation are used respectively. The results of this test are explained in chapter 7.
Keywords
High power ultrasound transducer
High power ultrasound system
Piezoelectric transducer
Transmitter
Receiver
Energy conversion
Piezoelectric effect
Switching components
Resonance frequency of ultrasound transducer
Electrical models of ultrasound transducer
Impedance of ultrasound transducer
Ultrasound wave ultrasound transducer excitation
Voltage ratio of ultrasound transducer
Principle of superposition
Fourier series expansion
Harmonic distortion
Current ripples
Ultrasound transducer characteristics
Ultrasound system behaviour
Nonlinear behaviour
High quality excitation signal
Voltage stress
Current source converter
Voltage source converter
DC/DC converter
Multilevel converter
Diode-clamped converter
Cascade converter
Multi-output DC/DC converter
Pulse Width Modulation (PWM)
Space vector modulation
Selective harmonic elimination technique
Contributions

❖ High frequency high power electronic converter
   ➢ Proposing a new harmonic elimination technique for a single-phase multilevel converter to reduce low order harmonics
   ➢ Developing a three-level and a four-level converters to study the effect of the new harmonic elimination technique on the output harmonics
   ➢ Investigating the effect of voltage stress on the ultrasound transducer as a load
   ➢ Developing a current source converter with adjustable magnitude to excite a high power ultrasound transducer

❖ High power ultrasound system
   ➢ Generating different excitation signals in different ranges of voltage and frequency using
     ✓ Signal generator
     ✓ Switched mode power converter
   ➢ Modelling of a high power piezoelectric transducer
   ➢ Modelling of a high power ultrasound system
   ➢ Proposing a frequency detection method to improve the efficiency of high power transducers
List of Publications

The Queensland University of Technology (QUT) allows the presentation of a thesis for the Degree of Doctor of Philosophy in the format of published or submitted papers, where such papers have been published, accepted or submitted during the period of candidature. This thesis is composed of six published/submitted papers, of which four have been published, one is under review and one is accepted for publication.

Published Peer Reviewed Journal Articles:


Peer Reviewed Journal under Review:

Published Peer Reviewed International Conference Papers:


List of chapters according to publications and contributions

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Statement of Original Authorship

“The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.”

Signature

Date
CHAPTER 1

Introduction
1.1. Description of the Research Problem

A high power ultrasound system is used in a wide range of applications where efficient and economical energy conversion is required. Two main parts of this system are a power driver and a piezoelectric transducer.

The piezoelectric transducer generates mechanical energy in response to an applied electrical excitation. The ability of the transducer in energy conversion is reversible. It means the transducer can also generate electrical energy in response to the applied mechanical stress. This reversible phenomenon is known as the piezoelectric effect. Once the piezoelectric transducer is excited by the electrical energy, the physical dimension of its material (crystal or ceramic) starts to change proportional to the applied electrical energy. The shape variation of the inside material results in generating ultrasound waves (mechanical energy).

The transducer can be used as a transmitter, a receiver or both of them in each ultrasound system. As a transmitter it converts electrical energy to mechanical energy while as a receiver, it performs the reverse energy conversion as a transmitter, i.e., converts mechanical energy to electrical energy.

The ultrasound waves, in interaction with different media such as fluids and solids, can be reflected, absorbed or pass through the media. Depending on the stiffness and the permeability of the media, the portion of reflected or absorbed ultrasound waves will vary. Those ultrasound waves which pass through the media in interaction with the surface of another transducer can be converted to electrical energy. Also, based on the pulse-echo technique, some parts of the reflected waves will be sensed by the first transducer and then converted to electrical energy. The absorbed waves increase the temperature of the media and dissipate as heat. The quality of the transducer performance (energy conversion) is highly related to its excitation signal. This means that a high quality signal with low distortion could result in better performance while low quality signal increases the power consumption and deteriorate the performance of the transducer. It is therefore really important to generate a high quality signal. From a quality point of view, a sinusoidal signal is a suitable option. To excite a high power ultrasound system, a high power signal with adjustable frequency and magnitude is required. In such a case, generating a high power sinusoidal signal is challenging and usually power converters are applied to generate a high power signal close to a sinusoidal one. To
improve the output quality of the power converters, several control methods and modulation techniques are introduced. To generate a desired high power signal, load characteristic should be taken into consideration. To drive a high power ultrasound system, non-linear characteristics of the piezoelectric transducer should be taken into consideration.

Improving the performance of an ultrasound system lead to two specific research problems:

**Problem #1: modelling of non-linear characteristics of a high power piezoelectric transducer**

Non-linear behaviour of a high power ultrasound transducer is one of main concerns in the ultrasound system excitation. The nonlinearity of the transducer results in increasing power consumption and decreasing efficiency of the ultrasound system. Power delivery at desired ranges of frequency and voltage is the main aim of using an ultrasound system in different applications. But this can be affected by the nonlinearity of the transducer. For instance, the characteristic of the transducer is similar to transformer behaviour, which saturates beyond threshold value of voltage. Based on the type of piezoelectric transducer, the threshold voltage will vary. Therefore, in order to design and develop a power driver for a high power ultrasound system, the nonlinearity of the transducer should be taken into account. Several tests have been carried out in this research to investigate the effect of different media and excitation signals on characteristics of an ultrasound system.

To study transducer characteristics, its impedance is usually measured using a network analyser. This method is helpful to find out the resonance frequencies of the transducer and its impedance in a wide range of frequencies. The drawback of this method is that it is a low power test. According to various electrical models of a piezoelectric transducer introduced in different literature, a piezoelectric transducer is modelled by parallel and series combinations of resistors, capacitors and an inductor. Due to nonlinearity of a high power ultrasound transducer, its equivalent models at low power and high power are totally different and should be investigated. Also, the ultrasound transducer impedance varies at different frequencies. Therefore, for developing a power driver, the electrical model of the ultrasound transducer at different ranges of frequency and power should be studied on-line. With this aim,
several prototypes are developed to measure the impedance of the transducer in this research.

**Problem #2: Generating a desired high power excitation signal**

The performance of a piezoelectric transducer can be easily affected by the quality of its electrical excitation signal. Distorted signal deteriorates its performance and results in undesired characteristics. The efficiency of the ultrasound system can be explained as power delivery at desired ranges of frequency and voltage. Here the undesired effect means that the ultrasound system cannot provide required power or delivers power at undesired frequencies. To avoid these effects, the power driver of the ultrasound system should be improved by properly considering the nonlinearity of the transducer.

Switched-mode power converters are widely used to generate a high power signal. In the case of high power ultrasound transducers, the quality of a high power staircase waveform is not high enough to be used as an excitation signal because of more harmonic contents in the output side compared to pure sinusoidal signal. To improve the quality of this signal, different methods are used such as Pulse Width Modulation (PWM) technique. But from a frequency point of view, there is a challenge to use switched-mode power converter with PWM method in high frequency applications (baseband is more than 20 kHz) like ultrasound. To generate a high power high frequency signal using a switched-mode power converter with PWM method, the switching frequency should be several times higher than baseband frequency. However, high switching frequency increases switching losses and decreases the efficiency of the system. To achieve a high power signal with high quality, a new harmonic elimination technique is proposed for multilevel converters in this research.

A piezoelectric transducer has a capacitive characteristic at almost frequencies so current source converter could have a better effect on the transducer performance. Therefore, a current source converter is developed in this research as another topology to drive a high power ultrasound transducer.
1.2. Literature Review

1.2.1. High power piezoelectric transducer

High power ultrasound system is an economical and powerful system which can be applied to a large number of applications where efficient energy conversion is required. The main part of the ultrasound system is a piezoelectric transducer which provides the ability of energy conversion for the ultrasound system. Each piezoelectric transducer can be in charge of the transmitter, the receiver or both, in the ultrasound system. As a transmitter, once the transducer is excited by electrical energy, piezoelectric materials start to vibrate and generate mechanical energy in the form of ultrasound waves. These waves transmit through different media and then will be transformed to electrical energy by a receiver. In such a system, different media are used for coupling the transmitter and the receiver. The quality of the energy conversion in an ultrasound system is highly related to the excitation signal. Applying a high quality excitation signal can improve the performance of the system while a low quality signal deteriorates it and increases power consumption.

For different applications, this innovative system is used in various ranges of voltage and frequency. These applications are generally divided into two groups:

- Industrial applications
- Biomedical applications

1.2.1.1. Industrial applications

The ability of a high power ultrasound transducer in generating high intensity ultrasound waves in different media which results in generation of heat, diffusion, friction, etc is extensively employed in different industrial applications [1-10]. One of these applications is dehydration of vegetables [1, 11-14]. To preserve foods, dehydration is a suitable technique to remove the water content from the solid materials. Hot air drying is a conventional method for dehydrating foods but for heat-sensitive materials, this method can cause deteriorative changes. To have much more effective dehydration, a high power ultrasound system is applied. In such a case, ultrasound waves are generated using the ultrasound system and then contacted with food samples directly. In the interaction between ultrasound waves and samples, ultrasound waves penetrate in samples which results in contractions and expansions of materials and moisture evaporation from samples [1, 11, 13, 14].
Another industrial application of high power ultrasound transducer is cleaning. Ultrasonic cleaning as a useful method facilitates surfaces cleaning, especially for those surfaces which are unreachable such as ball bearings. Once ultrasound waves pass through fluids, some cavitational bubbles are generated and grow to a certain size then burst. Exploding of these bubbles increases the temperature and pressure of the liquid and dislodges sticking dirt from surfaces [15-20].

Also, an ultrasound transducer is used for cutting food products. Based on different food materials, stiffness and softness, several cutting tools could be used for cutting food products. Ultrasound cutting at a frequency range of 20-40 kHz, is a suitable option for cutting all types of foods. Compared to conventional cutting methods, this method is sharper and faster [2].

Velocity measurement in underwater vehicles is another application of a piezoelectric transducer in which two transducers are used; one as a transmitter and another one as a receiver to estimate the velocity of vehicle [21].

To measure canopy size, several sensing methods are introduced in different literatures. Among these techniques, ultrasonic sensors are extensively used due to their capability of detecting canopy size regardless of colour variation in targets and uni directional sensing of row spacing [22].

1.2.1.2. Biomedical applications

Ultrasound-based technique is used in several biomedical applications like diagnostic and therapeutic applications. This needle-less method can be used for gene and/or drug delivery with minimal disruption to the tissue [23]. Diagnosis of osteoporosis is another application of the ultrasound technology in which the amplitude spectrum of an ultrasound pulse through the reference material and through the bone are analysed to find the cancellous bone [24-27].Clinical imaging of the eye, skin and arteries with high resolution is another important application of ultrasound technology[28, 29].

In some applications, the ability of a piezoelectric transducer in energy conversion is applied to create hearing aids. These devices are normally used to amplify sounds for the wearer. In such applications, sound waves are converted to electrical energy, which is amplified and converted back to sound energy using two piezoelectric traducers [30].
In addition, ultrasound transducers are used in human face identification systems. In this system, ultrasound transducer is applied to detect the human face by sending and receiving ultrasound waves [31].

1.2.2. Modelling of piezoelectric transducers

Several biomedical and industrial applications apply a piezoelectric transducer where energy conversion is the main issue. Once a piezoelectric transducer is excited by electrical energy, piezoelectric materials start to vibrate and thereby generate mechanical energy (ultrasound waves). Also, the transducer can generate electrical energy in response to applied mechanical pressure. An ultrasound system includes a power driver and a piezoelectric transducer. To improve the performance of the system and to generate a desired signal in the output side of the power driver, it is really important to find out an electrical model of the piezoelectric transducer. A good understanding of the piezoelectric transducer characteristics is helpful to generate a desired excitation signal and to avoid undesired effects such as high power consumption and increasing harmonics.

Several electrical models of the piezoelectric transducer are introduced in literatures such as Van Dyke model, Sherrit model and Easy model [32, 33]. As shown in Fig. 1.1, these electrical models are generally parallel and series combinations of resistor, capacitor and inductor.

Fig. 1.1. Electrical model of piezoelectric transducer (a) Van Dyke model (b) Sherrit model (c) Easy model.

The Van Dyke model is a basic electrical model of piezoelectric element which is introduced by the IEEE standard on piezoelectricity [34]. This model represents the electromechanical characteristics of piezoelectric materials. The Sherrit model is a parallel combination of a capacitor with a capacitor and an inductor in series. The
easy model is almost similar to Van Dyke model. In this model, the parallel connection is transformed to the series connection and vice versa [32, 35].

To determine values of the electrical model components, the impedance of the piezoelectric transducer is measured. To investigate the impedance, a network analyser is usually used. In such a case, a piezoelectric transducer is connected to a network analyser and excited by electrical energy (voltage). Then the feedback current is measured to determine the impedance of the transducer [35].

The impedance curves of different transducers show that the impedance amplitude of each transducer is decreased at several frequencies. These frequencies are known as resonance frequencies of that particular transducer. Once a piezoelectric transducer is attached to a setup (structure), its impedance could be affected by electromechanical coupling between the transducer and the structure and hence the resonance frequencies may change. Therefore, the electrical model of the transducer should be modified. An extended Van Dyke model of a piezoelectric transducer is shown in Fig. 1.2 [32]. As shown in this figure, some series RLC branches are connected to the basic Van Dyke model and they represent different frequencies of the transducer.

![Fig. 1.2. The extended Van Dyke model.](image)

Since the impedance magnitude of the transducer is decreased at resonance frequencies, higher energy conversion is attained at these frequencies. Among all the resonance frequencies of the transducer, the lowest magnitude of the transducer impedance is achieved in just one of them. This frequency is the main resonance frequency of the transducer. Compared to non-resonance frequencies, the magnitude of the piezoelectric material variation is greater at resonance frequencies. Efficiency of the ultrasound system could be meant as power consumption in the system. In some literatures, power consumption is considered as a function of a piezoelectric material and its geometric properties [36]. However, a number of researchers
represent power consumption as a function of frequency and voltage magnitude of the excitation signal [37-39]. To provide power requirements for such a system, it is very important to study non-linear characteristics of a piezoelectric transducer. Neglecting nonlinearity of the piezoelectric transducer results in inefficient design of the excitation signal and deterioration of the transducer performance. For instance, some portion of power will be delivered at generated high frequency harmonics (undesired frequencies) which results in power dissipation [40]. Another concern of nonlinearity of the transducer is generating high frequency harmonics which should be noted where a high power piezoelectric transducer is modelled.

The non-linear behaviour of a piezoelectric transducer was studied in different papers [38, 41-43]. According to these approaches, beyond threshold values of applied electric field or mechanical stress, a piezoelectric transducer will represent non-linear behaviour and could be saturated. However, below threshold values, it has linear characteristic [38, 44, 45]. Various measuring methods are introduced in [46, 47] to study the response of high power piezoelectric ceramics to amplitude changing of the applied electric fields and most of them observed nonlinearity of the piezoelectric transducer.

Since a piezoelectric transducer is a sensitive device, some important issues should be taken into consideration where an excitation system is designed. One of these issues is adjusting the fundamental frequency of the excitation signal to the main resonance frequency of the transducer since this frequency adaptation can lead to better performance of the transducer (less energy consumption and better energy conversion). Another issue is the quality of the input signal. High quality excitation signal plays an important role to improve the performance of the piezoelectric transducer.

1.2.3. Piezoelectric transducer excitation

Since excitation of a piezoelectric transducer can highly affect its performance so it is really important to generate a desired excitation signal. In this point of view, several excitation techniques are introduced [48-54]. Generating a high power high quality signal to excite a high power ultrasound transducer is challenging. Radio-frequency amplifiers were used to generate a signal with low distortion. The drawback of this system is that the output power of the amplifiers is limited so for a
high power ultrasound transducer, a number of MOSFETs are connected in parallel with amplifier to achieve higher range of power [48-50]. Adding MOSFETs imposes more cost to the system and increase size of the system. To avoid such problems, switched-mode power converters are used to generate a high power signal. Dealing with high switching losses and voltage or current stress on switching components restricts the usage of switched-mode power converters operating with Pulse Width Modulation in high frequency applications. Therefore, different methods are introduced to control and improve the quality of the output signal [48, 52, 55-57]. One of the introduced methods is using a resonant converter. Besides heavy weight and high cost of components, because the frequency of the output signal is limited by the resonant frequency of LC tank, this type of converter cannot be applied for all of high frequency applications. Another technique is using a LC filter to decrease harmonic contents. Similar to resonant converters, the output frequency is restricted by the filter components. Circuit diagrams of a resonant converter and a power converter with LLCC filter are shown in Fig. 1.3 [58].

Fig. 1.3. Circuit diagram of piezoelectric transducer excitation (a) resonant converter [59] (b) LLCC-PWM converter [58].
1.2.3.1. Conventional power converter

Voltage source or current source power converters operating with Pulse Width Modulation (PWM) technique are widely used to generate a high power signal with low distortion. The operational ranges of power and frequency of these types of converters are limited to the power and frequency of the components.

The concept of a Pulse Width Modulation method is based on modulation of a reference signal with a carrier signal. Increasing or decreasing the frequency of the carrier signal (switching frequency) results in improving or deteriorating the quality of the output signal respectively. Therefore, to increase the quality of the output signal, it is necessary to increase the switching frequency. Usually, the switching frequency is several times greater than the fundamental frequency [49]. In such case, switching losses will be increased as well. Also, the number of the output voltage levels is limited to the number of switching components and the number of voltage source.

A conventional converter is depicted in Fig. 1.4. As shown in this figure, each leg of converter includes two switches. Based on different switching states, two-level voltage signal is generated with the magnitude of \(+V_{dc}\), 0 and \(-V_{dc}\) as shown in Fig. 1.5.

![Fig. 1.4. Conventional voltage source converter.](image-url)
Since the quality of the signal is low compared to the sinusoidal signal, some harmonics are generated at higher frequency of the fundamental frequency. The output of a two-level converter in frequency domain is shown in Fig. 1.6.

The main drawback of the conventional converter is high voltage stress ($\frac{dv}{dt}$) across switches when the output voltage is regulated by changing switching states from ‘On’ to ‘Off’ and vice versa. In some applications where load has a capacitive characteristic, high $\frac{dv}{dt}$ decreases the output quality and increases harmonics. To remedy this problem current source converters can be applied. As shown in Fig. 1.7, the output current is changed at different switching states. So, this type of converters suit for capacitive loads and voltage source converters are much more effective for inductive load.
For some applications like driving a piezoelectric transducer, the quality of the excitation signal is a main concern because distorted signals can deteriorate the performance of the piezoelectric transducer. So applying a conventional power converter operating with PWM technique to generate a high power signal could not be a suitable choice due to high frequency harmonics.

In this regard, filters are used in some applications [49, 52, 60]. Although the quality of the signal will be improved using a designed filter, increasing overall cost and size of the system has limited the use of the filter in some applications. In addition, the capacitive and inductive characteristic of added filters can affect the characteristic of the transducer and remove its resonance frequency.

To remedy disadvantages of conventional power converters, multilevel converters are widely applied to generate a high power and high voltage signal.

1.2.3.2. Multilevel converter

To provide an opportunity of generating a high power and high voltage signal especially for those applications where a continuous high power and high quality signal is required, multilevel converters have been designed. Some of these applications are Uninterruptable Power Supply (UPS), renewable energy systems and motor drives [61-66]. The basic concept of operation of multilevel converters is based on different switching states of switching components. A series of these switching components are connected to several DC voltage sources with lower voltage ranges. By changing the switching states, it is possible to synthesize a
staircase signal in the output of the multilevel converter. The amplitude of the output voltage signal is much higher than the value of each DC link voltage source and can be adjusted by changing switching states. Compared to a conventional converter, a multilevel converter has a significant effect on reduction of voltage stress on switches, switching losses and Electromagnetic Interference (EMI) problem [67]. Different control methods are introduced to control switching states and achieve a desired output voltage waveform. Increasing the number of output voltage levels improves the output quality and reduces total distortion but there is a challenge between the number of output voltage levels and the number of components. To generate more output levels (high quality signal), more components and voltage sources are required while increment of the components imposes more complexity and cost to the system. In this point of view, it would be a valuable option to generate a high voltage signal without adding up any components and voltage sources. In this point of view, multilevel converters can be categorised by symmetric and asymmetric converter [68, 69]. As a symmetric configuration the voltages across DC link capacitors are equal while as an asymmetric configuration the voltage value across DC link capacitors are different.

In general case, three well known configurations of a multilevel converter are:

- Diode-clamped converter
- Flying capacitor converter
- Cascade converter

Three configuration of multilevel converter are depicted in Fig. 1.8.
Among different configurations of multilevel converters, diode-clamped configuration is highly used in different applications due to its capability of high voltage and high efficiency operation.

As shown in Fig. 1.8(a), each leg of a three-level diode-clamped converter includes two pairs of switches which each pair ($S_1$, $S_3$ and $S_2$, $S_4$) works in complementary. It means when $S_1$ is ‘On’ $S_3$ is ‘Off’ and vice versa. As it mentioned before, in symmetric multilevel converters the DC link voltage is distributed over the capacitors equally. Therefore, the output levels are same. Also, the number of output levels is equal to the number of DC link capacitors so for $m$-level converter with
symmetric configuration the total value of the output voltage is \( m \cdot (V_{DC}/n) \). Thus, it is clear that for increasing the output levels more DC link capacitors and components are required which results in more cost and complexity of the system. Another problem of symmetric converters is capacitor voltage unbalancing. To overcome these problems, asymmetric configuration is a helpful option. By this configuration, voltages across DC link capacitors are not equal and it is possible to achieve more different output voltage levels without adding up any components and capacitors [68, 70, 71]. A four-level diode-clamped converter is shown in Fig. 1.9.

![Fig. 1.9. Single phase diode-clamped four-level converter.](image)

As it is clear in this figure, four-level converter has one more DC link capacitor, two more switches and two more diodes per leg compared to three-level converter. A \( m \)-level diode-clamped converter includes \((m-1)\) DC link capacitors, \(2(m-1)\) switching components and \(2(m-2)\) clamping diodes per phase.

If the voltages across \( C_1, C_2 \) and \( C_3 \) are equal, this four-level converter is symmetric, otherwise it is asymmetric [72].

Table. 1.1 shows output voltages and switching states of a symmetric and an asymmetric four-level converter. Voltages across DC link capacitors for two different configurations are:

- Symmetric configuration: \( V_{C_1} = V_{C_2} = V_{C_3} = \frac{V_{DC}}{3} \)
Asymmetric configuration: \( V_{C1} = \frac{V_{DC}}{2} \), \( V_{C2} = \frac{V_{DC}}{4} \), \( V_{C3} = \frac{V_{DC}}{4} \).

Table. 1.1. Switching states and output voltage levels of symmetric and asymmetric four-level converter [72]

<table>
<thead>
<tr>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
<th>V_{output}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Symmetric Configuration</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-V_{DC}/3</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>-2V_{DC}/3</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-V_{DC}</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>V_{DC}/3</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
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<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-V_{DC}/3</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-2V_{DC}/3</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2V_{DC}/3</td>
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<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>V_{DC}/3</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
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<tr>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-V_{DC}/3</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>V_{DC}</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2V_{DC}/3</td>
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<tr>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>V_{DC}/3</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

From this table, it is clear that one more output level is achieved in asymmetric configuration with the same number of components. The output voltages of a symmetric and an asymmetric four-level converter are illustrated in Fig. 1.10.
Fig. 1.10. Output voltage of (a) symmetric (b) asymmetric four-level converter.

The main advantage of asymmetric configuration is depicted in this figure where one more output voltage level is generated with the same number of components. By this configuration, it is possible to achieve a high quality output signal with less control complexity and cost. Several modulation and control strategies are introduced to control the output signal of multilevel converters.

1.2.3.3. DC/DC converter

Energy conversion is a main task of power converters in which one level of electrical energy is converted to another level based on different switching states. One of famous power converters is DC/DC converter which is responsible for DC power regulation. In some of applications, it is highly required to adjust DC voltage for the system. As an example, the DC voltage generated by Photovoltaic (PV) system should be regulated before connecting to the network. Also, in cascade multilevel converters, a set of series connected cells are applied as the separate input DC supplies which should be adjusted using DC/DC converters [73]. DC/DC converters are classified as:

- Boost converter
- Buck converter
➤ Buck-Boost converter

Boost converters are widely used to regulate and boost the input voltage signal based on different switching states of boost switch. It means boost switch will turn on to increase the input voltage in order to achieve desired output voltage level. On the other hand, if the input voltage is more than the output voltage buck converters are applied to adjust the output by decreasing the input. Combination of boost converter and buck converter is named as buck-boost converter which is able to increase either decrease the input voltage. These three configurations are shown in Fig. 1.11.

![Diagram of DC/DC converters]

Fig. 1.11. Three configurations of DC/DC converters (a) boost configuration (b) buck configuration (c) buck-boost configuration.

To drive a high power ultrasound transducer, stand alone DC/DC converter is not a proper option but combination of a DC/DC converter and a multilevel converter
can be used as a current source multilevel converter to excite the transducer which has almost capacitive characteristic. The combination of a DC/DC converter (boost configuration) and a multilevel converter is shown in Fig. 1.12.

![Fig. 1.12. Combination of a DC/DC converter and a multilevel converter.](image)

By this combination, the current through the load and the voltage across it are controlled by controlling the current of the inductor in DC/DC converter. Therefore, it is possible to reduce the voltage stress \(\frac{dv}{dt}\) across switches and the load. The effect of this type of converter on the transducer performance is discussed more in section 1.3.3.2.

1.2.4. Control and modulation techniques for multilevel converter

Pulse Width Modulation techniques are widely used for different applications to control the output of multilevel converter. Some of these techniques are:

- Space vector modulation
- Carrier-based PWM method
- Selective harmonic elimination technique

1.2.4.1. Space vector Modulation (SVM)

This technique can easily apply for all three configurations of multilevel converter. In this method, desired output voltage is synthesized by sampling a reference signal which is generated according to two adjacent switching states of the multilevel converter in two-phase orthogonal (d-q) coordinates [74-77]. A circuit diagram and the space vector diagram of a three-phase two-level converter are depicted in Fig. 1.13.
The transformed parameters of a three phase two-level converter in orthogonal plane are represented by,

\[
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -1/2 \\
0 & \sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix}
\]

\[|V_{ref}| = \sqrt{V_d^2 + V_q^2}\]

\[\theta = \tan^{-1}\left(\frac{V_q}{V_d}\right)\]
As shown in Fig. 1.13, for a two level converter a hexagonal diagram is achieved according to adjacent switching states. Although, this technique is a suitable choice to improve the quality of the output signal, increasing the number of output levels results in redundancy of the switching states and complexity of this technique.

1.2.4.2. Carrier-based PWM technique

Compared to space vector modulation, this technique is much simpler and flexible. Since increasing the number of output levels influences the simplicity of space vector modulation and increases computational requirements so carrier-based PWM methods are widely used for controlling multilevel converters[78-81]. With this technique, it is possible to generate staircase output voltage with adjustable magnitude and frequency by controlling the amplitude and frequency of reference signal [82]. In this technique, a sinusoidal reference signal is sampled by carrier signal(s) over one or several periods of reference signal. As a result of this technique, some pulses are generated with different duty cycles which are used to drive switching components of the converter. The variation of the duty cycles provides the ability to adjust the output voltage levels. The frequency of the carrier signal is usually a multiple of the fundamental frequency of the reference signal and is limited to the maximum possible switching frequency of the components. This technique is illustrated in Fig. 1.14.
Since the maximum switching frequency of the components curbs the frequency of the carrier signal, there is no possibility to apply this method for high frequency applications. To remedy this problem, other control techniques are used for high frequency applications.

1.2.4.3. Selective harmonic elimination technique

In this technique, specific low order harmonics will be eliminated by determining the switching angles [74, 83-85]. To achieve this aim, the Fourier series expansion of the output voltage waveform is normally used. Due to the quarter-wave symmetry of the output waveform, there is no even harmonics in harmonic spectrum so the Fourier series expansion is given by:

\[
b_n = \sum_{i=1}^{m-1} \frac{4V_i}{n\pi} \cos(n\alpha_i) \tag{1-2}
\]

where:

- \(V_i\): the amplitude of each voltage level
- \(\alpha_i\): the \(i^{th}\) switching angle
n: odd harmonics (1,3,5,...)

m: the number of output voltage levels

In conventional harmonic elimination techniques, the output voltage steps are equal [86]. Therefore, Eq. 1-2 can be simplified as:

\[ b_n = \frac{4V_{dc}}{n(m-1)\pi} \sum_{i=1}^{m-1} \cos(n\alpha_i) \]  

(1-3)

According to Eq. 1-3, just switching angles are considered as variables to eliminate low-order harmonics and each output levels are equal to \( V_{DC}/(m-1) \) and the amplitude of output waveform is \( V_{DC} \). Therefore, the number of eliminated harmonics is limited to the number of switching angles. This limitation is a main concern in the conventional harmonic elimination technique because for eliminating more harmonics, more switching angles and thereby more output levels are required. As discussed before, more components are required to generate more output voltage levels which increase cost and complexity of the system. To remedy these problems, more variables are required to eliminate more low order harmonics. In this regard, besides of the switching angles the DC link voltages are determined in such a way to eliminate more harmonics. Drive pulses and output waveform of a m-level converter are shown in Fig. 1.15.
To calculate switching angles and the DC link voltages, several nonlinear equations should be solved. Based on the calculated values, DC link voltages are not equal so this configuration can be considered as an asymmetric configuration of a multilevel converter. To adjust unequal DC link voltages, DC/DC converters are connected in the input side of multilevel converter [73, 87].

1.3. Account of Research Progress Linking the Research Papers

Since this research is focused on improving ultrasound excitation systems to drive a high power ultrasound system at desired voltages and frequencies, several literature reviews were required to have a better understanding of a high power piezoelectric transducer characteristics, ultrasound system performance and different excitation techniques. According to preliminary literature review, it was deduced that several factors can affect the performance (energy conversion) of the piezoelectric transducer as well as the ultrasound system. Among these factors, it was shown that the behaviour of the transducer and the quality of the excitation signal can highly influence the performance of the transducer and the system. Therefore, it was highly important to study the piezoelectric transducer characteristic and find out how it is possible to improve the quality of the excitation signal.
The potential of the piezoelectric transducer in energy conversion is widely used in different applications from industrial to biomedical. A piezoelectric transducer is normally made of crystal or ceramics. Once a piezoelectric transducer is excited by electrical energy, its inside materials will start to vibrate and generate mechanical energy in forms of ultrasound waves correspond to the applied electrical energy. The ability of this device in energy conversion is known as piezoelectric effect and is a reversible process. As a direct piezoelectric effect, a transducer converts an applied electrical charge to a mechanical strain. During this process, the transducer acts as a transmitter. However, as a receiver the transducer exhibits reverse piezoelectric effect where it converts an applied mechanical force to electrical energy. A piezoelectric transducer is a main part of an ultrasound system and can operate as a transmitter, a receiver or both. A block diagram of an ultrasound system is depicted in Fig. 1.16.

![Block Diagram of an Ultrasound System with a Transducer](image1)

**Fig. 1.16.** A block diagram of an ultrasound system with a transducer.

As mentioned before, in some applications, an ultrasound transducer includes two transducers one as a transmitter and one as a receiver. A block diagram of such a system is shown in Fig. 1.17.

![Block Diagram of an Ultrasound System with Two Transducers](image2)

**Fig. 1.17.** A block diagram of an ultrasound system with two transducers.
Since a piezoelectric transducer is used for energy conversion in an ultrasound system, its nonlinear characteristics can easily affect the efficiency of the system by increasing power consumption of the system. A piezoelectric transducer has a frequency domain characteristic with a wide bandwidth \((F_L - F_H)\) which is shown in Fig. 1.18. In some applications especially in biomedical systems, it is essential to control the output voltage (generated electrical field) at desired frequencies and voltage levels. In this regard, it is highly required to reduce bandwidth of piezoelectric transducer to a narrower band one \((f_1 - f_2)\).

![Piezoelectric transducer transfer function in frequency domain.](image)

Fig. 1.18. Piezoelectric transducer transfer function in frequency domain.

In order to control the frequency bandwidth and compensate the variation of piezoelectric transducer output voltage, a power converter is required to generate a high quality signal with adjustable frequency and magnitude. To achieve this aim, some aspects should be taken into consideration.

1.3.1. Modelling of a piezoelectric transducer

Studying the nonlinearity of a piezoelectric transducer is the first aim of this research. To achieve this aim, several simulations and laboratory tests have been performed to analyse the nonlinearity of the piezoelectric transducer. The outcome of this investigation is submitted to IEEE transactions on ultrasonics, ferroelectrics, and frequency control (chapter 4).

According to different electrical models of a piezoelectric transducer, they are all based on series and parallel combinations of resistor, capacitor and inductor. It is obvious that the impedance amplitude of a piezoelectric transducer changes at
different frequencies. The electrical characteristic of a piezoelectric transducer in frequency domain is illustrated in Fig. 1.19.

![Impedance diagrams of two piezoelectric transducers](image1)

Fig. 1.19. Electrical characteristic of a piezoelectric transducer.

Impedance diagrams of two piezoelectric transducers are shown in Fig.1.20. At some frequencies which are known as resonance frequencies of the transducer, the amplitude of the transducer impedance is much lower.

![Amplitude of Impedance](image2)
As shown in this figure, each piezoelectric transducer has several resonance frequencies. One of these frequencies is called as the main resonance frequency of the transducer where the impedance of the transducer has the lowest amplitude. For example, the main resonance frequency of the transducer shown in Fig.1.20 (a) is 78 kHz while in Fig.1.20 (b) is 1 MHz. Sometimes a piezoelectric transducer is known by its main resonance frequency.

Usually, the transducer is excited at resonance frequencies (or minimum impedance) and thereby highest energy conversion is achieved at these frequencies. In this regard, it is necessary to find out these frequencies. Several methods are applied to determine resonance frequencies. A frequency estimation algorithm is proposed in this research to determine resonance frequencies of transducers. The ability of this algorithm in detection of resonance frequencies is examined for two practical cases. The results of this technique are published for IET Science, Measurement & Technology entitled “Improving the Efficiency of High Power Piezoelectric Transducers for Industrial Applications” (chapter 2). The advantages of the proposed method in comparison with other methods are illustrated in Table. 1.2.
In this table, as a traditional method several sinusoidal signals with different fundamental frequencies have been applied to excite the transducer. Also, an R&S ZVL3 vector network analyser has been applied to obtain the amplitude and phase of the transducer impedance. For a step pulse and white noise methods, the impedance is measured by dividing the Fourier transform of the output into the Fourier transform of the input. For a step pulse, a staircase waveform is used to drive the transducer and as white noise, the transducer is excited by a constant amount of energy per frequency band.

Considering resonance frequencies of a piezoelectric transducer, the electrical model of the transducer can be extended by adding more parallel RLC branches. The extended electrical model of a high power piezoelectric transducer considering several resonance frequencies is shown in Fig. 1.21.

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 in phase and equal in amplitude, they cancel each other. In this case, the RLC branch related to that resonance frequency can be simplified as a resistor. Therefore, at each resonance frequency the resistor delivers energy to the secondary side of the system.

![Extended electrical model of a high power piezoelectric transducer.](image)
### Table 1.2. Comparison between resonance frequencies detection methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
</table>
| Traditional                   | • Easy to implement  
• Low expense  
• Direct frequency output | • Circuit stability required  
• Labour intensive  
• Not applicable for online process |
| Network Analyser              | • Provides complete impedance frequency response  
• High accuracy due to calibration | • High expense  
• Not applicable for online process  
• Not applicable on high power converter  
• Slow due to the complex measurement procedure |
| Impulse Response (Step Excitation) | • Provides impedance frequency response  
• Easy to generate with power converter  
• Can be generated at high power  
• Can be applied for online process | • Slower than the proposed method (because the applied step is longer than the pulse).  
• Sensitive to the noise |
| White Noise Excitation        | • Provides impedance frequency response  
• Can be applied for online process | • Not easy to generate especially at high power  
• Not possible to generate with power converter  
• Sensitive to the noise |
| Proposed                      | • Provides impedance frequency response  
• Easy to generate with power converter  
• Can be generated at high power  
• Can be applied for online processes | • Sensitive to the noise |
To measure the impedance of a piezoelectric transducer, a network analyser is usually used in some applications.

A network analyser operates in a broad frequency range but at low power. Therefore, for a high power piezoelectric transducer some errors maybe appear in impedance diagrams when the transducer operates at its maximum power range. To remedy this problem and study the impedance behaviour of a high power piezoelectric transducer at higher power, two methods are applied in this research.

**Using a sinusoidal signal**

As it is discussed in previous section, due to power limitation of a network analyser another test is required to measure the impedance of a high power piezoelectric transducer. In this regard, a signal generator, a linear power amplifier (OPA549) and a high frequency transformer with turn ratio of (10 : 100) are applied to generate a sinusoidal signal with adjustable frequency and amplitude. A block diagram of this test is depicted in Fig. 1.22.

![Fig. 1.22. A block diagram of a piezoelectric transducer excitation using sinusoidal signal.](image)

In this test, two same transducers (78 kHz) are used. To measure the current through this transducer, a resistor (1 Ω) is placed in series with transducer 1. The voltage across transducer 1 ($V_1$) and the current through it ($i$) are measured to calculate its impedance ($Z=V_1/i$). To study the effect of amplitude and frequency variations of the input signal on the transducer impedance, two individual input signals with different amplitudes (15 V and 50 V) are generated. The frequency of these signals varies between 30 kHz to 90 kHz. The result of this test is shown in Fig. 1.23.
Fig. 1.23. Impedance measurement using sinusoidal excitation signal.

This test result is compatible to the result presented in Fig.1.20(a) because in both of these tests a 78 kHz transducer is applied.

As shown in this figure, the impedance of the transducer is a function of input voltage and frequency because if the input voltage magnitude and frequency are changed, the impedance of the transducer will be changed as well which is due to nonlinearity of the piezoelectric transducer. Thus it is possible to show the impedance of the transducer as:

\[ R_i = g(V_{\text{input}}, f_i) \]  \hspace{1cm} (1-4)

where:

\( R_i \): resistance of \( i \)th resonance frequency of the ultrasound transducer

\( f_i \): frequency of \( i \)th resonance frequency

If a piezoelectric transducer has a linear characteristic, its impedance diagrams should be same regardless of input amplitude and frequency changes.

For more clarification, a narrowband frequency of Fig. 1.23 is shown in Fig. 1.24.
From Fig. 1.24, it is obvious that if the input voltage amplitude is changed, the transducer impedance will be changed as well. For instance, if the input amplitude changes from 15 V to 50 V, the impedance will change from 250 Ω to 800 Ω. Also, the impedance of the transducer varies at different frequencies. As clear in this figure, if \( V_{\text{input}} = 15 \text{ V} \) at 77.8 kHz, \( R_{77.8} = 550 \Omega \) while at 78.2 kHz, \( R_{78.2} = 980 \Omega \). These results validate Eq.1-4.

For more clarification, the superposition principle is used to prove the nonlinearity of the transducer. According to this pattern, the sum of the responses of transducer 2 to two individual input signals (test condition 1) should be the same as its response to the sum of two simultaneous signals (test condition 2). The results of this test are depicted in Fig. 1.25.
To study nonlinearity of the transducer at different frequencies, two fundamental frequencies are chosen for the input signals, 39 kHz (non-resonance frequency) and 61 kHz (resonance frequency). As it is clear in this figure, the results are not same. For example, for $V_{\text{input}}=15$ V the impedance of the transducer is 921 $\Omega$ in Fig. 1.25(a) but 882 $\Omega$ in Fig. 1.25(b). This mismatch proves that the transducer does not obey the superposition rule and thereby is nonlinear.

Since a high power ultrasound transducers are widely used in high power applications such as biomedical applications, so it is important to analyse nonlinearity of the transducer in that range of power. In this regard, a three-level power converter is developed to drive the transducer.

As it is mentioned before, a piezoelectric transducer performance can be affected by the quality of the excitation signal. As the output of a switched-mode power converter is not a pure sinusoidal signal, some harmonics will be generated in sidebands of the fundamental frequency. The transducer is excited by a 39 kHz staircase waveform so first sideband of the fundamental frequency will be appeared at 78 kHz which is the main resonance frequency of the transducer. In this case, it is easy to study the effect of distorted excitation signal on the transducer performance. Also, to study the nonlinearity of the transducer correspond to amplitude variation of input signal, the amplitude of input signal is changed from 25 V to 200 V (peak).

From Fig. 1.26 the nonlinearity of the transducer is obvious where impedance increments do not match with the input voltage increments. As an example, if $V_{\text{input}}$ increases from 50 V to 200 V at 39 kHz, the impedance decreases from 370 $\Omega$ to 350 $\Omega$. 

![Fig. 1.25. Results of superposition law (a) test condition 1 (b) test condition 2.](image)
In some applications it is highly important to deliver power at desired frequency but generation of higher harmonics would cause energy deposition to undesired frequencies which is not accepted. For instance, in above test the fundamental frequency is adjusted to 39 kHz and it is required to deliver power just at this frequency but as clear in test results shown in Fig. 1.26 some portion of energy is delivered at 78 kHz.

![Impedance of Transducer](image)

Fig. 1.26. Impedance diagram of the transducer excited by staircase waveform.

1.3.2. Modelling of a ultrasound system

In some applications like [24], two ultrasound transducers are applied one as a transmitter and another one as a receiver to convert energy. In such a system different media are used to couple these two transducers such as water, oil, .... The effect of these media on the behaviour of the ultrasound system has been discussed in different literature [88-90]. The nonlinearity of the ultrasound transducer is discussed in previous section. There is no doubt that the nonlinearity of the transducer can affect the performance of the ultrasound system. Several simulation and laboratory tests are carried out in this research to study the nonlinearity of the ultrasound system including two same piezoelectric transducers respect to the input voltage and frequency variations. Analysis of the ultrasound system behaviour is published in proceeding of ICIEA conference 2012 entitled “Power Electronic Converters for High Power Ultrasound Transducers” (chapter 5). Two types of media, water and oil, are applied as a coupling media. In this research, the responses of the system to different input signals such as sinusoidal signal and square wave signal are measured to study the behaviour of the system. The main concept of measuring the output of the system is that if the output variation is compatible to the input changes this
system is linear otherwise is nonlinear. A block diagram of the ultrasound system is shown in Fig. 1.27.

![Block Diagram of Ultrasound System](image)

Fig. 1.27. A block diagram of the ultrasound system excitation using sinusoidal signal.

In the first step, an EZ Digital FG 7020A function generator and a power amplifier (OPA549) are used to generate two sinusoidal signals with different fundamental frequencies (39 kHz and 61 kHz) and amplitudes (15 V<sub>peak</sub> and 30 V<sub>peak</sub>). Transducer 1 (transmitter) is excited by generated signals and the output voltage is measured across transducer 2 (receiver) as a response of the system to the input signal. These fundamental frequencies are chosen to drive the transducer at its resonance (61 kHz) and non-resonance (39 kHz) frequencies. According to frequency domain test results shown in Fig. 1.28, this system is nonlinear because the output variations is not match to the input changes. Compared to input voltage amplitudes, the measured output amplitudes are attenuated due to dissipation of generated ultrasound waves in the water. Dissipation of Ultrasound waves is because of propagation, absorption and reflection of ultrasound waves during transferring through water. Therefore, intensity of the ultrasound waves received by transducer 2 is reduced. Since receiver convert mechanical energy (ultrasound waves) to electrical energy, this attenuation results in reduction of the output voltage.
The superposition principle is applied to evaluate nonlinearity of the system. The results of this test are explained more in chapter 4 and 5.

In the second step, a three-level converter is implemented to generate a high power square wave signal. In previous test, there is no possibility to drive the transducer with high voltage signal because of voltage limitation of amplifier. Doing this test provides opportunity to analyse the nonlinearity of the ultrasound system in higher voltage range. A block diagram and test results of this test are shown in Fig. 1.29.
Fig. 1.29. Ultrasound system excitation using a three-level converter (a) block diagram and test results (b) normalised input voltages (c) normalised output voltages.

In this test, the fundamental frequency is chosen as 39 kHz to excite the transducer and deliver power just at this frequency. But as it is clear in this figure, the distorted signal (not pure sinusoidal signal) affects the output voltage where some portion of the power is delivered at 78 kHz. In some applications especially in biomedical applications, generation of higher harmonics can cause undesired effect. For instance, when a damaged tissue is going to be treated, energy displacement affects the lateral tissue which is unaccepted. To have a better view of the system behaviour, all results are normalised to 50 V. As shown in this figure, all input signals are matched each other but the output signals are mismatched due to the nonlinearity of the system. Another important issue illustrated in this figure is that the increment of the input voltage does not necessarily result in the output increment and it seems that the system behaves like a transformer which saturates at higher
range of voltage. For example, for $V_{input}$=50 V the output voltage is 1.7 V while for $V_{input}$=300 V, the output voltage is 0.5 V.

Considering an electrical model of the transducer, it is possible to develop an electrical model of the ultrasound system as shown in Fig. 1.30.

![Circuit diagram of an ultrasound system.](image)

Since at each resonance frequency of the transducer, inductive and capacitive reactance cancel out each other so this leg could be modelled just as the resistor at that frequency. By this assumption, the output voltage is a function of voltage across resistor at each resonance frequency.

This fact is shown in Eq. 1-5.

$$V_{output}=g(V_{R_{f_i}})$$  \hspace{1cm} (1-5)

where:

- $V_{output}$: the output voltage of the ultrasound system
- $V_{R_{f_i}}$: the voltage across
- $R_{f_i}$: resistance of $i^{th}$ resonance frequency of the ultrasound transducer
- $f_i$: frequency of $i^{th}$ resonance frequency

If a sinusoidal signal with fundamental frequency close to one of the resonance frequencies of the transducer is applied as an input signal then $V_{output}$ is just a function of $V_{R_{f_i}}$ at fundamental frequency. However, $V_{output}$ will be a function of other frequencies if the piezoelectric transducer is excited by several frequencies like excitation by square wave signal.

To clarify Eq. 1-5, the output voltage is measured in a laboratory test and then normalized to compare with the simulated voltage across resistor at 78 kHz. The test and simulation results are depicted in Fig. 1.31.
As 78 kHz is the main resonance frequency of the applied transducers, the fundamental frequency of the input signal is adjusted to 78 kHz to achieve better performance of this transducer. The output voltage is measured across transducer 2 (in a practical test) and compared with simulated voltages across resistors at that particular frequency range. As shown in Fig. 1.31, the output voltage at 78 kHz is 18.37 V which is really close to $V_{R_{78}} = 18.66$ at same frequency (78 kHz).

### 1.3.3. Piezoelectric transducer excitation

The quality of the input signal is one of the main issues which should be taken into consideration for driving a piezoelectric transducer. As shown in test results in this research, higher harmonics are generated if a distorted signal is applied as an excitation signal. Also, it has been discussed that to excite a high power piezoelectric transducer, a high power signal is required. To generate a high power signal, switched-mode power converters are normally used but the drawback is the Low
quality of the square wave signals compared to sinusoidal signals. Several
modulation technique and control methods are introduced in different literature to
improve the quality of the output waveforms of multilevel converters like harmonic
elimination techniques. As a conventional harmonic elimination technique, the
number of the eliminated harmonics is limited by the number of switching angles. In
this case, to eliminate more harmonics, more switching angles and thereby more
output voltage levels are necessary. To improve the output quality of the multilevel
converters without increasing the number of components, a new harmonic
elimination technique is proposed in this research (chapter 6). This technique takes
the advantage of asymmetric multilevel converters in generating of more output
levels. The effect of this technique on harmonic elimination is illustrated in several
simulation and laboratory tests. These results are published in proceeding of EPE
conference 201, Birmingham, UK entitled “A New Unequal DC link Voltage
Configuration for a Single Phase Multilevel Converter to Reduce Low Order
Harmonics”.

1.3.3.1. New harmonic elimination technique

Traditionally, the output voltage levels of multilevel converters are equal and
curbed by the number of components and the DC link capacitors. To increase the
number of the output voltage levels with same component, one possible option is
using unequal DC link voltage configuration. In this configuration, the voltages
across DC link capacitors are different so steps of the output staircase waveform are
different as well. As a harmonic elimination method, switching angles are calculated
offline in such way to reduce harmonics by solving several nonlinear equations. To
achieve this aim, Fourier series expansion is used.

Fourier series expansion of m-level converter is given by Eq. 1-2.

In the conventional harmonic elimination technique, the DC link voltages are
equal so \( V_1 = V_2 = \ldots = V_m = V_{dc}/(m-1) \). By this assumption, switching angles are the
only parameters which are calculated from Eq. 1-2. MATLAB software is used to
solve the Eq. 1-2. For instance, to eliminate 3th and 5th harmonics of a four-level
converter with the fundamental component of \( b_1 = 0.6 \) (per unit) and
\( V_{dc} = 0.7 \) (per unit), Eq. 1-2 is rewritten as:
\[ b_1 = \frac{4V_{dc}}{3\pi} (\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3)) = 0.6 \]

\[ b_3 = \frac{4V_{dc}}{9\pi} (\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3)) = 0 \quad (1-6) \]

\[ b_5 = \frac{4V_{dc}}{15\pi} (\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3)) = 0 \]

Calculated switching angles are:

\[ \alpha_1 = 0.3090 \text{ rad}, \quad \alpha_2 = 0.5306 \text{ rad}, \quad \alpha_3 = 1.3649 \text{ rad} \]

Output voltages of the four-level converter in time and frequency domain considering calculated switching angles are depicted in Fig. 1.32.

Fig. 1.32. Output of a four-level converter operating with conventional harmonic elimination technique (a) time domain (b) frequency domain.
As it is clear in this figure the number of eliminated harmonics is curbed by the number of the switching angles \((\alpha_1, \alpha_2, \alpha_3)\). To increase the number of switching angles more output voltage levels and thereby more components are required. To remedy this problem and eliminate more harmonics, more variables are required for Eq. 1-2. In this regard, in new harmonic elimination technique, besides switching angles, DC voltage levels are considered as additional variables and calculated offline by solving Eq. 1-2.

For above four-level converter, the calculated DC voltages and switching angles are:

\[
V_1 = 0.2625 \text{ V} \quad V_2 = 0.2105 \text{ V} \quad V_3 = 0.1168 \text{ V}
\]

\[
\alpha_1 = 0.2244 \text{ rad} \quad \alpha_2 = 0.6732 \text{ rad} \quad \alpha_3 = 1.1220 \text{ rad}
\]

For more clarification, the effect of the new harmonic elimination on the output of above four-level converter is shown in Fig. 1.33.
As shown in this figure, 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th} and 9\textsuperscript{th} harmonics are eliminated. Compared to Fig. 1.32, two more harmonics (7\textsuperscript{th} and 9\textsuperscript{th}) are eliminated using this new technique because the number of variables in previous case was 3 (\(a_1, a_2, a_3\)) and for this case is 6 (\(a_1, a_2, a_3\) and \(V_1, V_2, V_3\)). The main advantage of this technique in comparison with conventional harmonic elimination method for a same multilevel converter is eliminating more harmonic contents without adding up more components. The benefit of proposed technique in harmonic reduction is an attractive aspect for some applications in which a high power and high quality signal should be generated while the number of components is limited. One of these applications is high power ultrasound transducer excitation where low quality excitation signal deteriorates the performance of the transducer and results in energy displacement to undesired location.

The main concern associated with multilevel converters controlled by new modulation technique is regulating DC link voltages according to calculated DC voltages. In this case, a DC/DC converter is a suitable choice to generate desired voltages. Also, for those applications where a renewable energy source such as PV or fuel cell is a voltage source for a cascade converter, the proposed modulation can be used to generate unequal voltage levels because of their flexibility to generate various DC link voltages through a DC/DC converter [91].
Among DC/DC converters, multi-output converters provide the opportunity of generating several output levels without different power sources [92, 93]. A circuit diagram of this converter is shown in Fig. 1.34.

![Circuit diagram of a three output voltage sharing converter connected to a four-level converter](image)

Fig. 1.34. Circuit diagram of a three output voltage sharing converter connected to a four-level converter [92].

As it is mentioned in this section, a multilevel converter operating with proposed harmonic elimination technique draws great interest in driving a high power ultrasound transducer. To study the effect of a multilevel converter on the performance of a piezoelectric transducer, a two-level and a four-level converter are implemented to drive the ultrasound system presented in section 1.3.2. Both of implemented converters are controlled by the proposed harmonic elimination technique. The results of this test presented in chapter 3 prove the ability of the multilevel converter and the proposed harmonic elimination technique in harmonic reduction. The outcomes of these tests are published in IET transaction on power electronics entitled “A Harmonic Elimination Technique for a Single-phase Multilevel Converter with Unequal DC Link Voltage Levels”.

1.3.3.2. Current source multilevel converter

As shown in Fig. 1.19, a piezoelectric transducer has a capacitive characteristic at most of frequencies. The current through the transducer for those frequency durations in which it has a capacitive characteristic is \( i_C = C \frac{dV}{dt} \). Therefore, a high voltage stress \( \left( \frac{dV}{dt} \right) \) across a piezoelectric transducer leads to generate a significant leakage current. To analyse this issue a laboratory setup of a voltage source four-
A level converter is developed to excite a set of 1 MHz transducers. In this test two 1 MHz transducers are coupled with ultrasound gel. The current through transducer 1 and the voltage across transducer 2 are measured. This laboratory setup is depicted in Fig. 1.35. Due to the switching frequency limitation of IGBTs (100 kHz), the fundamental frequency of the input signal is adjusted to 100 kHz in this test. The results of this test are shown in Fig. 1.36.

Fig. 1.35. Experimental setup of a four-level voltage source diode-clamped converter.
Fig. 1.36. The output voltage of a four-level converter and (a) the voltage across transducer 2 (b) the current through transducer 1.
As it is obvious in Fig. 1.36, the voltage variation across transducer results in generation of current spikes which can decrease the quality and efficiency of the system. To overcome these problems, LC filter is used in some applications. In ultrasound applications where a piezoelectric transducer should be excited, the LC filter will change the characteristic and the resonant frequency of the piezoelectric transducer. Several tests and simulations are carried out to show the effects of the LC filter on the output voltage of a high power ultrasound system. In these tests, the output voltage is measured across the second transducer when the first transducer (transmitter) is excited by a voltage source converter (see chapter 7). The laboratory test results with and without LC filter are shown in Fig. 1.37.

![Graph](image)

(a) Output voltage (Without Filter) (b) Output voltage (With Filter)

Fig. 1.37. Output voltage (a) without LC filter (b) with LC filter.

In this figure the effect of LC filter on the output voltage is clear where the resonance frequency of the transducer is displaced. For instance, without filter, the peak of output voltage is located at 78.14 kHz while after using filter it is moved to
77.75 kHz. Also, the amplitude of the output voltage is decreased from 24.58 V to 21.7 V at 78.14 kHz after using LC filter.

In such a case, a current source converter might be a good choice to solve the problem associated with high $\frac{dv}{dt}$. In current source converters, instead of input voltage, input current is controlled to generate a desired output signal and thereby the voltage stress across transducer will be decreased. Also, in a current source converter topology, the current through the load (piezoelectric transducer) is unidirectional so no reverse diode is required in parallel with each switch of the converter. Several simulation and laboratory tests are carried out in this research to illustrate the effect of current source converter on piezoelectric transducer excitation (chapter 7). The results of these tests are published as a conference paper entitled ‘A High Frequency Current Source Converter with Adjustable Magnitude to Drive High Power Piezoelectric Transducers’ at EPE 2012, Novi Sad, Serbia.

A current source converter is implemented and utilized to excite a high power piezoelectric transducer (78 kHz). In this test, a hysteresis control and a unipolar modulation technique are applied to control the input current and the output voltage of the converter respectively. All switching pattern signals are controlled using a digital signal controller (TMS320F28335). The practical test results are illustrated in Fig. 1.38.
The experimental results prove the ability of the current source converter in reduction of current spikes and show how the output current and voltage are controlled in desired ranges (1-1.5 A and -40 V to 40 V) by controlling the input current between 1-1.5 A.

Reference


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Statement of Contribution of Co-Authors

The authors listed below have certified that:
1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit, and
5. they agree to the use of the publication in the student’s thesis and its publication on the Australasian Research Online database consistent with any limitations set by publisher requirements.

In the case of this chapter:

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Statement of contribution*</th>
</tr>
</thead>
<tbody>
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<tr>
<td>16 Nov 2012</td>
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CHAPTER 2

IMPROVING THE EFFICIENCY OF HIGH POWER PIEZOELECTRIC TRANSDUCERS FOR INDUSTRIAL APPLICATIONS

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Abstract—Most high power ultrasound applications are driven by 2-level inverters. However, the broad spectral content of the 2-level pulse results in undesired harmonics which can decrease the performance of the system significantly. On the other hand, it is crucial to excite the piezoelectric devices at their main resonant frequency in order to have maximum energy conversion. Therefore a high quality, low distorted power signal is needed to excite the high power piezoelectric transducer at its resonant frequency. This paper proposes an efficient approach to develop the performance of high power ultrasonic applications using multilevel inverters along with a frequency estimation algorithm. In this method, the resonant frequencies are estimated based on relative minimums of the piezoelectric impedance frequency response. The algorithm follows the resonant frequency variation and adapts the multilevel inverter reference frequency to drive an ultrasound transducer at high power. Extensive simulation and experimental results indicate the effectiveness of the proposed approach.

2.1. Introduction

Wide spread research has been conducted on piezoelectric transducer applications since 1880, the year that Pierre and Jacque Curie discovered the phenomenon of piezoelectricity [1], [2]. Piezoelectric transducers convert electric power to acoustic power and vice versa, with most of the applications to date being low power ones. In the last decade, however, high power ultrasound applications have gained significant importance [3-8]. These types of applications have great potential in chemical and bio-technology processing, specifically for enhancing chemical reaction kinetics and new reaction pathways. Such enhancements allow changing the production from batch processing to continuous flow processing, thereby reducing investment and operational costs.

Improvement of ultrasound systems has very significant environmental implications, particularly in the area of renewable energy (bio-mass and bio-fuel), waste-water treatment and biomedical applications. High power ultrasound technology is already being used to address these areas of need, but to a very limited extent due to the very inefficient nature of the state of the art in energy conversion.

The critical behaviour of a piezoelectric device is encapsulated in its resonance
frequencies due to its maximum transmission performance at these frequencies [1, 2, 9-11]. Hence, ideal scenario is to have a sinusoidal excitation signal at the resonant frequency. But at high power and high voltage, which is the focus area of this paper, generating pure sinusoidal signals is not possible.

The most efficient way to generate power signals is to use a 2-level power inverter. Specifically, switch mode inverters are used for piezoelectric high power applications due to their high power density, efficiency, low cost and size compared to conventional linear power supplies [7, 12, and 13]. However, the harmonics present in the output waveform produce undesired side bands which are not suitable in many applications. Moreover, they also cause unnecessary power dissipation which reduces the efficiency of the power converter [3, 14].

On the other hand, for ultrasound applications which operate at high fundamental frequency power converters based on a PWM strategy with high switching frequency index \( f_s/f_o \) cannot be a practical solution. In such applications, the maximum possible fundamental frequency of a converter is restricted by the switching transients of each power switching event and the number of switching events per cycle.

In this regard, to reduce the number of switching transients and eliminate the undesired harmonics, the most effective way is to use multilevel inverters [15-18]. Through these inverters, it is possible to produce quasi-sine waves with low total harmonic distortion at high power. Multi-level inverters can increase the quality and efficiency of the high voltage supply compared to the conventional 2-level inverters. This permits the semiconductor devices to operate at lower switching frequencies with higher efficiency as well as lower voltage stress across switches and loads which minimize electromagnetic and ultrasound noise emissions. Fig. 2.1 depicts typical voltage waveforms and their harmonic spectra. It can be seen that the harmonics are depressed for multilevel inverters such that they can be easily filtered out from the frequency range of interest.

To improve the performance of the piezoelectric transducer for high power applications, in addition to the multilevel converter, the device needs to be excited at its resonant frequency. Piezoelectric devices typically have multiple resonant frequencies, but only the major resonant frequency is generally targeted for excitation in practice. Structural and environmental changes of a piezoelectric system can affect variations in the resonant frequencies [2, 13]. Therefore, it is
important to estimate the main resonant frequency in order to maintain efficient system operation. Therefore, the multilevel converter needs to be adapted with a suitable frequency estimation algorithm.
The most effective way to find the resonant frequencies of a piezoelectric transducer is by evaluating its impedance frequency response [19-28]. A minimum in the impedance response corresponds to a resonant frequency, $f_r$. The impedance frequency response is the ratio of the voltage spectrum to the current spectrum. To calculate the piezoelectric impedance response, a voltage source needs to be applied to the device as an excitation signal and current needs to be measured simultaneously. In order to obtain the response of the device for a specific range of frequencies, $f_0$ to $f_s$, a multi-level waveform is used to eliminate harmonics.

Fig. 2.1. Effect of using multi-level waveform in harmonic elimination.
frequencies, the excitation signal should cover the entire frequency range. The idea of calculating the piezoelectric impedance is inspired by the general concept of performing system identification (i.e. finding the system transfer function [29]). It is therefore possible to benefit from the existing knowledge base of excitation signals for system identification. Considering the above mentioned features, a broad-band excitation signal is the most appropriate candidate [29, 31].

![Diagram](image)

Fig. 2.2. Exploiting online resonance frequency estimation in high power applications of piezoelectric devices.

This paper advocates the advantage of using multilevel inverters along with an efficient frequency estimation algorithm (as depicted in Fig. 2.2) to develop the performance of the high power ultrasonic applications. In the proposed algorithm, a 1 kHz rectangular pulse with 10% duty cycle is applied to the device and the current is measured as the response. Then the captured data is cropped to retain only one cycle of the applied input voltage and corresponding output current. In the next step, FFT (Fast Fourier Transform) is applied to both the signals and the impedance response is found as a ratio of the voltage to current transforms. Finally, the relative minimum values are estimated and sorted according to both impedance derivative and impedance magnitude. The FFT is used because it can be computed relatively efficiently (with order $N \log N$ operations), thus enabling real-time operations. Finally, the multilevel inverter reference frequency is updated with the estimated resonance frequency. The proposed method has been evaluated in simulations (using an electrical circuit model) and experimentally (using two piezoelectric devices). The results obtained indicate the efficiency and high performance of the proposed method.
2.2. Methodology and Approach to Estimate Resonance Frequency

2.2.1. Excitation Signal

Piezoelectric devices have different resonance frequencies which are sometimes described as vibration modes. To identify these frequencies, the excitation signal needs to be wide-band. In the proposed approach, a sequence of rectangular pulses is applied to the device. The pulse widths are 0.1ms and the pulses are reapplied every 1ms. It is quite easy to generate the selected pulse stream and the pulses occur fast enough to enable the system to create regular updates of the resonance frequency online.

Fig. 2.3(a) shows the frequency response of a typical rectangular pulse. As can be seen the energy in the spectrum is well spread, but varies considerably in intensity as a function of frequency. The frequency response of the output current will be moderated by this input spectrum since it is not possible to study the piezoelectric characteristic by just looking at the response to the rectangular pulse. One needs to compute the impedance response by forming the quotient of the input and output responses.

Fig. 2.3(b) and (c) show a sample of the captured voltage and current after applying the proposed excitation signal. As can be seen, an imperfect pulse is obtained in a practical situation. This imperfection actually proves to an advantage because the practical spectrum does not suffer from the problem of having zero energy at some frequency components (see Fig. 2.3(d)).
Fig. 2.3. (a) ideal pulse frequency response, (b) captured voltage, (c) captured response (current), (d) practical pulse frequency response.
2.2.2. Estimating Impedance

The response due to the excitation signal (also known as the ‘residual vibrations’) is given by:

\[ y(t) = \sum_{k=1}^{n} A_k \sin(2\pi f_k t) \exp(-a_k t) \]  \hspace{1cm} (2-1)

where, \( n \) is the number of resonance frequencies, \( A_k \) is the amplitude, \( f_k \) is the frequency and \( a_k \) is the damping coefficient of the \( k^{th} \) resonance frequency.

A current sensor is used to capture the response (residual vibrations) of the device. The current and voltage across the piezoelectric are captured simultaneously. To get the best results, one cycle of the excitation pulse, along with the corresponding current response, needs to be extracted from the captured signals. The starting point of the voltage waveform is specified on the leading edge of the pulse. Then, from a knowledge of the sampling rate and the length of the signal (which is 1ms) the end point is determined. Based on these starting and end points the voltage and current waveforms are cropped from the captured signals (see Fig. 2.3(b) and (c) for sample captured signals).

After cropping, the FFT of the both signals are calculated as follows:

\[ X(k) = \sum_{n=1}^{N-1} x(n) e^{-i2\pi k n} \frac{N}{N} , \quad k = 0, 1, ..., N - 1 \]  \hspace{1cm} (2-2)

where \( x(n) \) and \( X(k) \) are the discrete inputs and outputs respectively. To find the power spectrum of the voltage and current signals the FFT outputs are multiplied by their conjugates as per equation (2-3) and finally the impedance is calculated based on equation (2-4).

\[ P_x = \frac{X \cdot X^*}{N} \]  \hspace{1cm} (2-3)

\[ P_z(f) = \frac{P_z(f)}{P_i(f)} , \quad f = F_s(0 : \frac{N}{2})/N \]  \hspace{1cm} (2-4)

where \( F_s \) denotes the sampling frequency and \( N \) is the number of FFT points.
2.2.3. Extracting Resonant Frequencies

The resonant frequencies correspond to the local (or relative) minimums of the piezoelectric impedance. The relative minimums of a function are the points where that the slope of the tangent changes from $-$ to $+$. Fig. 2.4(a) shows a power spectrum, $P_z(f)$ of an impedance and the change of slope in the resonant frequency. At point $A$, $P'_z(f)$ is equal to zero. Moreover, immediately to the left of this point at point $B$ the slope is negative while at point $C$ the slope is positive.

Motivated by the above, the derivative of $P_z(f)$ is calculated and all the points where $P'_z(f)$ changes sign from $-$ to $+$ are extracted. As the final step, at the extracted frequencies, a sorting is performed based on the magnitude of $P_z(f)$. The main resonant frequency is the one with the lowest magnitude.

The procedure described above is depicted as an algorithm flowchart in Fig. 2.4(b). Within that flowchart $R$ is a constant defining the number of resonant frequencies needing to be extracted. The algorithm can be used both for offline and online systems. It is important to note that, repeating the proposed algorithm, while applying a repetitive pulse and averaging, results in an increase of the estimation accuracy.
Finding the starting and end points
Cropping the signals
Saving as relative minimum
Sorting using amplitude
Finding the minimum amplitude

(b)

Fig. 2.4. Extracting resonant frequencies: (a) change of slope at relative minimum (resonant frequency), (b) flowchart of the proposed algorithm.

2.2.4. Noise Issues

In practical systems the presence of noise is inevitable. Fortunately, at resonant frequencies, the impedance of the device is minimum and current increases significantly. The signal-to-noise ratio is therefore relatively high. Noise is nonetheless an issue, and noise removal is therefore required.

Several approaches have been introduced for noise reduction. One of the most common ways to reduce the noise is to use an anti-aliasing filter [30]. This type of filter is used before sampling to limit the bandwidth of a signal. A simple anti-aliasing filtering is proposed for use on the analogue signal before sampling. This is in keeping with the goal to devise a simple method which is easy to implement and fast enough to follow the resonant frequency variations. In addition to a low-pass
filter, it is also important to choose the sampling frequency in accordance with the Nyquist theorem [30] and to ensure that there is a good coupling at sampling points.

It is recommended that a simple RC low-pass filter be used between the current sensor and the capturing device. The cut-off frequency of the filter is selected according to:

\[ f_c = \frac{1}{2\pi R_f C_f} \]  \hspace{1cm} (2-5)

### 2.3. Simulation and Experiment

In this section, in order to show the performance of the proposed method in frequency estimation, the proposed algorithm is evaluated via both simulations and experimentation. The effect of using a multilevel inverter is shown in the last part as a practical evaluation using ultrasound interface. The proposed frequency estimation algorithm is compared with the three key types of alternative impedance analysing methods. These alternative methods are:

a) *The traditional method:* In this method several single frequency sine waves from 30 kHz to 80 kHz have been applied separately to the piezoelectric. The frequency step size was set to 1 kHz.

b) *The Network Analyser method:* An R&S ZVL3 vector network analyser has been used to obtain the impedance frequency response of a piezoelectric device in the frequency range of 30 kHz to 80 kHz.

c) *The unit step and white noise excitation method:* In order to compare the proposed method with different wide-band excitation signals, the impedance frequency behaviour has been obtained based on step response and white noise.

- *Step Pulse:* From system identification theory, it is known that the Fourier transform of the impulse response \((h(t))\) of a system gives the system transfer function. Since generating an impulse \((\delta(t))\) at high power is highly impractical a step \((u(t))\) is preferable. Here a 1ms step is applied to the device and as discussed in the previous section the impedance response can be obtained by dividing the Fourier transform of the output into the Fourier transform of the input.

- *White Noise:* One of the most popular excitation signals used in system identification is white noise [29], [31]. As white noise theoretically has a constant amount of energy per frequency band, it is possible to simply look at the captured
To find the resonant frequencies. To account for the fact that white noise spectra are not always perfectly flat in practice, the impedance response is calculated in the same way as the other two methods – by dividing the Fourier transform of the output into Fourier transform of the input.

The software that was used for simulation and analysis of experimental results was Matlab 7.10. The sampling frequency in both simulation and experimental results was 2 MHz and the number of FFT points, N, was set to 1024. Here two different kinds of piezoelectric devices were used (Type A and Type B). Type A has three dominant resonant frequencies while Type B has just one. For the simulation and experimental evaluations the piezoelectric devices were immersed in housing containing water.

2.3.1. Simulation Results

In order to simulate and compare the proposed method with other methods, a circuit model of the piezoelectric device was needed. The electrical circuit model [26] of a piezoelectric transducer is shown in Fig. 2.5(a). The parameters in the electrical circuit model were determined for the experimental piezoelectric device by performing measurements on a network analyser. These values are presented in Table 2.1.
The accuracy of the circuit model was further evaluated by comparing simulated and measured impedance responses from a network analyser. Fig. 2.5(b) shows the impedance responses of the piezoelectric device obtained from real measurements and from simulation. As can be seen from the figure only three resonant frequencies have been modelled. With the model established the next step was to compare the proposed method with the alternatives via simulations. To this end the resonant frequencies for all methods were calculated based on the model in Fig. 2.5(a) and are presented in Table. 2.2.

Table. 2.1. Values of the Components in the Electrical Circuit Model

<table>
<thead>
<tr>
<th></th>
<th>Non-resonant part</th>
<th>First resonant mode (70.19 kHz)</th>
<th>Second resonant mode (48.6 kHz)</th>
<th>Third resonant mode (38.81 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_0(F)$</td>
<td>$R_s(\Omega)$</td>
<td>$R_p(\Omega)$</td>
<td>$R_1(\Omega)$</td>
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<tr>
<td></td>
<td>$3 \times 10^{-9}$</td>
<td>10</td>
<td>$1 \times 10^{-5}$</td>
<td>492.3</td>
</tr>
<tr>
<td></td>
<td>$R_2(\Omega)$</td>
<td>$L_2(H)$</td>
<td>$C_2(F)$</td>
<td>$R_3(\Omega)$</td>
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<tr>
<td></td>
<td>640.0795</td>
<td>$483 \times 10^{-4}$</td>
<td>2.184 $\times 10^{-10}$</td>
<td>582.744</td>
</tr>
</tbody>
</table>
### Table 2.2. Estimated Resonant Frequencies in Simulation

<table>
<thead>
<tr>
<th>Method</th>
<th>$F_{r1}$</th>
<th>$F_{r2}$</th>
<th>$F_{r3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance Measurement</td>
<td>70.19</td>
<td>48.6</td>
<td>38.81</td>
</tr>
<tr>
<td>Impulse Response (Step Excitation)</td>
<td>70.31</td>
<td>48.83</td>
<td>39.06</td>
</tr>
<tr>
<td>White Noise</td>
<td>70.31</td>
<td>48.83</td>
<td>39.06</td>
</tr>
<tr>
<td><strong>Proposed</strong></td>
<td>70.31</td>
<td>48.83</td>
<td>39.06</td>
</tr>
</tbody>
</table>

#### 2.3.2. Experimental Results

Two different piezoelectric devices Type A and Type B were considered for experimental evaluation. As was the case with the simulation testing, the impedance of both devices was obtained in the frequency range of 30 kHz to 80 kHz. For the proposed method a power converter was used for generating pulses. For the traditional and broadband excitation methods a G5100A function waveform generator was used as the signal generator source and the signals were amplified using an OPA549. Fig. 2.6 shows the experimental setup for the proposed method. All signals were captured using a RIGOL DS1204B oscilloscope. As the frequency was between 30 kHz and 80 kHz, the cut-off frequency of the filter was set to 100 kHz. Hence, according to equation (2-5), capacitor and resistor values of $C_f = 1nF$ and $R_f = 1.59K\Omega$ respectively were selected for the low pass filter. The measured impedance frequency behaviour of the Type A piezoelectric device for all methods is shown in Fig. 2.7(a). Table. 2.3 also shows the extracted frequencies for the three strongest resonant frequencies.
Fig. 2.6. Experimental setup for the proposed method.
Fig. 2.7. Experimental results obtained for the piezoelectric devices impedance response:

(a) Type A,  (b) Type B.

Fig. 2.7(b) shows the impedance frequency response of the second piezoelectric device. The estimated frequencies for the first three resonant frequencies are shown in Table 2.4. As can be seen from the measured results, the white noise method did not result in accurate estimation of $F_{r2}$ and $F_{r3}$ compared to the other methods. The main reason is that in each experiment the level of power in white noise changes randomly over time, and may even go to zero at particular frequencies. Therefore for resonances which are not especially strong (as was the case for $F_{r2}$ and $F_{r3}$ in the Type B device) the results are unreliable.

It should be noted that the electrical circuit model of the piezoelectric device is a simple model which is not able to perfectly model the piezoelectric device nonlinearity, time variations and high frequency behaviour. That is why there are small differences between the simulation and test results. The advantages and drawbacks of the various methods are summarized in Table 2.5. The proposed method offers simplicity and high performance in addition to its ability to be used for online systems.
Table. 2.3. Estimated resonant frequencies of the Type A piezoelectric device

<table>
<thead>
<tr>
<th>Method</th>
<th>$F_{r1}$</th>
<th>$F_{r2}$</th>
<th>$F_{r3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Analyser</td>
<td>70.18</td>
<td>48.62</td>
<td>38.82</td>
</tr>
<tr>
<td>Impulse Response (Step Excitation)</td>
<td>70.31</td>
<td>48.83</td>
<td>39.06</td>
</tr>
<tr>
<td>White Noise</td>
<td>70.31</td>
<td>48.83</td>
<td>39.06</td>
</tr>
<tr>
<td>Traditional</td>
<td>70</td>
<td>49</td>
<td>39</td>
</tr>
<tr>
<td>Proposed</td>
<td>70.31</td>
<td>48.83</td>
<td>39.06</td>
</tr>
</tbody>
</table>

Table. 2.4. Estimated resonant frequencies of the Type B piezoelectric device

<table>
<thead>
<tr>
<th>Method</th>
<th>$F_{r1}$</th>
<th>$F_{r2}$</th>
<th>$F_{r3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Analyser</td>
<td>78.08</td>
<td>47.48</td>
<td>66.94</td>
</tr>
<tr>
<td>Impulse Response (Step Excitation)</td>
<td>78.13</td>
<td>46.88</td>
<td>66.41</td>
</tr>
<tr>
<td>White Noise</td>
<td>78.13</td>
<td>44.92</td>
<td>68.36</td>
</tr>
<tr>
<td>Traditional</td>
<td>78</td>
<td>47</td>
<td>67</td>
</tr>
<tr>
<td>Proposed</td>
<td>78.13</td>
<td>46.88</td>
<td>66.41</td>
</tr>
<tr>
<td>Method</td>
<td>Advantages</td>
<td>Drawbacks</td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Traditional</td>
<td>• Easy to implement</td>
<td>• Circuit stability required</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Low expense</td>
<td>• Labour intensive</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Direct frequency output</td>
<td>• Not applicable for online process</td>
<td></td>
</tr>
<tr>
<td>Network Analyser</td>
<td>• Provides complete impedance frequency response</td>
<td>• High expense</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• High accuracy due to calibration</td>
<td>• Not applicable for online process</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Not applicable on high power converter</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Slow due to the complex measurement procedure</td>
<td></td>
</tr>
<tr>
<td>Impulse Response</td>
<td>• Provides impedance frequency response</td>
<td>• Slower than the proposed method (because the applied step is longer than the pulse).</td>
<td></td>
</tr>
<tr>
<td>(Step Excitation)</td>
<td>• Easy to generate with power converter</td>
<td>• Sensitive to the noise</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can be generated at high power</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can be applied for online process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White Noise Excitation</td>
<td>• Provides impedance frequency response</td>
<td>• Not easy to generate especially at high power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can be applied for online process</td>
<td>• Not possible to generate with power converter</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Sensitive to the noise</td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>• Provides impedance frequency response</td>
<td>• Sensitive to the noise</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Easy to generate with power converter</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can be generated at high power</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can be applied for online processes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3.3. Ultrasound Interface

The performance of the proposed frequency estimation algorithm was evaluated in the previous sections, but as already mentioned, exciting the device at its resonant frequency is not enough to achieve maximum power conversion. The excitation signal harmonics also need to be considered.

In this section the advantage of exciting a piezoelectric transducer using a multi-level waveform at the resonant frequency compared with a uni-polar waveform is illustrated. For the comparison, one multi-level waveform and one uni-polar waveform were generated with peak to peak voltage of 120V at 39 kHz (Type A device resonant frequency).

To perform the evaluation, one pair of the Type A piezoelectric transducers was placed face to face as sender and receiver. For the first experiment, a unipolar pulse was applied to one of the piezoelectric devices and the voltage across the other one was captured. Fig. 2.8(a) shows the applied voltages. To show their influence on piezoelectric devices the frequency responses of applied and captured voltages are illustrated in Fig. 2.8(b). As can be seen from Fig. 2.8(b) the captured response contains several harmonics, due to the excitation signal having much energy away from the fundamental frequency.

For the next test, a multi-level waveform was applied to the piezoelectric device. As can be seen from Fig. 2.8(c), harmonic levels are attenuated significantly. This was due to the use of a multi-level waveform which damped the harmonics in the vast area around the fundamental frequency.

Comparing the Fig. 2.8(b) with Fig. 2.8(c), illustrates that the maximum energy is achieved at the resonant frequency. Higher efficiency is obtained for multi-level signal. In particular the method is quite effective for reducing the harmonic content. In addition, the presence of harmonics not only adversely affects frequency sensitive applications, but also causes an increase in temperature and an increase in power loss. Moreover, when using filters for attenuating remaining harmonics the filter cost and size decreases when multi-level topology is employed.
(a) Input voltage (unipolar)

(b) Input voltage (unipolar)
Output voltage (unipolar)

Magnitude

Frequency (kHz)

(c)

Amplitude (V)

Time (ms)

(d)
Fig. 2.8. Obtained results for the ultrasound interface: (a) applied uni-polar pulse at 39 kHz in time domain, (b) frequency response of the applied uni-polar pulse (input signal), (c) frequency response of the output signal when the input is a uni-polar pulse, (d) applied multi-level pulse at 39 kHz in time domain, (e) frequency response of the applied multi-level pulse (input signal), (f) frequency response of the output signal when the input is a multi-level pulse.
2.4. Conclusions

In this paper, a new method is proposed for improving the efficiency of high power ultrasound applications. It has been seen that the resonant frequencies vary under different system conditions. Moreover, the advantage of exciting the piezoelectric device at the exact resonant frequency using multi-level waveform generation has been illustrated. An algorithm which extracts the resonant frequencies and updates the system is therefore needed. The proposed method has been compared with different methods and excitation signals. The comparative results have been conducted based on experimentation and simulation. The results obtained demonstrated the high performance of the proposed method.

Acknowledgments

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Statement of Contribution of Co-Authors

The authors listed below have certified that:

1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit, and
5. they agree to the use of the publication in the student’s thesis and its publication on the Australasian Research Online database consistent with any limitations set by publisher requirements.

In the case of this chapter:
A Harmonic Elimination Technique for a Single-phase Multilevel Converter with Unequal DC Link Voltage Levels, Accepted for publication at: IET transaction on Power Electronics.

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<tr>
<td>Negareh Ghasemi</td>
<td>Proposed the initial design and conducted simulation studies and data analysis, designed the control strategy, implementation hard ware set-up and conducted experimental verification and wrote the manuscript.</td>
</tr>
<tr>
<td>16 Nov 2012</td>
<td></td>
</tr>
<tr>
<td>Firuz Zare</td>
<td>Proposed the initial design and supervised the validity studies including; conducting the simulations and experimental studies and writing the manuscript.</td>
</tr>
<tr>
<td>Arash Abbasalizadeh Boora</td>
<td>Aided experimental design.</td>
</tr>
<tr>
<td>Arindam Ghosh</td>
<td>Aided planning the control strategies and writing the paper.</td>
</tr>
<tr>
<td>Christian Langton</td>
<td>Provided us with general information about ultrasound system specifications and its applications.</td>
</tr>
<tr>
<td>Frede Blaabjerg</td>
<td>Aided planning the control strategies and writing the paper.</td>
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Principal Supervisor Confirmation
I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

A/Prof. Firuz Zare  [Signature]  16 Nov 2012
CHAPTER 3

HARMONIC ELIMINATION TECHNIQUE FOR A SINGLE-PHASE MULTILEVEL CONVERTER WITH UNEQUAL DC LINK VOLTAGE LEVELS

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Abstract— Multilevel converters, due to the benefits they attract in generating high quality output voltage, are used in several applications. Various modulation and control techniques are introduced by several researchers to control the output voltage of the multilevel converters like Space Vector Modulation (SVM) and Harmonic Elimination (HE) methods. Multilevel converters may have a DC link with equal or unequal DC voltages. In this paper a new harmonic elimination technique based on the harmonic elimination method is proposed for multilevel converters with unequal DC link voltage. The DC link voltage levels are considered as additional variables for the harmonic elimination method and the voltage levels are defined based on the harmonic elimination results. Increasing the number of voltage levels can reduce lower order harmonic content due to the fact that more variables are created. In comparison to previous methods, this new technique has a positive effect on the output voltage quality by reducing its Total Harmonic Distortion (THD), which must take into consideration for some applications such as Uninterruptable Power Supply (UPS), motor drive systems and piezoelectric transducer excitation. In order to verify the proposed modulation technique, MATLAB simulations and experimental tests are carried out for a single-phase four-level diode-clamped converter.

Index Terms— Multilevel Converter, Modulation Technique, Harmonic Elimination Method, Piezoelectric Transducer Excitation.

3.1. Introduction

A high power and high quality signal with low harmonics is required in different applications. To achieve this aim, multilevel converters have been developed which indicate some important advantages when compared to the conventional converter (two-level converter), such as:

- generating high power and high quality staircase waveform close to a sinusoidal waveform
- decreasing harmonic distortion and therefore reducing filter size
- increasing the output voltage quality
- achieving higher output voltages
- reducing switching losses
- reducing stress voltage and remedying the Electromagnetic Interference (EMI) problem

Three well-known topologies of multilevel converters are diode-clamped, flying capacitor and cascade.

The output voltage of a conventional converter (two-level) and a multilevel converter in the time and frequency domain, together and three topologies of multilevel converters are depicted in Fig. 3.1.
Fig. 3.1. Output of (a) a two-level converter and a multilevel converter and one leg of the multilevel converter topologies (b) diode-clamped (c) flying capacitor (d) cascade.
As is clear in Fig. 3.1(a), the sideband harmonics are decreased in the case of the multilevel converter, so this type of converter has the ability to improve the output quality as well as achieve the higher voltage levels.

In a diode-clamped configuration, the DC link voltage ($V_{dc}$) is divided into a number of output levels by some series-connected capacitors [1]. From Fig. 3.1(b), it can be seen that the DC voltage is divided into three levels by DC link capacitors $C_1$ and $C_2$. This type of multilevel converter is popularly used in motor drive applications due to the simplicity of the DC link voltage for a back-to-back configuration [2]. In a flying capacitor converter, the desired output voltage levels are generated by distributing the DC voltage among the capacitors. The third well-known configuration is a cascade converter, in which several H-bridge single-phase converters with distinct DC sources are connected in series [3]. Cascade converters are especially suited for renewable energy systems or Static VAR Compensators (SVCs) [2, 3].

In all these configurations, an output voltage staircase is achieved based on different switching states, providing different DC link voltages across a load. Fig. 3.2(a) and Fig. 3.2(c) show equal and unequal m-pulses which are added together at the output of a multilevel converter, and two generated output voltage waveforms with equal ($V_1=V_2=\ldots=V_m$) and unequal ($V_1\neq V_2\neq\ldots\neq V_m$) DC link configurations are shown in Fig. 3.2(b) and Fig. 3.2(d) respectively.
Fig. 3.2. Equal voltage levels (a) m-pulses (b) output voltage, unequal voltage levels (c) m-pulses (d) output voltage for a multilevel converter.

Traditionally, the output voltage levels of a multilevel converter are equal and the numbers of the output voltage levels are limited by the numbers of components and the DC voltage sources. Hence, more output voltage levels can impose more cost and complexity on the system. To achieve more output voltage levels without adding up components, an unequal DC link diode-clamped converter has been introduced in [4]. In this case, it is possible to generate more output voltage levels according to different switching states and unequal DC link voltages. Thus, the output voltage levels may be increased with less components and DC voltage sources [5].

To achieve a high quality output and less switching losses, an appropriate pulse width modulation and a suitable control technique are required to control the output voltage waveform of a multilevel converter. Several modulations and control techniques are introduced such as: Sinusoidal Pulse Width Modulation (SPWM), Space Vector Modulation (SVM) and the Selective Harmonic Elimination (SHE) method [1]. Among these modulation techniques, SPWM and SVM techniques can be applied for power converters by comparing a reference signal with triangular
signals, [1],[6-10]. In [11], a Selective Harmonic Elimination (SHE) technique is combined with the Optimized Harmonic Stepped Waveform (OHSW) method to decrease the output harmonic contents and the filter size with less complexity of the system and switching losses. This technique proposes extra notches with their angles in the output levels, which assists a better control of the output waveform and harmonics reduction.

A new harmonic elimination technique is proposed in this paper, suitable for a single-phase multilevel converter with unequal DC link voltages. In this case, the DC link voltage levels are considered as additional variables for the harmonic elimination method and defined based on the harmonic elimination results. The proposed modulation technique provides more variables for eliminating more low order harmonic contents compared to conventional harmonic elimination methods in which the output voltage levels are equal and the number of variables for harmonic elimination is limited just to the number of switching angles. Therefore, by using this new modulation technique, it is possible to improve the quality of the generated output voltage and reduce THD. In order to validate the proposed new harmonic elimination technique, two single-phase multilevel converters with four and five voltage levels are simulated and the results are compared with the conventional harmonic elimination technique.

Due to the ability of a multilevel converter to generate a high quality output voltage with adjustable magnitude and frequency, it is a suitable option for different applications. Power converters normally operate at low voltage (i.e. <1000 V) and at low fundamental frequency (5-500 Hz) in most switched mode power supplies, motor drive systems (for commercial and residential applications) and grid connected renewable energy systems for distribution networks [12, 13]. Also, multilevel converters can generate a high power and high voltage signal for some applications such as Industrial motor drives (i.e. 3.3 kV to 11 kV) and grid connected renewable energy systems for low voltage transmission line (i.e. above 11 kV). In the grid connected renewable energy systems, voltage and frequency adjustment are necessary before connecting these systems to the grid, [14, 15].

A multilevel converter has additional benefits for some applications such as ultrasound systems which operate at high fundamental frequencies (more than 20 kHz) and require a high quality signal to excite piezoelectric transducers [16].
Since undesired electrical excitation can deteriorate the performance of the piezoelectric transducer, impose higher harmonics to the system and increase power consumption, the excitation signal has to be designed appropriately [17]. For instance, in biomedical applications, ultrasound interference caused by high power piezoelectric transducers generates ultrasound noise emission, which may affect diagnostic and monitoring sensors. Thus a high quality power converter with a well-defined frequency range is required.

Several methods are introduced for piezoelectric transducer excitation: high power linear amplifier, switched-mode power converter with different modulation techniques [16]. A high power linear amplifier can convert a low power and low voltage signal (generated by a signal generator) to the high power and high voltage signal suitable to drive piezoelectric transducers but due to heavy weight and power losses, the amplifier cannot be a proper choice to drive a piezoelectric transducer. However, switched-mode power converters such as a multilevel converter with a suitable control algorithm, provide the opportunity to improve the performance of the piezoelectric transducer by generating a high power and high quality excitation signal with lower harmonic content and higher energy efficiency. Due to the main constraint of ultrasound applications (operating at high fundamental frequency), power converters based on a PWM strategy, with a high switching frequency index \( f_s/f_o \), cannot be a practical solution. In such an application, the maximum possible fundamental frequency of a converter is restricted by switching transition of each power switching event and the number of switching per cycle. In such a case, a multilevel converter operating with the new harmonic elimination method has more advantages than other conventional harmonic elimination techniques.

### 3.2. Basics about Modulation

To generate a medium - high power signal with lower THD by a multilevel converter, different modulation techniques are introduced [1, 9]. In most of these techniques, Fourier series expansion is normally used to find out switching angles and to eliminate desired harmonic contents. The output staircase waveform includes no even harmonics due to the quarter-wave symmetry of the generated waveforms. In the conventional harmonic elimination method, the differences between each two consequent output voltage levels are equal and the switching angles are the only
variables for this modulation. Fourier series expansion of an m-level converter is given by:

\[ b_n = \sum_{i=1}^{m-1} \frac{4V_i}{n\pi} \cos(n\alpha_i) \]  

(3-1)

where:

- \( V_i \): the amplitude of each voltage level
- \( \alpha_i \): the \( i \)th switching angle
- \( n \): odd harmonics (1,3,5, …)
- \( m \): the number of output voltage levels

In the conventional harmonic elimination technique, the DC link voltage levels are equal, \( V_1=V_2=…=V_m=V_{dc}/(m-1) \). Therefore, (3-1) can be rewritten to:

\[ b_n = \frac{4V_{dc}}{n(m-1)\pi} \sum_{i=1}^{m-1} \cos(n\alpha_i) \]  

(3-2)

Fourier series expansion for a four-level converter is given by

\[ b_n = \frac{4V_1}{n\pi} \cos(n\alpha_1) + \frac{4V_2}{n\pi} \cos(n\alpha_2) + \frac{4V_3}{n\pi} \cos(n\alpha_3) \]  

(3-3)

In this case, \( V_1=V_2=V_3=V_{dc}/3 \) and three variables \( (\alpha_1, \alpha_2, \alpha_3) \) exist. According to these three variables, the above non-linear equation may be solved in MATLAB to eliminate 3\(^{\text{th}}\) and 5\(^{\text{th}}\) harmonics and to calculate the fundamental amplitude.

As an example, (3-4) is derived from (3-3) to calculate switching angles of a four-level converter with fundamental component of \( b_1=0.6 \) (per unit) and \( b_3=b_5=0 \) and \( V_{dc}=0.7 \) (per unit). The fundamental component and DC link voltage are specified in terms of ‘per unit’, while there is also the possibility to specify these parameters in volt.

\[
\begin{aligned}
    b_1 &= \frac{4V_{dc}}{3\pi} (\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3)) = 0.6 \\
    b_3 &= \frac{4V_{dc}}{9\pi} (\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3)) = 0 \\
    b_5 &= \frac{4V_{dc}}{15\pi} (\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3)) = 0
\end{aligned}
\]  

(3-4)
The calculated switching angles then are:
\[
\alpha_1 = 0.3090 \text{ rad}, \quad \alpha_2 = 0.5306 \text{ rad}, \quad \alpha_3 = 1.3649 \text{ rad}
\]

From (3-1), it is clear that more variables are required to eliminate more low order harmonic components. This means for reducing more harmonics, we need to increase the number of switching angles or the number of output voltage levels. In order to analyse the effect of more variables, a five-level converter is simulated.

Calculated variables (based on (3-2)) for this simulation are as follows:
\[
\alpha_1 = 0.0577 \text{ rad}, \quad \alpha_2 = 0.5016 \text{ rad}, \quad \alpha_3 = 0.7897 \text{ rad}, \quad \alpha_4 = 1.4570 \text{ rad}
\]

Fig. 3.3 shows the output of a four-level and five-level converters in time and frequency domains.
Fig. 3.3. Output voltage waveforms of two multilevel converters with conventional harmonic elimination technique:

a four-level converter in (a) a time domain and (b) a frequency domain.

a five-level converter in (c) a time domain and (d) a frequency domain.

As is shown in Fig. 3.3(b), the 3\textsuperscript{rd} and the 5\textsuperscript{th} harmonics are eliminated, while in Fig. 3.3(d), the 3\textsuperscript{rd}, the 5\textsuperscript{th} and the 7\textsuperscript{th} harmonics are eliminated, which it proves the effect of more variables on harmonic reduction. To generate more output voltage levels, more components are essential, which can also impose more complexity on the system.
3.3. New Harmonic Elimination Technique for a Single-Phase Multilevel Converter

As is mentioned in [18], a drawback of the conventional harmonic elimination technique is the range of variables (switching angles) which limits the harmonic elimination method in improving the quality of the output voltage. In order to overcome this problem, a new harmonic elimination technique is proposed in this paper, to decrease the number of lower order harmonics and to improve the output voltage quality. Unlike the conventional harmonic elimination method, DC voltage levels and switching angles of the output voltage waveform of a power converter are considered as variables which should be calculated off-line by solving several non-linear equations. This means that the DC link voltages are not equal compared to the conventional harmonic elimination technique, multilevel configuration. In the conventional harmonic elimination techniques, the range of variables is limited to the number of switching angles, because the output voltage levels are equal. In [4] a multilevel converter with asymmetrical configuration is introduced to attain desired output voltage levels with higher quality. In this configuration the voltages across DC link capacitors are unequal, so more output levels will be achievable based on various switching states with less components. In this case, each DC link voltage level (capacitor voltage level) is an integer multiple of the lowest DC link voltage level, \( V_i = nV_1 \):

where \( V_i \) is a DC link voltage, \( n \) is an integer number and \( V_1 \) is the lowest DC link voltage level.

However, for the proposed method, the DC link voltage levels are not equal and integer multiples of the lowest DC link voltage level. Since the range of the variables is extended to the switching angles and the unequal DC link voltage levels, it is possible to eliminate more low order harmonics. For instance, in a conventional harmonic elimination technique with \( m \)-output voltage levels and \( s \)-switching angles, it is possible to generate the fundamental component and eliminate \((s-1)\) harmonics. But in the new harmonic elimination technique, with the same switching angles and output voltage levels, the fundamental component can be generated and \((m+s)-2\) harmonics can be eliminated. Table 3.1 shows the difference between these two techniques for a four-level converter. A comparison between the conventional
harmonic elimination technique and the new harmonic elimination technique, in terms off-line solving non-linear equations, is illustrated by flow-chart shown in Fig. 3. In this flow-chart, $\alpha_1, \alpha_2, \ldots, \alpha_n$ are the switching angles of pulses used in a multilevel converter, $V_1, V_2, \ldots, V_m$ are the output voltage levels and $V_{ref}$ is the magnitude of the fundamental component.

Table 3.1: A comparison between the conventional and the new harmonic elimination technique

<table>
<thead>
<tr>
<th>Harmonic Elimination Technique</th>
<th>Conventional Method</th>
<th>New Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Switching Angles</strong></td>
<td><strong>Output Voltage Steps</strong></td>
<td><strong>Switching Angles</strong></td>
</tr>
<tr>
<td>$\alpha_1, \alpha_2, \alpha_3$</td>
<td>$V_1=V_2=V_3$</td>
<td>$\alpha_1, \alpha_2, \alpha_3$</td>
</tr>
<tr>
<td><strong>Variables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td><strong>The Number of Eliminated Harmonics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 3.4. Flow-chart of the calculation method for switching angles and output voltage levels.
To study and analyse the proposed modulation technique, several simulations are carried out using MATLAB. In the first simulation, the new harmonic elimination technique is applied for a four-level converter with unequal DC link voltages ($V_1 \neq V_2 \neq V_3$). A Fourier series expansion is solved using MATLAB in order to find the DC link voltage levels and the switching angles. In this case the number of variables is six ($\alpha_1$, $\alpha_2$, $\alpha_3$ and $V_1, V_2, V_3$) and it is expected that five harmonics will be eliminated. The calculated variables are as below:

$$V_1 = 0.2625 \text{ pu}, \quad V_2 = 0.2105 \text{ pu}, \quad V_3 = 0.1168 \text{ pu}$$
$$\alpha_1 = 0.2244 \text{ rad}, \quad \alpha_2 = 0.6732 \text{ rad}, \quad \alpha_3 = 1.1220 \text{ rad}$$

For further clarification, a five-level diode-clamped converter is simulated. With one extra voltage level, it is possible to eliminate two more harmonics due to the fact that there are two more variables ($\alpha_4$ and $A_4$). However, in the conventional harmonic elimination technique, there is just one more variable which can eliminate one more harmonic. For the five-level converter, the calculated parameters are as below:

$$V_1 = 0.2063 \text{ pu}, \quad V_2 = 0.1814 \text{ pu}, \quad V_3 = 0.1346 \text{ pu}, \quad V_4 = 0.0716 \text{ pu}$$
$$\alpha_1 = 0.1745 \text{ rad}, \quad \alpha_2 = 0.5236 \text{ rad}, \quad \alpha_3 = 0.8727 \text{ rad}, \quad \alpha_4 = 1.2217 \text{ rad}$$

The output voltage waveform of a four-level and a five-level converter operating with the new harmonic elimination technique and their harmonic spectrum are depicted in Fig. 3.5. The calculated voltage levels are unequal which means the output voltage steps of these converters are not equal while in the conventional harmonic elimination technique, these DC voltage levels are equal.
As shown in Fig. 3.5(b), the 3\textsuperscript{rd}, the 5\textsuperscript{th}, the 7\textsuperscript{th}, the 9\textsuperscript{th} and the 11\textsuperscript{th} harmonics are all eliminated in this modulation technique. In comparison with the conventional harmonic elimination technique, due to the unequal DC link voltage levels, three
more variables exist to eliminate three more harmonics. Therefore, it is concluded that for the same number of DC link voltage levels, this proposed modulation technique can reduce lower order harmonics and further minimize the THD. In Fig. 3.5(d), the 13th and the 15th harmonics are also eliminated, compared to the results shown in Fig. 3.5(b). Analysing the simulation results shown in Fig. 3.5(b) and Fig. 3.5(d), verifies the effect of the new harmonic elimination method for a multilevel converter with unequal DC voltages in improving the quality of the output voltage and reducing THD. Table 3.2 shows a comparison between the conventional and the proposed harmonic elimination technique based on MATLAB simulations for a four-level and a five-level converter.

Table 3.2: Comparison between harmonic elimination techniques

<table>
<thead>
<tr>
<th>Eliminated Harmonic(s)</th>
<th>Conventional Technique</th>
<th>New Modulation Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4-level Converter</td>
<td>5-level Converter</td>
</tr>
<tr>
<td></td>
<td>3th and 5th</td>
<td>3th, 5th, 7th</td>
</tr>
<tr>
<td></td>
<td>4th</td>
<td>5th, 7th, ..., 11th</td>
</tr>
<tr>
<td></td>
<td>5th</td>
<td>5th, ..., 15th</td>
</tr>
<tr>
<td>THD%</td>
<td>2.8556</td>
<td>1.2839</td>
</tr>
<tr>
<td></td>
<td>0.7986</td>
<td>0.4697</td>
</tr>
<tr>
<td>1st</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>3rd</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5th</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7th</td>
<td>0.1014</td>
<td>0</td>
</tr>
<tr>
<td>9th</td>
<td>0.0029</td>
<td>0.547</td>
</tr>
<tr>
<td>11th</td>
<td>0.0226</td>
<td>0.0032</td>
</tr>
<tr>
<td>13th</td>
<td>0.0143</td>
<td>0.0348</td>
</tr>
<tr>
<td>15th</td>
<td>0.0048</td>
<td>0.0109</td>
</tr>
<tr>
<td>17th</td>
<td>0.0132</td>
<td>0.02</td>
</tr>
<tr>
<td>19th</td>
<td>0.0128</td>
<td>0.0249</td>
</tr>
<tr>
<td>21th</td>
<td>0.0029</td>
<td>0.0006</td>
</tr>
</tbody>
</table>
3.4. DC Link Voltage Control

One of the issues in multilevel converters is controlling the DC link voltages. There are a number of techniques used to control and adjust DC link voltages of multilevel converters with equal DC link voltages. A multilevel converter with unequal DC link voltages is a new configuration which allows less freedom of choice in controlling the voltage of each capacitor based on switching states.

Among DC/DC converters, multi-output converters can generate several output levels without different power sources[19]. A three-Output Voltage Sharing (3-OVS) converter introduced in [20, 21] has some benefits such as regulating the DC link voltages asymmetrically regardless of input distortion. Also, this type of converter is able to increase and regulate the input voltage asymmetrically to adjust desired output voltage levels. The circuit diagram of this converter is depicted in Fig. 3.6.

![Circuit Diagram](image_url)
To remedy the problem of capacitor voltage imbalance, a diode-clamped converter can be connected to this type of converter. The main aim of using this converter is to control the output voltage levels and utilizing high modulation index regardless of input variation and high power factor loads [21]. For further clarification, the duty cycle, switching states and output currents are depicted in Fig. 3.7.
Fig. 3.7. Duty cycles, switching states and output currents for Basic, Buck and Boost 3OVS converters.

In Fig. 3.7, the ripple of the inductor current ($i_L(t)$) is neglected and the duty cycles of complementary input switches are shown by $D_1$, $D_2$ and $D_6$. Also, the duty cycles of complemented output switches are $D_3$, $D_4$, $D_5$ and $D_7$. In addition, the
output switches ($S_4$ and $S_5$) control $i_2(t)$ and $i_3(t)$ and $i_{in}(t)$ is controlled by $s_1$ and $i_0(t)$ and $i_1(t)$ are controlled by both input and output switches. The relationship between duty cycles of switches, the output currents and the inductor current are illustrated in (3-5) [21].

$$\begin{align*}
\vec{i}_{in}(t) &= D_1 i_L(t) \\
\bar{i}_0(t) &= (D_1 + D_6 - D_7) i_L(t) \\
\bar{i}_1(t) &= (D_1 + D_6 - D_7 - (D_4 + D_5)) i_L(t) \\
\bar{i}_2(t) &= D_4 i_L(t) \\
\bar{i}_3(t) &= D_5 i_L(t)
\end{align*}$$

(3-5)

To keep the voltage of capacitors constant, the average current through the capacitors during one switching cycle should be zero. In this regard, the input and the output currents of each capacitor must be equal. The output voltages can be formulated as functions of duty cycles and inductor current the same as (3-6).

$$\begin{align*}
\bar{I}_{C1} &= 0 \rightarrow V_1 = (D_1 + D_6 - D_7) R_1 i_L \\
\bar{I}_{C2} &= 0 \rightarrow V_2 = (D_4 + D_5) R_2 i_L \\
\bar{I}_{C3} &= 0 \rightarrow V_3 = D_5 R_3 i_L
\end{align*}$$

(3-6)

where:

$D_j$: duty cycle of the switch $S_j$

$I_L$: the average of inductor current over one switching cycle

Also,

$$V_L = D_1 V_{in} + \left( 1 - (D_1 + D_6) \right) V_1 - (D_3 + D_4 + D_5) V_1 + (D_4 + D_5) V_2 + D_5 V_3$$

(3-7)

The inductor voltage will be zero in steady state condition. So

$$D_1 V_{in} = \left( D_1 + D_6 - D_7 \right) V_1 + (D_4 + D_5) V_2 + D_5 V_3$$

(3-8)

By applying (3-6) to (3-8),

$$I_L = \frac{D_1}{(D_1 + D_6 - D_7)^2 R_1 + (D_4 + D_5)^2 R_2 + D_5^2 R_3} V_{in}$$

(3-9)

(3-10) is derived from (3-9) and (3-6).
\[
V_1 = \frac{D_1^2 R_1}{(D_1 + D_6 - D_7)^2 R_1 + (D_4 + D_5)^2 R_2 + D_5^2 R_3} V_{in} \\
V_2 = \frac{D_1 (D_4 + D_5) R_2}{(D_1 + D_6 - D_7)^2 R_1 + (D_4 + D_5)^2 R_2 + D_5^2 R_3} V_{in} \\
V_3 = \frac{D_1 D_3 R_3}{(D_1 + D_6 - D_7)^2 R_1 + (D_4 + D_5)^2 R_2 + D_5^2 R_3} V_{in}
\] (3.10)

Fig. 3.6 shows that in the steady state condition to have Basic, Buck and Boost 3-OVS converter, the below condition should be considered:

Basic 3-OVS: $D_6 = 0$ and $D_7 = 0$

Buck 3-OVS: $D_7 = 0$

Boost 3-OVS: $D_6 = 0$

According to Fig. 3.7, by switching states “1” and “2”, $C_1$ and $C_2$ can be charged individually. Also, $C_1$ can be charged when $C_2$ and $C_3$ are charging as well. The input voltage is chopped and the output voltages will be stepped down by switching states “6”, “7” and “8”. Switching state “10” provides an opportunity to step up the output voltages by increasing the inductor current.

### 3.5. Test Results

As is mentioned previously, a multilevel converter operating with the proposed method could be helpful for such applications in which a high power signal with high quality and low harmonic distortion is required. The piezoelectric transducer excitation system is one of those applications. To clarify the effect of this method on this application, a four-level converter has been developed and connected to a three-output Boost converter to drive a piezoelectric transducer effectively by using a proper high quality signal with low harmonic distortion. In order to control and adjust the calculated switching angles and the DC voltage levels for the practical test, a Texas Instruments TMS320F2833X Digital Signal Controller (DSC) is used. Fig. 3.8 shows a block diagram and experimental setup of a single-phase four-level diode-clamped converter with asymmetric DC link voltage connected to a piezoelectric transducer.
Fig. 3.8. A single-phase four-level diode-clamped converter with asymmetrical DC link voltage connected to a high power piezoelectric transducer (a) circuit diagram and (b) experimental setup.

The output voltage waveforms of a four-level converter operating with the conventional and new harmonic elimination technique are depicted in Fig. 3.9. As expected, in the conventional harmonic elimination technique, there are three
variables in eliminating two harmonics (the 3th and the 5th) while in the new harmonic elimination method, there are six variables (three output DC voltage levels and three switching angles) in eliminating the 3th, 5th, 7th, 9th and 11th harmonics. In these tests, due to the limitation of the switching transient time, the fundamental frequency of the input signal is adjusted to 2 kHz.

From Fig. 3.9(b) and Fig. 3.9(d), two harmonics are eliminated, based on a conventional harmonic elimination technique with three switching angles. As is clear in these figures, the 3th and the 5th harmonics are eliminated and the 7th harmonic exists at 14 kHz. In Fig. 3.9(f) and Fig. 3.9(h), it is obvious that five harmonics (the 3th, ..., the 11th) are eliminated and the 13th and the 15th harmonics are located at 26 kHz and 30 kHz. The comparison between Fig. 3.9(b), Fig. 3.9(d), Fig. 3.9(f) and Fig. 3.9(h) improves the effect of new harmonic elimination technique on harmonic elimination. Therefore, applying this new harmonic elimination method for multilevel converters enables a decrease in the output harmonics and improves the output quality without imposing more complexity on the system.

![Output of four-level converter](image)
(b) FFT

Amplitude, V

Harmonics

2kHz

14kHz (7th Harmonic)

(c) Amplitude, V

Time, us
Fig. 3.9. A four-level converter with:

conventional harmonic elimination method, simulation results (a) output voltage waveform, (b) harmonic contents; experimental results (c) output voltage waveform, (d) harmonic contents.

new harmonic elimination method, simulation results (e) output voltage waveform, (f) harmonic contents and experimental results (g) output voltage waveform, (h) harmonic contents.

A piezoelectric transducer, as a main part of the ultrasound system converts electrical energy to mechanical energy and vice versa. Since undesired electrical excitation signals can affect the performance of a piezoelectric transducer, it is really important to drive a piezoelectric transducer by a signal with low THD. In order to have better view of piezoelectric transducer performance, a high power test using a power converter connected to a piezoelectric transducer is performed.

To study the effect of a multilevel converter on the performance of a piezoelectric transducer, a 39 kHz piezoelectric transducer is excited by two-level and four-level converters. In these tests, two identical piezoelectric transducers are used, in which piezoelectric transducer 1 plays the role of a transmitter and piezoelectric transducer 2 is a receiver. Piezoelectric transducer 1 is driven so as to vibrate at one of its resonance frequencies (39 kHz) using two different types of converters, a two-level and a four-level converter operating at a fundamental frequency of 39 kHz. For both
tests the magnitude of DC voltage is 60 V. In this test the real-time voltage waveforms across the piezoelectric transducer 1 (input voltage) and the piezoelectric transducer 2 (output voltage) are measured, using differential probes in the laboratory, then MATLAB software, which is used to compute the FFT of the measured input and output voltages off-line. The test results of a piezoelectric transducer excitation are depicted in Fig. 3.10.

(a)

(b)
Fig. 3.10. Measured results frequency response for ultrasound interface for:

39 kHz unipolar (two-level) pulse: (a) Input voltage, (b) Output voltage.

39 kHz four-level waveform: (c) Input voltage, (d) Output voltage.
For both of these tests, the new harmonic elimination technique is applied to reduce output harmonics. The output voltage waveform of the converter is not exactly a pulse shape at the high fundamental frequency (39 kHz), as the switching transient time is not negligible compared to the switching period, so some unwanted harmonics are created in practical cases as shown in Fig. 3.10. Therefore, in order to improve the quality of output voltage in a practical case, the switching transient time should be reduced, resulting in the benefit of reducing switching losses of power switches. As shown in Fig. 3.9, this practical problem does not occur for a multilevel converter operating at low fundamental frequencies (for example below 2 kHz) due to the fact that the switching transient time is negligible compared to the switching period.

3.6. Conclusion

Multilevel converters play a significant role in some applications in which a signal close to a sinusoidal waveform with low harmonic distortion should be generated. Several modulation techniques are introduced to control and eliminate the output harmonics of multilevel converters. The conventional harmonic elimination method is used for those multilevel converters in which the output voltage steps are equal, so the range of modulation variables is limited to the number of the switching angles. To improve the output voltage quality and reduce more low order harmonics, a new harmonic elimination technique is introduced in this paper. In this modulation method, the output voltage levels are defined as new variables which double the number of variables for the harmonic elimination method. In this regard, different simulations are carried out in this research to verify the effect of this method compared to the conventional one. Application of a front-end DC/DC converter is suggested to generate the desired voltage levels. This type of converter suits some industrial applications such as UPS and piezoelectric transducer excitation, due to its ability to adjust DC link voltage for single-phase applications. As a practical test, a four-level converter is implemented and tested with the proposed method in the laboratory, and the results are discussed in this paper.
References


Statement of Contribution of Co-Authors

The authors listed below have certified that:

1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit, and
5. they agree to the use of the publication in the student’s thesis and its publication on the Australasian Research Online database consistent with any limitations set by publisher requirements.

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CHAPTER 4

ANALYSIS OF NON-LINEAR BEHAVIOUR OF HIGH POWER ULTRASOUND SYSTEMS

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Submitted at: IEEE transactions on ultrasonics, ferroelectrics, and frequency control
Abstract— Several factors can affect the performance of an ultrasound system such as quality of the excitation signal, the ultrasound transducer characteristics and the ultrasound system behaviour. In this paper, it is shown that the output voltage of ultrasound system is a function of the voltages across resistors related to the resonance frequencies of the ultrasound transducer. The behaviour of these resistors determines the ultrasound transducer characteristics. The characteristics of a high power ultrasound transducer and system are investigated and analysed for a range of voltages (15 V- 300 V). High power excitation signals (sinusoidal signals and square wave signals) are applied. The behaviour of the transducer is studied based on its impedance. The nonlinearity of the ultrasound transducer is observed in the test results especially at high voltage ranges. Also, the nonlinear behaviour of the ultrasound system is verified based on the measured input and the output voltage signals of the system.

Index Terms — High power ultrasound transducer behaviour, ultrasound system excitation, ultrasound system characteristic.

4.1. Introduction

High power ultrasound system plays a significant role in different applications where energy conversion at different ranges of voltage and frequency is required. In such a system, a high power ultrasound transducer converts electrical energy (voltage) to mechanical energy (ultrasound wave) and vice versa [1-7]. These transducers can be employed as transmitters, receivers or both. As a transmitter, the ultrasound transducer converts electrical energy to mechanical energy and as a receiver it converts mechanical energy to electrical energy [2].
Fig. 4. 1. A block diagram of the ultrasound system excitation.

Fig. 4. 1 shows a block diagram of high power ultrasound system excitation. To achieve high power energy conversion, a transmitter should be excited with high power voltage signal. Normally, power electronic converters are utilised to generate a high power signal. The associated control system generates the desired signal. For the control system, an output feedback is required. The accuracy of such a control system is highly related to the load behaviour where the nonlinearity of the load can decrease the accuracy, which can result in an undesired output signal of low quality. If the load is a high power ultrasound system, distorted excitation signal can deteriorate the performance of the system and increase the power consumption [8].

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 and this deformation depends on the applied electrical energy across the ultrasound transducer. In this case, to have better performance of the ultrasound transducer, an appropriate excitation signal with high quality (low distortion) is required [2-3], [8].

According to industrial and biomedical applications of the high power ultrasound system, this system can be applied to convert energy in desired ranges of voltage and frequency. To achieve a better performance of the ultrasound system, studying and analysis of the ultrasound transducer and the ultrasound system behaviours at different ranges of voltage and frequency could be a valuable option.

An ultrasound transducer has several resonance frequencies in which the ultrasound transducer has lowest impedance and highest efficiency compared to non-resonance frequencies [9-11]. Usually each of these frequencies can be represented
by a parallel combination of a RLC leg in electrical model of an ultrasound transducer. Several electrical models of an ultrasound transducer are introduced in literature [9], [12-14]. Some of them are illustrated in Fig. 4.2. The Van Dyke model is the basic model of the transducer which is a parallel connection of a series RLC leg and a capacitor [14]. 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 [9]. An electrical model of the ultrasound transducer with multiple resonance frequencies is shown in Fig. 4.2(d).

Fig. 4.2. Electrical model of an ultrasound transducer (a) Van Dyke model, (b) Sherrit model and (c) Easy model (d) with multiple resonance frequencies.

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 in phase and equal in amplitude, they cancel each other. In this case, the resistor of that particular leg converts electrical energy to mechanical energy. Therefore, at each resonance frequency the resistor delivers the mechanical energy to the secondary side of the
system. Since the output voltage of the system is related to the generated mechanical energy in the input side of the receiver, it could be concluded that the output power is a function of the voltages across the resistors at resonance frequencies. A circuit diagram of the ultrasound system is depicted in Fig. 4.3.

From Fig. 4.3, \( V_{\text{output}} \) is given by:

\[
\begin{align*}
V_{\text{output}} &= g(V_{R_{f_i}}) \\
R_{f_i} &= g(V_{\text{input}}, f_i)
\end{align*}
\]  

(4-1)

where:

- \( V_{\text{output}} \): the output voltage of the ultrasound system
- \( V_{R_{f_i}} \): the voltage across \( R_{f_i} \)
- \( R_{f_i} \): resistance of \( i^{th} \) resonance frequency of the ultrasound transducer
- \( f_i \): frequency of \( i^{th} \) resonance frequency

From (4-1), if the input voltage is a sinusoidal signal with fundamental frequency close to one of the resonance frequencies of the ultrasound transducer, \( V_{\text{output}} \) is a function of \( V_{R_{f_i}} \), otherwise if it is excited by several frequencies (such as a square wave), it is a function of other frequencies.

Therefore, at each resonance frequency the impedance behaviour of the ultrasound transducer is related to the resistor characteristic at that frequency.

To find out the resonance frequencies and the impedance of an ultrasound transducer at different frequency and low voltage ranges, a network analyser is usually used [15-16].
Due to the constraint of network analyser which is operating at low voltage, other methods are used to measure the impedance of the ultrasound transducer at high voltage ranges.

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 [17-19].

In this paper, a high power ultrasound system is implemented to investigate the behaviour of the high power ultrasound transducer as a main part of the ultrasound system and the characteristics of the whole ultrasound system. In this regard, the 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 in low and high voltage ranges. Also, to study the behaviour of the ultrasound transducer at its resonance and non-resonance frequencies, the ultrasound transducer is excited at different frequencies. Different methods are used in this paper to evaluate the characteristics of a high power ultrasound transducer and the ultrasound system, which includes two ultrasound transducers. These methods are classified as below:

- Low voltage (< 30 V)
  - network analyser (impedance measurement)
  - signal generator
- High voltage (> 30 V)
  - switched mode power converter

### 4.2. Impedance Characteristic of the Ultrasound Transducer

To find out the resonance frequencies and measure the impedance of a high power ultrasound transducer, a vector network analyser (R&S ZVL3) is used. Since the voltage range of network analyser is limited (< 2 V), another test is required to measure the impedance of the ultrasound transducer in higher voltage range (2 V<V≤ 30 V). In this regard, a sinusoidal signal is generated to drive the ultrasound transducer using a signal generator and a power amplifier (OPA549). Then the voltage and the current of the ultrasound transducer are measured to compute its impedance. Due to the voltage limitation of the power amplifier, a
A switched-mode power converter is used to generate a high voltage signal (30 V<V≤ 300 V) that is nearly sinusoidal with low distortion.

**4.2.1. Using a Vector Network Analyser (R&S ZVL3)**

A vector network analyser drives the ultrasound transducer by applying an input signal then measures the voltage and the feedback current to obtain the impedance of the ultrasound transducer. The measured impedance of the high power ultrasound transducer is shown in Fig. 4.4(a).

As it is clear in this figure, this ultrasound transducer has several resonance frequencies in which its impedance amplitude is minimum compared to non-resonance frequencies. Based on the minimum values of the impedance amplitude, maximum values of the output power are attained at these resonance frequencies. Among these resonance frequencies, at 78 kHz the lowest impedance is achievable and this frequency is defined as the main resonance frequency of the ultrasound transducer. From (4-1), \( V_{\text{output}} \) is a function of the voltages across the resistors associated to resonance frequencies of the ultrasound transducer. Also, \( f_i \) can be a function of \( V_{\text{input}} \) and \( f_i \). To validate (4-1) for the ultrasound transducer in this research, the measured ultrasound transducer impedance at a narrow frequency range (close to 78 kHz), the measured \( V_{\text{output}} \) and simulated at 78 kHz are depicted in Fig. 4.4(b), Fig. 4.4(c) and Fig. 4.4(d) respectively. In Fig. 4.4(b), the impedance of the ultrasound transducer is a function of \( V_{\text{input}} \) and \( f_i \). For instance, at 78 kHz if \( V_{\text{input}}=15 \) V the ultrasound transducer impedance equals to 250 Ω while for \( V_{\text{input}}=50 \) V it is 800 Ω. Also, if \( V_{\text{input}}=15 \) V the ultrasound transducer impedance at 78 kHz is 250 Ω while it is 1000 Ω at 78.2 kHz. As is shown in Fig. 4.4(c) and Fig. 4.4(d), since 78 kHz is the main resonance frequency of the ultrasound transducer, and cancel each other and the output voltage variations are very close to the changes of the voltage across \( R_{78} \).
As shown in Fig. 4.4(c) and Fig. 4.4(d), the output voltage changes are a function of variations. The amplitude of the output voltage is then decreased because of the attenuation of the mechanical energy in the ultrasound system.

To achieve the impedance of the ultrasound transducer at higher voltage ranges (2 V ≤ V ≤ 30 V), a high voltage signal should be generated to drive the ultrasound transducer.

### 4.2.2. Using a Sinusoidal Signal

The ultrasound transducer performance is highly dependent on its excitation signal and therefore care should be taken in generating this signal since a distorted signal could degrade the performance. Among different excitation methods introduced in [20-21], generating a sinusoidal signal with low distortion is an appropriate option.

In this regard, to drive the ultrasound transducer in this research, a sine wave is generated using a signal generator. To adjust the amplitude of the excitation signal to 15 V and 30 V a linear power amplifier (OPA 549) is used. To measure the current through the first transducer, a small resistor (1Ω) is placed in series with the transducer 1. To study the characteristic of the ultrasound transducer impedance at different frequencies, the frequency of the excitation signal is adjusted to 39 kHz and 61 kHz. The voltage across transducer 1 (V₁) and the current through it (i) are
measured to calculate its impedance \((Z = V / i)\).

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

**Principle of Superposition**

According to the principle of 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 [22]. This principle is shown by:

\[
g(V_1 + V_2 + ...) = g(V_1) + g(V_2) + ...
\]

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

- Test condition 1: Exciting by two separate input sinusoidal signals (39 kHz and 61 kHz)
- Test condition 2: Exciting by two simultaneous input sinusoidal signals (39 kHz + 61 kHz)

The block diagram of this setup and test results are depicted in Fig. 4.5. To meet the test condition 1, two input sinusoidal signals with different fundamental frequencies (39 kHz and 61 kHz) are generated to excite the ultrasound transducer individually. The amplitude of these signals are adjusted first to 15 V and then to 30 V using the amplifier. The responses of the ultrasound transducer to these individual input signals are added together in the frequency domain as shown in Fig. 4.5(b).

In the next step, two sinusoidal signals at 39 kHz and 61 kHz are generated simultaneously using two signal generators and then added together using the op-amp (OPA 549). The amplitudes of these signals are adjusted to 15 V and 30 V same as previous case. The comparison between the calculated impedances makes it clear whether the ultrasound transducer has linear or nonlinear characteristic. The calculated ultrasound transducer impedances for test condition 2 are illustrated in Fig. 4.5(c).
It can be seen from Fig. 4.5(b), based on two input voltages 15 V and 30 V at 39 kHz, the amplitudes of the ultrasound transducer impedances obtained are 1133.5 Ω and 1131.5 Ω respectively which are approximately same. Also, at 61 kHz the impedances of the ultrasound transducer are 921 Ω and 919 Ω for input voltages of 15 V and 30 V respectively. Fig. 4.5(c) shows that the differences between impedance amplitudes are increased according to test condition 2. For instance, based on two input signals with the amplitudes of 15 V and 30 V at 39 kHz, the impedance amplitudes are 1115 Ω and 1135 Ω respectively. In addition, these test results verify that the ultrasound transducer impedance is a function of the resonance frequency of the transducer and the input voltage signal. For example, the impedance amplitudes at 39 kHz are higher than the impedance amplitudes at 61 kHz even the amplitudes of the input signals are same at these frequencies. Also, based on (4-2) the ultrasound transducer has nonlinear characteristics due to mismatch of the calculated impedances according to the test condition 1 and test condition 2 which can be seen from the comparison between Fig. 4.5(b) and Fig. 4.5(c). A high voltage input signal is required to investigate the impedance of ultrasound transducer at high voltage range.
4.2.3. Using a Three-Level Converter

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 application, whereas it is used at higher voltage range for treatment [1]. To attain a better performance of the ultrasound transducer studying its characteristics at higher voltage ranges is necessary.

The maximum voltage of the generated sinusoidal signal is limited to the voltage range of the power amplifier. To overcome the voltage limitation of the excitation signal, a three-level inverter is implemented to generate an appropriate high voltage signal ($< 200$ V). The generated square wave signal (unipolar modulation) can inject harmonics to the system. Since minimum impedance and maximum output power of each ultrasound transducer is achieved at its resonance frequencies, the switching frequency of the inverter is regulated to generate a waveform with fundamental frequency close to those resonance frequencies. To study the response of the ultrasound transducer to the amplitude and frequency variations of the input voltage, the DC link voltage and the fundamental frequency of the inverter are changed in different stages. 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. To show this, the fundamental frequency of input signal ($f_s$) is adjusted to $f_s=39$ kHz and then $f_s=78$ kHz in two stages and each stage is repeated four times based on the
DC link voltage regulation (25 V, 50 V, 100 V and 200 V). The block diagram and a laboratory setup of this test are shown in Fig. 4.6(a) and Fig. 4.6(b) respectively. In this test, two differential probes are used to measure the voltage across transducer 1 (V₁) and the current through it (i). Then the impedance is computed using MATLAB from the measured voltage and current values obtained from the laboratory test. The results of this test are depicted in Fig. 4.6(c) and Fig. 4.6(d).

As is clear in Fig. 4.6(c) and Fig. 4.6(d), this test is carried out at two different frequencies in which the input voltage amplitude is changed four times. The nonlinearity of the ultrasound transducer is shown in this test results where the impedance amplitude is changed based on the amplitude variations of the input voltage signal. In Fig. 4.6(c), if the input voltage is changed from 25 V to 100 V, the impedance amplitude of the ultrasound transducer is changed from 350 Ω to 370 Ω. This variation is due to nonlinearity of the ultrasound transducer; otherwise the impedance amplitude should be same. Also, the increment sequence of the impedance amplitudes shown in Fig. 4.6(c) is different from the input voltage increment sequence. For example, at 39 kHz if the input voltage is increased from 50 V to 200 V, the ultrasound transducer impedance decreases from 360 Ω to 350 Ω. In comparison between Fig. 4.6(d) and Fig. 4.6(c), for fₛ=78 kHz and Vₑ=50 V the impedance of the ultrasound transducer is 80 Ω while for fₛ=39 kHz and Vₑ=50 V the ultrasound transducer impedance is 360 Ω. This comparison proves that the ultrasound transducer at its main resonance frequency (fₛ=78 kHz) has the lowest impedance. Since the generated signal is not a purely sinusoidal, some harmonic components are located at the sidebands of the fundamental frequency. For instance, if the fundamental frequency of the generated signal is adjusted to 39 kHz some harmonics are clear at 78 kHz shown in Fig. 4.6(c). 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. In Fig. 4.6(c), energy conversion happens at 39 kHz and 78 kHz while the fundamental frequency of excitation signal is adjusted to 39 kHz to achieve energy conversion just at 39 kHz not at 78 kHz. In such case the sidebands harmonics should be filtered to avoid undesired effects. In these test results it is observed that if 78 kHz is the fundamental frequency of the input signal (see Fig. 4.6(d)), the increment sequence of the impedance amplitudes is same as the input increment sequence while this sequence is changed if 78 kHz is a sideband of
the fundamental frequency (see Fig. 4.6(c)). Therefore, it can be concluded that at lower resonance frequencies and higher voltage range, the ultrasound transducer could be saturated and will have a nonlinear behaviour. Moreover, Fig. 4.6(d) shows that at lower input voltage range (25 V- 100 V) the differences between amplitudes are small but for 200 V, this difference increases dramatically. Overall, the nonlinearity of the ultrasound transducer is concluded from these test results.
Fig. 4.6. Test with three-level inverter (a) block diagram of setup and (b) experimental setup and test results (c) $f_s=39$ kHz, (d) $f_s=78$ kHz.

4.3. Ultrasound System Characteristic

As shown in Fig. 4.1, 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 waves 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 [23]. 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 analysed according to the comparison of the input and 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 [23]. The responses of the second ultrasound transducer to the input voltages with different amplitudes are measured to illustrate the characteristic of the system.

4.3.1. 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 excited by a sinusoidal signal is depicted in Fig. 4.7. In this test, transducer 1 plays a role of the transmitter and transducer 2 is the receiver. Two sinusoidal signals with different fundamental frequencies (39 kHz and 61 kHz) are generated individually. The amplitudes of these signals are adjusted to 15 V and 30 V 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. 4.8 are illustrated in the frequency domain.

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 be a function of the input voltage changes. As is shown in Fig. 4.8(b) and Fig. 4.8(d), the amplitudes of the output signals are decreased dramatically compared to the amplitudes of the input signals (depicted in Fig. 4.8(a) and Fig. 4.8(c)) due to the attenuation of the mechanical energy in the system. Also, in Fig. 4.8(b) the responses of the system to two input voltage signals are approximately 0.5 V. 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 with same amplitudes at different frequencies will be changed which is obvious in comparison of Fig. 4.8(b) and Fig. 4.8(d). For instance, if $V_{\text{input}}=15$ V, the output voltage at 39 kHz is 0.48 V while at 61 kHz is 1 V.

According to these test results, it could be concluded that this system has nonlinear behaviour. Same as other systems, to clarify whether the ultrasound system is linear, superposition law is used.

![Block Diagram of Ultrasound System Excitation](image)

**Fig. 4.7.** A block diagram of the ultrasound system excitation using sinusoidal signal.

![Graphs of Input and Output Voltage Signals](image)

**Fig. 4.8.** Test results of ultrasound system excitation using sinusoidal signal:

- input voltage signals (a) at 39 kHz and (c) at 61 kHz.
- output voltage signals (b) at 39 kHz and (d) at 61 kHz.
**Principle of Superposition**

Based on (4-2), the ultrasound system is linear if its responses to the test condition 1 and the test condition 2 from section 2.2.2 are same. To meet test condition 1, the ultrasound system is excited by two individual input signals with different frequencies (39 kHz and 61 kHz). The responses of the system to these input signals are added together in frequency domain. As a test condition 2, two input sinusoidal signals with fundamental frequencies of 39 kHz and 61 kHz are added together and generate a new signal to drive the ultrasound system. The amplitude of the input signals are adjusted first to 15 V and then to 30 V for both test conditions. The results of this test are shown in Fig. 4.9.

According to Fig. 4.9(a), the amplitudes of the output voltages at 39 kHz are same (0.5 V) even the amplitudes of the input voltage signals are different (15 V and 30 V). In Fig. 4.9(b), the output voltage amplitudes are 0.5 V and 1.2 V at 39 kHz based on V_{input}=15 V and V_{input}=30 V respectively.

The differences between test results shown in Fig. 4.9(a) and Fig. 4.9(b) verify that this system does not obey the superposition rule so it is a nonlinear system.

![Fig. 4.9. Test results of (a) test condition1, (b) test condition 2.](image)

**4.3.2. Using a Three-Level Converter**

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, a power converter is used to generate a high voltage square wave signal.
The voltages across transducer 1 and transducer 2 are measured as the input and the output voltages respectively using two differential probes. The captured data of this test are analysed in frequency domain using MATLAB. The generated signal has a fundamental content and some components in its sidebands in frequency domain because 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 first sideband will appear 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, 200 V and 300 V therefore the responses of the ultrasound system to the input voltage signals with different amplitudes are studied. The block diagram of this test and the measured input and output voltages in frequency domain are depicted in Fig. 4.10.

To have a better comparison, the amplitudes of the input and the output voltages are normalized at 50V dividing by factors of 1, 2, 4 and 6. As it is clear in Fig. 4.10(b), all normalized input voltage signals match each other. For instance, at 39 kHz all normalized input signals have same amplitudes (50 V). Despite the input voltage signals, the normalized output voltages do not match each other and some differences can be seen in Fig. 4.10(c). For example, at 39 kHz the response of the system to the input voltage signal with the amplitude of 300 V is 0.5 V but the response to 100 V input voltage signal is 1.7 V. As a linear ultrasound system the measured voltage in the output side should commensurate with the applied voltage in the input side, but the results of this test show that this system does not obey this rule and has nonlinear behaviour. Since 78 kHz is the main resonance frequency of the ultrasound transducer, undesired excitation at this frequency or close to it can highly affect the performance the ultrasound system and cause power delivery at undesired frequencies. The effect of the first sideband of the input signal (at 78 kHz) on the output signal is clear in Fig. 4.10(c). In addition, the amplitudes of the output voltage signals are decreased compared to the amplitude of the input voltage signals due to the attenuation of the mechanical energy in the system.
Fig. 4.10. Ultrasound system excitation using a three-level converter (a) block diagram and test results (b) normalised input voltages (c) normalised output voltages.
4.4. Conclusion

The load behaviour should be taken into consideration when a high power converter is going to be designed. Therefore, it is really important to consider the characteristics of the high power ultrasound transducer and the high power ultrasound system where a high power converter is developed to excite an ultrasound transducer or system. The characteristics of the high power ultrasound transducer and the ultrasound system in low and high voltages are investigated in this paper. A setup of an ultrasound system including two high power ultrasound transducers are implemented and tested. According to the test results, it is concluded that the equivalent resistor at each resonance frequency of the ultrasound transducer delivers power to the output side of the ultrasound system. Therefore, the behaviour of the ultrasound transducer at each resonance frequency is highly affected by the characteristics of the equivalent resistor at that frequency. A low voltage sinusoidal signal and a high voltage square wave signal are generated to excite the ultrasound transducer and ultrasound system in different frequency ranges. The test results present a nonlinear behaviour of the ultrasound transducer especially in high voltage ranges because the impedance amplitude of the ultrasound transducer varies by the amplitude variations of the input voltage signals. Also, the characteristic of the ultrasound system is analysed in low and high voltage ranges based on the voltage ratio of the ultrasound system. The nonlinearity of the ultrasound system has been seen in the test results where the measured output voltage amplitudes of the system are not related to the amplitude changes of the input voltage signals.

References


Arnau A., Jimenez Y., Sogorb T.: ‘An extended Butterworth Van Dyke model for quartz crystal microbalance applications in viscoelastic fluid


**Statement of Contribution of Co-Authors**

The authors listed below have certified that:

1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit, and
5. they agree to the use of the publication in the student’s thesis and its publication on the Australasian Research Online database consistent with any limitations set by publisher requirements.

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16 Nov 2012
CHAPTER 5

POWER ELECTRONIC CONVERTERS FOR HIGH POWER ULTRASOUND TRANSUDERS

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Abstract—Piezoelectric transducers convert electrical energy to mechanical energy and play a great role in ultrasound systems. Ultrasound power transducer performance is strongly related to the applied electrical excitation. To have a suitable excitation for maximum energy conversion, it is required to analyse the effects of input signal waveform, medium and input signal distortion on the characteristics of a high power ultrasound system (including ultrasound transducer). In this research, different input voltage signals are generated using a single-phase power inverter and a linear power amplifier to excite a high power ultrasound transducer in different mediums (water and oil) in order to study the characteristics of the system. We have also considered and analysed the effect of power converter output voltage distortions on the performance of the high power ultrasound transducer using a passive filter.

Keywords-component — Power Converter, Piezoelectric Transducer Excitation.

5.1. Introduction

Much research has been conducted on piezoelectric behaviour since 1880, the year that Pierre and Jacques Curie discovered the phenomenon of piezoelectricity. The critical behaviour of a piezoelectric device is encapsulated in its resonant frequencies and the most efficient way to find the critical piezoelectric specifications is to analyse its impedance frequency response[1]. IEEE Standard on Piezoelectricity introduced the basic equivalent circuit model characterizing a piezoelectric ceramic near the resonant frequency which is known as Van Dyke Model. This model is often adapted to model electromechanical resonance characteristics of crystal oscillators. The Van Dyke Model is a parallel connection of a series RLC representing mechanical damping, mass, and elastic compliance and a capacitor representing the electrostatic capacitance between the two parallel ceramic plates[2]. When a piezoelectric ceramic is mounted to a mechanical structure, a loaded piezoelectric ceramic experiences multiple resonances, a circuit model (Fig. 5.1(a)) for a wide frequency range with multiple resonant frequencies can be employed to model the behaviour of a loaded piezoelectric ceramic.

Ultrasound systems are used in different industrial and medical applications. According to various applications, an ultrasound system can be used in low
(1-100 W) and high (0.1- 50 kW) power and frequency ranges. For instance, in biomedical applications a high frequency ultrasound system is used for diagnosis (low power) or therapeutic application (high power). In order to generate ultrasound wave, piezoelectric transducer is a key part of the ultrasound system which converts electrical to mechanical energy. A most important issue in exciting a high power ultrasound transducer is quality and shape of the electrical signal which drives the power transducer [3-9]. It is important to generate a high quality power signal at its resonant frequency with low distortion to attain the highest energy conversion. Different methods are introduced to generate a suitable signal to drive a power transducer such as radio-frequency linear amplifiers and switched mode power converters [6]. A main advantage of switched mode power converters compare to power amplifiers is its high efficiency at high power operation. Fig. 5.1(b) and Fig. 5.1(c) show a power converter connected to a piezoelectric transducer as a load and the output voltage levels of a power converter respectively. Multilevel converters are suitable power converters to drive power transducers due to their attractive ability to generate a high quality power waveform with low harmonic distortion and voltage stress [10-12].

In order to drive a power transducer with an appropriate signal, it is essential to study and analyse the impedance of a piezoelectric transducer at different frequency and power ranges. Usually, a network analyser is used to measure piezoelectric transducer impedance and its resonant frequencies in frequency domain. It is not possible to analyse and study the characteristics of a high power transducer using a network analyser due to the fact that a network analyser operates at low power[5]. Therefore, some tests have been carried out in this research to study the performance and behaviour (linear or nonlinear) of ultrasound system at high power range which are presented in the next sections.
Fig. 5.1. (a) Van Dyke Model, (b) a power converter, (c) output voltage of power converter.
5.2. Experimental Procedure

In this research work we have used a power ultrasound transducer which has some resonant frequencies below 100 kHz and high energy conversion happens at those resonant frequencies. Table 5.1 shows a summary of all test conditions which have been carried out at different mediums and input voltages. In the first two tests, sinusoidal voltage waveforms are generated by a linear power amplifier to drive the piezoelectric transducers. In these two tests, nonlinear characteristic of the high power ultrasound system is analysed using superposition method.

In the other tests, a high power single phase inverter is used to generate high voltage and high frequency signals (square wave) to analyse behaviour of ultrasound system when it is driven by non-sinusoidal signals.

In test 1 and test 2, a power amplifier (OPA 459) is connected to a step-up transformer to generate a high voltage signal to excite a high power transducer as shown in Fig. 5.2. Two transducers (same type) are placed in a container (exactly opposite to each other) and one transducer is excited by the electrical signal as a transmitter and the other one converts the generated ultrasound signal to electrical energy at the other side of the container as a receiver.

Since the performance of the piezoelectric transducer is highly dependent on its excitation, generating a proper sinusoidal signal with low order harmonics is required. If the frequency of the excitation signal is same as the resonant frequency of the transducer, the highest energy conversion will be attained. A signal generator and a high power amplifier (OPA 459) are used to generate a high power signal (up to 8 A at 30 Volts) but a high frequency step-up transformer is used to increase the output voltage level. The piezoelectric has some resonant frequencies around 39 kHz. We have generated two sinusoidal signals at 39 kHz and 61 kHz in two different tests. In test 1, the magnitudes of the sinusoidal signals are adjusted at 15 V and 30 V and we have excited the first transducer at 39 kHz and 61 kHz separately and have measured the output voltage of the second transducer in time domain. In order to check the quality of the input and output voltages at 15 V and 30 V, the signals are shown in frequency domain (Fig. 5.3).

The test results show that the output voltage measured by the second transducer is not proportional to the input voltage. This test verifies that the ultrasound system has
nonlinear behaviour at its resonant frequencies. In order to study the performance of the ultrasound system more, a superposition law is used as a key factor. Based on this principle, if the ultrasound system has linear characteristics, the responses of the system with two sinusoidal signals (as follow) should be same:

a) separately excited by two signals at 39 kHz and 61 kHz and adding the output signals

b) simultaneously excited by two signals at 39 kHz and 61 kHz

Table. 5.1. Test conditions and setups

<table>
<thead>
<tr>
<th>Test</th>
<th>Medium</th>
<th>Excitation System</th>
<th>Input Voltage Magnitude (peak)</th>
<th>Frequency of Input Signal (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>water</td>
<td>Signal Generator, a power amplifier and a high frequency transformer</td>
<td>15 V and 30 V</td>
<td>39 kHz and 61 kHz</td>
</tr>
<tr>
<td>Test 2</td>
<td>water</td>
<td>Signal Generator, a power amplifier and a high frequency transformer</td>
<td>15 V + 30 V (time domain)</td>
<td>39 kHz and 61 kHz</td>
</tr>
<tr>
<td>Test 3</td>
<td>oil</td>
<td>three-level inverter</td>
<td>50 V, 100 V, 200 V and 300 V</td>
<td>39 kHz</td>
</tr>
<tr>
<td>Test 4</td>
<td>oil</td>
<td>three-level inverter and a tube between two transducers</td>
<td>50 V, 100 V, 200 V and 300 V</td>
<td>39 kHz</td>
</tr>
<tr>
<td>Test 5</td>
<td>oil</td>
<td>three-level inverter and a filter</td>
<td>50 V, 100 V, 200 V and 300 V</td>
<td>39 kHz</td>
</tr>
<tr>
<td>Test 6</td>
<td>water</td>
<td>three-level inverter</td>
<td>50 V, 100 V, 200 V and 300 V</td>
<td>39 kHz</td>
</tr>
</tbody>
</table>
Fig. 5.2. A block diagram of a lab prototype for test 1 and test 2.

(a)

(b)
Therefore, in test 2, the same transducer is excited by two signals at 39 kHz and 61 kHz which are added together at the input side of the power amplifier. We expect the output voltages of the ultrasound system in two different tests should be exactly same as each other if the system has a linear characteristic. The test result for each voltage level is shown in Fig. 5.4(a).

Fig. 5.3.(a) input signals at 39 kHz (b) output signals at 39 kHz (c) input signals at 61 kHz (d) output signals at 61 kHz.
(a) 

(b)
Fig. 5.4. (a) test 1: summation of two output signals (at 39 kHz & 61 kHz) for \( V_{\text{in}} = 15 \text{V} \) and \( V_{\text{in}} = 30 \text{V} \).

(b) test 2: two output signals for \( V_{\text{in}} = 15 \text{V} \) and \( V_{\text{in}} = 30 \text{V} \).

(c) comparing the results of test 1 and test 2 for \( V_{\text{in}} = 15 \text{V} \).

(d) comparing the results of test 1 and test 2 for \( V_{\text{in}} = 30 \text{V} \).

In order to compare this test results with the previous one, we have added the output voltage results of test 1 at 39 kHz and 61 kHz in time domain and the results
are shown in Fig. 5.4(b). The output voltage of each test at 15 V and 30 V are shown in Fig. 5.4(c) and Fig. 5.4(d) and it is clear that the output voltages (separately and simultaneously excited) are not same. A difference between these test results shows the ultrasound system has a nonlinear characteristic when the input voltage and power are increased.

The results of Fig. 5.4 show that the ultrasound system does not obey the superposition principle and it has nonlinear behaviour as the output voltages of the two tests at 30 V are not same. In order to study the nonlinearity of the ultrasound system at higher power and different mediums, different tests have been carried out using a single phase inverter, generating a square wave uni-polar voltage waveform. A laboratory setup of this configuration is shown in Fig. 5.5.

A coupling box of laboratory setup is filled of oil or water for different tests in this research. A block diagram of the setup of test 3 is shown in Fig. 5.6.

In this test, a power converter generates a square wave signal (uni-polar modulation) at different voltage levels (50V, 100V, 200V and 300V) and at 39 kHz including some harmonics. In order to compare the quality of all input voltages, we have normalized all input voltage at 50 Volts (dividing all input voltages by factors of 1, 2, 4 and 6, respectively) and the input voltage waveforms are shown in frequency domain (Fig. 5.7(a)). Then, we have measured the output voltage of the second transducer at different excitation voltages and the results are shown in Fig. 5.7(b). Similar to the input voltages, we have divided the output voltages by the same factors (1, 2, 4 and 6, respectively) in order to compare the output voltages. The results show that the ultrasound system has nonlinear characteristics at different voltage levels and the output voltages are not same when they are normalized.
Fig. 5.5. The experimental setup.

Fig. 5.6. A block diagram of test 3.
According to the applied input voltages, an ultrasound wave is generated and transferred to the second transducer. But some of the generated wave will be attenuated due to interaction with inhomogeneous material. The velocity and attenuation of generated wave are highly dependent on the mechanical and structural properties of the medium [13, 14]. To study the effect of attenuation of generated ultrasound wave, a tube is placed between the two transducers in which ultrasound wave is guided from the first transducer to the second transducer. It is expected that the tube reduces the propagation of generated wave and thus increases the intensity.

Fig. 5.7. The results of test 3 (a) input signals and (b) output signals.
of the wave at the second transducer. A block diagram of this configuration is illustrated in Fig. 5.8.

Similar to the previous test, we have normalized all input and output voltages in order to check the quality of the input voltages and compare the output voltages in frequency domain. As is shown in Fig. 5.9 the output voltage magnitudes are increased compare to the previous test result (Fig. 5.7(b)) but there are still differences in the output voltage magnitudes due to the nonlinear behaviour of the system at those frequencies.

The output voltage of the power inverter generates voltage stress (dv/dt) across the piezoelectric transducer. This voltage with the capacitive characteristics of the piezoelectric transducer can generate significant current spikes which increases losses and high frequency noise. Since the input voltage distortion can tend to deteriorate the output voltage quality and can increase the power dissipation, a 990 μH inductor as a filter is placed between the power converter and the transducer to reduce the input voltage distortion across the first transducer. Fig. 5.10 shows a block diagram of the setup.

The added filter reduces the amplitude of the output voltage in frequency domain (Fig. 5.11) compared to the test results shown in Fig. 5.7 but this filter has not a significant effect on the characteristics of the ultrasound system and it has still a nonlinear characteristics at those frequencies which is shown in Fig. 5.11(b).

In order to study the effects of medium on the ultrasound system characteristics, we have performed a new test similar to test 3 but with water (instead of oil). A block diagram of the setup is shown in Fig. 5.12.
Fig. 5.8. A block diagram of test 4.

Fig. 5.9. The results of test 4 (a) input signals and (b) output signals.
Fig. 5.10. A block diagram of test 5.

Similar to the previous test results, when the input and output voltages are normalized at 50 V, there are still significant differences between the output voltages at different frequencies shown in Fig. 5.13. The nonlinear behaviour of a high power ultrasound system is obvious in this figure due to mismatch of the responses of the ultrasound system to the normalized input voltages. The nonlinearity of the ultrasound system has been shown in different cases where a high power ultrasound transducer was excited by a sinusoidal and a pulse voltage waveform.
Fig. 5.11. The results of test 5 (a) input signals and (b) output signals.

Fig. 5.12. A block diagram of test 6.
Fig. 5.13. The results of test 6 (a) input signals and (b) output signals.

5.3. Conclusion

In this research a high power transducer is driven by different input signals and the performance of ultrasound system is studied and analysed in several frequencies. According to the first and the second test results, it is obvious that the ultrasound system has nonlinear behaviour at high voltage and high power. In order to analyse the effects of a) input signal waveform, b) medium and c) input signal distortion on characteristics of an ultrasound system, several tests with different setups are carried out. According to the test results of this study and research work, it is concluded that a high power ultrasound system has nonlinear characteristics with respect to the input voltage magnitude. The results verify that the nonlinear characteristics of a high power ultrasound system exist in different medium. It means that a high power ultrasound system may be saturated when the input voltage magnitude is increased and the piezoelectric ceramic plates cannot vibrate proportional to the input voltage.

References


Statement of Contribution of Co-Authors

The authors listed below have certified that:
1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit, and
5. they agree to the use of the publication in the student’s thesis and its publication on the Australasian Research Online database consistent with any limitations set by publisher requirements.

In the case of this chapter:
A New Unequal DC link Voltage Configuration for a Single Phase Multilevel Converter to Reduce Low Order Harmonics, Presented and published at: the 14th European Conference on Power Electronics and Applications (EPE 2011), Birmingham, UK.

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Statement of contribution*</th>
</tr>
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<tbody>
<tr>
<td>Negar Ghasemi</td>
<td>Proposed the initial design and conducted simulation studies and data analysis, designed the control strategy, implemented hardware set-up and conducted experimental verification and wrote the manuscript.</td>
</tr>
<tr>
<td>16 Nov 2012</td>
<td></td>
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<tr>
<td>Firuz Zare</td>
<td>Proposed the initial design and supervised the validity studies including: conducting the simulations and experimental studies and writing the manuscript.</td>
</tr>
<tr>
<td>Christian Langton</td>
<td>Provided us with general information about ultrasound system specifications and its applications.</td>
</tr>
<tr>
<td>Arindam Ghosh</td>
<td>Aided planning the control strategies and writing the paper.</td>
</tr>
</tbody>
</table>

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A/Prof. Firuz Zare 16 Nov 2012

Name  
Signature  Date
CHAPTER 6

A NEW UNEQUAL DC LINK VOLTAGE CONFIGURATION FOR A SINGLE PHASE MULTILEVEL CONVERTER TO REDUCE LOW ORDER HARMONICS

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Presented and published at: the 14th European Conference on Power Electronics and Applications (EPE 2011), Birmingham, UK.
**Abstract**—Multilevel converters are used in high power and high voltage applications due to their attractive benefits in generating high quality output voltage. Increasing the number of voltage levels can lead to a reduction in lower order harmonics. Various modulation and control techniques are introduced for multilevel converters like Space Vector Modulation (SVM), Sinusoidal Pulse Width Modulation (SPWM) and Harmonic Elimination (HE) methods. Multilevel converters may have a DC link with equal or unequal DC voltages. In this paper a new modulation technique based on harmonic elimination method is proposed for those multilevel converters that have unequal DC link voltages. This new technique has better effect on output voltage quality and less Total Harmonic Distortion (THD) than other modulation techniques. In order to verify the proposed modulation technique, MATLAB simulations are carried out for a single-phase diode-clamped inverter.

**Keywords** — Multilevel converters, Modulation strategy, Harmonics, Renewable energy systems.

### 6.1. Introduction

Multilevel converters are widely used in high voltage and high power applications because of their ability to generate staircase output voltage close to a sinusoidal waveform with lower harmonic distortion, higher output voltage levels and reduce switching losses which can remedy Electromagnetic Interference (EMI) problem. Three well-known topologies of multilevel converters are diode-clamped, flying capacitor and cascade, which are shown in Fig. 6.1.
Fig. 6.1. One leg of a multilevel converter with (a) diode-clamped (b) flying capacitor (c) cascade topology.

In a diode-clamped configuration, the DC link voltage is divided into a number of output levels by some series-connected capacitors [1]. Using the topology of
Fig. 6.2 (a), the DC voltage can be divided into three levels by DC link capacitors ($C_1$ and $C_2$). This type of multilevel converters is popularly used in motor drive applications due to the simplicity of the DC link voltage for a back-to-back configuration [2]. In a flying capacitor converter, desired output voltage levels are generated by distributing the DC voltage among the capacitors. The third well-known configuration is a cascade converter in which several H bridge single phase converters with distinct DC sources are connected in series [3]. Cascade converters are suitable for renewable energy system integration or as Static VAR Compensators (SVCs) [2, 3].

In all mentioned configurations, an output voltage staircase is achieved based on different switching states, providing different DC link voltages across a load. Fig. 6.2 shows $m$-pulses which are added together at the output of a multilevel converter to get two separate output voltage waveforms – one with equal dc link voltage ($V_1=V_2=\ldots=V_m$) (Fig. 6.2(b)) and the other with unequal dc link voltage ($V_1\neq V_2\neq\ldots\neq V_m$) (Fig. 6.2(c)).
Traditionally, the output voltage levels of a multilevel converter are equal and the numbers of the output voltage levels are limited by the numbers of components and the DC voltage sources. Hence, more output voltage levels can impose more cost and complexity to the system. To achieve more output voltage levels without adding up
components, unequal DC link diode-clamped converters have been introduced [4]. In this case, it is possible to generate more output voltage levels according to different switching states and unequal DC link voltages. Thus, the output voltage levels may be increased with less components and DC voltage sources [5].

To have an optimal operation and better output voltage quality and also to control output voltage waveform of a multilevel converter, an appropriate pulse width modulation and a suitable control technique are required. Several modulations and control techniques are introduced such as: Sinusoidal Pulse Width Modulation (SPWM), Space Vector Modulation (SVM) and Selective Harmonic Elimination (SHE) method [1]. Among these modulation techniques, SPWM and SVM modulation techniques can be applied for power converters by comparing a reference signal with triangular signals, [1], [6],[7],[8]. In [9], a Selective Harmonic Elimination (SHE) technique is combined with Optimized Harmonic Stepped Waveform (OHSW) method to decrease output harmonic contents and filter size with less complexity and switching losses. This technique proposes extra notches with their angles in the output levels, which are helpful to have better control on output waveform and harmonics reduction.

A new modulation technique based on harmonic elimination method is introduced in this paper for a multilevel converter with unequal DC link voltage to eliminate more harmonic contents at output of a converter compared to traditional harmonic elimination method. Due to unequal DC link voltages. The proposed technique can have more variables such as switching angles and output voltage levels. Therefore this technique is very effective in reducing THD. In order to validate the proposed new modulation technique, single phase multilevel converters with four and five voltage levels are simulated and the results are compared with the traditional harmonic elimination technique.

**6.2. Selective Harmonic Elimination**

Harmonic elimination technique is an offline method in which switching angles are used to control the fundamental component and to eliminate low order harmonic contents. Switching angles are calculated in such a way to eliminate lower order harmonics by solving several nonlinear equations [9]. Fourier series expansion is used to find out switching angles and eliminate desired harmonic contents. The output staircase waveform includes no even harmonic contents, since it is symmetric.
In the conventional method, the differences between each two consequent output voltage levels are equal and the switching angles are the only variables for this modulation. Fourier series expansion of m-level converter is given by:

\[ b_n = \sum_{i=1}^{m-1} \frac{4V_i}{n\pi} \cos(n\alpha_i) \]  \hspace{1cm} (6-1)

where:

- \( V_i \): the amplitude of output voltage
- \( \alpha_i \): the \( i \)th switching angle
- \( n \): the number of odd harmonics
- \( m \): the number of output voltage levels

In the conventional harmonic elimination technique: \( V_1=V_2=\ldots=V_m=V_{dc}/(m-1) \).

Therefore, (1) can be rewritten as

\[ b_n = \frac{4V_{dc}}{n(m-1)\pi} \sum_{i=1}^{m-1} \cos(n\alpha_i) \]  \hspace{1cm} (6-2)

Fig. 6.3 shows the output of a four-level converter in time and frequency domains. Fourier series expansion for this four-level converter is given by

\[ b_n = \frac{4V_1}{n\pi} \cos(n\alpha_1) + \frac{4V_2}{n\pi} \cos(n\alpha_2) + \frac{4V_3}{n\pi} \cos(n\alpha_3) \]  \hspace{1cm} (6-3)

In this case, \( V_1=V_2=V_3=V_{dc}/3 \) and we have only three variables \( (\alpha_1,\alpha_2,\alpha_3) \).

According to these three variables, the above non-linear equation is solved in MATLAB to eliminate 3\textsuperscript{rd} and 5\textsuperscript{th} harmonics and to calculate the fundamental amplitude.

As an example, (3-4) is derived from (3-3) to calculate the switching angles of a four-level inverter with fundamental component of \( b_1=0.6 \) (per unit), \( b_2=b_3=0 \) and \( V_{dc}=0.7 \) (per unit).

\[ b_1 = \frac{4V_{dc}}{3\pi} (\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3)) = 0.6 \]

\[ b_3 = \frac{4V_{dc}}{9\pi} (\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3)) = 0 \]  \hspace{1cm} (6-4)

\[ b_5 = \frac{4V_{dc}}{15\pi} (\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3)) = 0 \]
The calculated switching angles then are:

\[ \alpha_1 = 0.3090 \text{ rad}, \quad \alpha_2 = 0.5306 \text{ rad}, \quad \alpha_3 = 1.3649 \text{ rad} \]

Fig. 6.3. Output voltage waveform of a four-level converter operating with conventional technique in (a) a time domain and (b) a frequency domain.

As is shown in Fig. 6.3 (b), 3th and 5th harmonics are eliminated. From (6-1), it is clear that more variables are required to eliminate more lower order harmonics. This implies that for eliminating more harmonic components, we need to increase the number of switching angles or the number of output voltage levels. In order to analyse the effect of more variables, a five-level converter is simulated. The output voltage waveform of this converter is shown in Fig. 6.4. Calculated variables for this simulation are:
\[ \alpha_1 = 0.0577 \text{ rad}, \quad \alpha_2 = 0.5016 \text{ rad}, \quad \alpha_3 = 0.7897 \text{ rad}, \quad \alpha_4 = 1.4570 \text{ rad} \]

Fig. 6.4. output voltage waveform of a five-level converter operating with conventional technique in (a) a time domain and (b) a frequency domain.

From Fig. 6.4 (b) it can be seen that 3\(^{\text{rd}}\), 5\(^{\text{th}}\) and 7\(^{\text{th}}\) harmonics are eliminated. This shows the effect of more variables on harmonic reduction.

6.3. New Modulation Technique

As it is mentioned in [10], the conventional harmonic elimination technique can have only a restricted range of variables (switching angles) and this is a limitation in harmonic elimination. In order to overcome this problem, a new modulation technique is proposed in this paper to decrease lower order harmonics even more to improve the output voltage quality. Unlike the conventional method, DC voltage levels and switching angles of the output voltage waveform of a power converter are
considered as variables which should be calculated offline by solving several nonlinear equations. This means that the DC link voltages are not equal compared to the traditional multilevel configuration. In the conventional modulation method, the range of variables is limited to the number of switching angles, because the output voltage levels are equal. However, in the proposed modulation technique, due to the unequal output voltage levels, the range of the variables is extended to the switching angles and the output voltage levels. For instance, in a traditional technique with m-output voltage levels and s-switching angles, it is possible to generate the output voltage waveform by eliminating (s-1) harmonics. But in the new modulation technique, with the same switching angles and output voltage levels, we can generate a voltage waveform that does not contain (m+s)-2 harmonics. For both traditional and new modulation technique s=m. Table. 6.1 shows the difference between these two techniques for a four-level converter. A comparison between the traditional technique and the new modulation technique, in terms of solving nonlinear equations, is illustrated by a flowchart as shown in Fig. 6.5. In this flowchart, (a₁,a₂,…,aₙ) are switching angles of pulses, (V₁,V₂,…,Vₚ) are the output levels and Vᵣₑᶠ is the magnitude of the fundamental component. Note that it is possible to generate unequal DC voltages using DC/DC converters as explained in the next section.

Table. 6.1: A comparison between the conventional and the new modulation technique

<table>
<thead>
<tr>
<th>Harmonic Elimination Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional method</strong></td>
</tr>
<tr>
<td>Switching Angles</td>
</tr>
<tr>
<td>α₁, α₂, α₃</td>
</tr>
<tr>
<td>Output Voltage Steps</td>
</tr>
<tr>
<td>V₁=V₂=V₃</td>
</tr>
<tr>
<td>Variables</td>
</tr>
<tr>
<td>The number of eliminated harmonics</td>
</tr>
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Fig. 6.5. A flowchart to calculate the switching angles and output voltage levels.

To study and analyse the proposed modulation technique, several simulations are carried out using MATLAB. In the first simulation, this new technique is applied to a four-level converter with unequal DC link voltages \( (V_1 \neq V_2 \neq V_3) \). A Fourier series expansion is solved using MATLAB in order to find out the DC link voltage levels and the switching angles. In this case, the number of variables is six \((\alpha_1, \alpha_2, \alpha_3 \text{ and } V_1, V_2, V_3)\) and it is expected that five harmonics will be eliminated. The calculated variables are as below:

\[
\begin{align*}
V_1 &= 0.2625 \text{ V,} \\
V_2 &= 0.2105 \text{ V,} \\
V_3 &= 0.1168 \text{ V} \\
\alpha_1 &= 0.2244 \text{ rad,} \\
\alpha_2 &= 0.6732 \text{ rad,} \\
\alpha_3 &= 1.1220 \text{ rad}
\end{align*}
\]
The output voltage waveform of the four-level converter operating with the new harmonic elimination technique and its harmonic spectra are depicted in Fig. 6.6. The calculated voltage levels are unequal which means the output voltage steps of this converter are not equal, while they are equal in the conventional method.

![Output of four-level converter](image)

(a)

![FFT](image)

(b)

Fig. 6.6. A four-level converter operating with the new modulation technique (a) output voltage waveform, (b) harmonic contents.

As shown in Fig. 6.6(b), 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, 9\textsuperscript{th} and 11\textsuperscript{th} harmonics are eliminated in this modulation technique. Therefore, it can be concluded that for the same DC link voltage level, this proposed modulation technique is more effective in reducing THD.

To study the effectiveness of the scheme further, a five-level converter is simulated as well. With one extra voltage level, it is possible to eliminate two more harmonics due to the fact that there are two more variables (\(a_4\) and \(A_4\)). However, in the conventional technique, there is just one more variable which can eliminate one more harmonic. For the five-level converter, the calculated parameters are as below:
$V_1 = 0.2063\, V, \quad V_2 = 0.1814\, V, \quad V_3 = 0.1346\, V, \quad V_4 = 0.0716\, V$

$\alpha_1 = 0.1745\, \text{rad}, \quad \alpha_2 = 0.5236\, \text{rad}, \quad \alpha_3 = 0.8727\, \text{rad}, \quad \alpha_4 = 1.2217\, \text{rad}$

The output voltage waveform of the five-level converter operating with the proposed new modulation technique is shown in Fig. 6.7.

![Output of five-level converter](image)

(a)

![FFT](image)

(b)

Fig. 6.7. A five-level converter operating with the new modulation technique (a) output voltage waveform, (b) harmonic contents.

From Fig. 6.7(b) it can be seen that $13^{\text{th}}$ and $15^{\text{th}}$ harmonics are also eliminated in addition to the results shown in Fig. 6.6(b). The simulation results of Fig. 6.6(b) and Fig. 6.7(b) verify the effectiveness of the new modulation method for a multilevel converter with unequal DC voltages. Table 6.2 gives a comparison between the traditional and the proposed modulation technique based on MATLAB simulations for a four-level and a five-level converters.
Table 6.2: Comparison between modulation techniques

<table>
<thead>
<tr>
<th>Eliminated Harmonic(s)</th>
<th>Conventional Technique</th>
<th>New Modulation Technique</th>
</tr>
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<tbody>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; and 5&lt;sup&gt;th&lt;/sup&gt;</td>
<td>4-level converter</td>
<td>5-level converter</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;, 5&lt;sup&gt;th&lt;/sup&gt;, 7&lt;sup&gt;th&lt;/sup&gt;</td>
<td>4-level converter</td>
<td>5-level converter</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;, 5&lt;sup&gt;th&lt;/sup&gt;, ..., 11&lt;sup&gt;th&lt;/sup&gt;</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;, 5&lt;sup&gt;th&lt;/sup&gt;, ..., 15&lt;sup&gt;th&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>THD%</td>
<td>2.8556</td>
<td>1.2839</td>
</tr>
<tr>
<td></td>
<td>0.7986</td>
<td>0.4697</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Amplitude of Output Harmonics</th>
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<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
</tr>
<tr>
<td>0.6</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
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<tr>
<td>0</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt;</td>
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<tr>
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<td>0.1014</td>
</tr>
<tr>
<td>9&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>0.0029</td>
</tr>
<tr>
<td>11&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>0.0226</td>
</tr>
<tr>
<td>13&lt;sup&gt;th&lt;/sup&gt;</td>
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<tr>
<td>0.0143</td>
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<tr>
<td>15&lt;sup&gt;th&lt;/sup&gt;</td>
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<tr>
<td>0.0128</td>
</tr>
<tr>
<td>21&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>0.0029</td>
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6.4. Applications

Multilevel converter is widely applied in industrial applications because of its attractive abilities such as generating signal close to sinusoidal waveform in high and low frequencies with low harmonic distortion and low switching stress. Hence, this type of converter suits for those high power and high voltage applications. One of the issues in multilevel converters is controlling DC link voltages. There are a number of techniques to control and adjust DC link voltages of multilevel converters with equal DC link voltages. A multilevel converter with unequal DC link voltages is a new configuration which has less choice of freedom to control capacitor voltages in the DC link, only based on switching states.

One of the industrial applications of multilevel converters can be for Uninterruptable Power Supplies (UPS) in which continuous sinusoidal voltage
waveform with high quality must be generated [11]. Environmental problems push industry to generate electrical power by using renewable energy systems. These renewable energy sources can be wind turbine, photovoltaic (PV), fuel cells, etc. The abilities of multilevel converters make them suitable for renewable energy applications in medium-high voltage and low frequency ranges [12]. The advantage of the proposed modulation technique for multilevel converters with renewable energy sources is that the each DC voltage level can be regulated through each separated renewable energy source.

As an example, a block diagram of a cascade multilevel with several PV systems is shown in Fig. 6.8. Thus, for renewable energy systems where several energy sources such as photovoltaic systems or fuel cells are connected through DC-DC converters, the capacitor voltage balancing is not an issue any more. For those applications where a renewable energy source such as PV or fuel cell is a voltage source for a cascade converter, the proposed modulation can be used to generate unequal voltage levels because of their flexibility to generate various DC link voltages through a DC/DC converter [13].

Among DC/DC converters, multi-output converters have drawn great interest in generating several output levels without different power sources [14]. A three-Output Voltage Sharing Boost converter is introduced in [15] which has some benefits such as regulating DC link voltages asymmetrically regardless of input
voltage distortion. Also, this type of converter is able to boost and regulate the input voltage asymmetrically to adjust desired output levels. The circuit diagram of this converter is depicted in Fig. 6.9.

![Circuit Diagram of Boost-3OVS Topology](image)

Fig. 6.9. Boost-3OVS topology connected to four-level inverters.

To remedy the problem of capacitor voltage imbalance in diode-clamped configuration, this type of converter is useful. The main aim of using this converter is improving the performance and utilizing high modulation index regardless input variation and high power factor loads.

### 6.5. Conclusion

Multilevel converters have the potential to play a major role in high and medium voltage applications in which a signal close to a sinusoidal waveform with low harmonic distortion should be generated. Several modulation techniques are introduced to control and eliminate the output harmonics of multilevel converters. Conventional harmonic elimination method is used for those multilevel converters in which the output voltage steps are equal so the range of modulation variables is limited to the number of the switching angles. To improve output voltage quality and reduce more low order harmonics; a new modulation technique is introduced in this paper. In this modulation method, the output voltage levels are defined as new variables which double the number of variables for harmonic elimination method. Different simulations are carried out in this paper to verify the effectiveness of this method compared to the conventional one.
References


Statement of Contribution of Co-Authors

The authors listed below have certified that:
1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to those criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit, and
5. they agree to the use of the publication in the student’s thesis and its publication on the Australasian Research Online database consistent with any limitations set by publisher requirements.

In the case of this chapter:


<table>
<thead>
<tr>
<th>Contributor</th>
<th>Statement of contribution*</th>
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</thead>
<tbody>
<tr>
<td>Negereh Ghasemi</td>
<td>Proposed the initial design and conducted simulation studies and data analysis, designed the control strategy, implementation hardware set-up and conducted experimental verification and wrote the manuscript.</td>
</tr>
<tr>
<td>16 Nov 2012</td>
<td></td>
</tr>
<tr>
<td>Firuz Zare</td>
<td>Proposed the initial design and supervised the validity studies including: conducting the simulations and experimental studies and writing the manuscript.</td>
</tr>
<tr>
<td>Arindam Ghosh</td>
<td>Aided planning the control strategies and writing the paper.</td>
</tr>
<tr>
<td>Christian Langton</td>
<td>Provided us with general information about ultrasound system specifications and its applications.</td>
</tr>
</tbody>
</table>

Principal Supervisor Confirmation
I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

A/Prof. Firuz Zare 16 Nov 2012

Name Signature Date
CHAPTER 7

A HIGH FREQUENCY CURRENT SOURCE CONVERTER WITH ADJUSTABLE MAGNITUDE TO DRIVE HIGH POWER PIEZOELECTRIC TRANSUCERS

Negareh Ghasemi, Firuz Zare, Arindam Ghosh, Christian Langton

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Abstract — A general electrical model of a piezoelectric transducer for ultrasound applications consists of a capacitor in parallel with RLC legs. A high power voltage source converter can however generate significant voltage stress across the transducer that creates high leakage currents. One solution is to reduce the voltage stress across the piezoelectric transducer by using an LC filter, however a main drawback is changing the piezoelectric resonant frequency and its characteristics. Thereby it reduces the efficiency of energy conversion through the transducer. This paper proposes that a high frequency current source converter is a suitable topology to drive high power piezoelectric transducers efficiently.

Keywords — High power converter, piezoelectric transducer, current source converter, modelling, filter

7.1. Introduction

Voltage source two-level converters provide an opportunity to generate a desired voltage waveform across the load based on different modulation techniques [1]. This type of converter plays a great role to adjust the output voltage especially for those applications in which the load has inductive characteristic. However, current source two-level converters could be an attractive choice for those applications in which their load has a capacitive characteristic such as piezoelectric transducer. Two-level voltage source converter in presence of a capacitive load can generate current spikes across the load because of higher voltage stress compared to a current source converter. High power piezoelectric transducers converter electrical energy to mechanical energy and their performances and efficiency depend on their excitation signal. It is therefore necessary to generate a desired signal close to sinusoidal one with lower harmonic distortion. To generate an appropriate excitation signal, considering the electrical characteristic of the transducer is undeniable. In this regard, various literatures have focused on this area. The results of these literatures show that the transducers have almost capacitive characteristic in different frequency ranges. Fig. 7.1(a) shows the amplitude of impedance of 78 kHz transducer. Based on the characteristic of the transducer different electrical models are introduced such as Van
Dyke model which is illustrated in Fig. 7.1(b) [2-4].

![Graph showing impedance vs frequency](image)

As is shown in Fig. 7.1(b), the electrical model of the 78 kHz transducer has a capacitor C in parallel with several RLC legs. Thus, a current source converter could be a suitable choice to generate a desired signal to drive the transducer.

### 7.2. Current Source Topology and Control System

Due to the capacitive characteristic of piezoelectric transducers, a voltage source converter is not a suitable topology to drive high power ultrasound transducers due to
the fact that high voltage pulses with significant $dv/dt$ can create significant leakage current through the transducer and decrease the quality and efficiency of the system. One of the solutions to reduce the voltage stress across the transducer is to use an LC filter but a main drawback is that the filter will change the characteristic and the resonant frequency of the piezoelectric transducer. Several tests and simulations have been carried out to show the effects of the LC filter on the output voltage of a high power transducer when it is excited by a voltage source converter. A block diagram and an experimental setup of a high power ultrasound excitation using a signal generator and a filter are depicted in Fig. 7.2. The simulation and test results are shown in Fig. 7.3 and Fig. 7.4, respectively. As shown in Fig. 7.3, the simulation results illustrate that the resonant frequency of a transducer is changed by using a filter. Also, Fig. 7.4 shows the voltage across the resistor ($R_1$) (at the resonant frequency of the transducer without the filter) is decreased after using the filter in the system. The resistor $R_1$ (in the RLC legs shown Fig. 7.1(b)) corresponds to the energy conversion from electrical to mechanical. In order to validate that, the voltage across the second transducer is measured in a practical case and the results show that at same frequency the output voltage is decreased when the LC filter is placed between the transducer and the voltage source. In fact the resonant frequency of the transducer is changed and hence the energy conversion from electrical to mechanical is decreased.
Fig. 7.2. Exciting a high power ultrasound transducer by a voltage source and a filter (a) block diagram (b) prototype of test.
Fig. 7.3. Simulation results (a) without filter (b) with filter.
A suitable power converter to drive high power ultrasound transducers is a current source converter where chopping DC current based on a modulation strategy can charge and discharge a capacitor and control its voltage waveform to follow a reference signal with low Total Harmonic Distortion (THD) [5-6]. In this paper, the proposed topology is based on a buck converter (a current source) which is connected to a single phase current source converter. The current source is controlled based on hysteresis current control as shown in Fig. 7.5(a). The current source converter consists of two legs and it is controlled based on a hysteresis voltage control. The switching states of the converter depend on the modulation method: bipolar or unipolar (see Fig. 7.5(b) and Fig. 7.5(c)).

In order to provide a current loop for the buck converter and also to reduce the number of power switches, the two switches in each leg of the converter are turned on in the unipolar modulation in which the inductor current is circulated through them. For instance, when the output voltage should be increased, the switches $S_1$ and $S_4$ are turned on and $S_2$ and $S_3$ are turned on to decrease the output voltage. In addition, either $S_1$ and $S_3$ or $S_4$ and $S_2$ are turned on to keep constant the output voltage (zero current from the current source). While in the bipolar modulation, the pair switches $S_1$ & $S_4$ and $S_2$ & $S_3$ are turned on and off simultaneously to increase or decrease the output voltage, respectively. In the unipolar modulation, we need to
define two hysteresis bands in order to change the output current from positive current to zero or from zero to negative current.

![Diagram of a current source converter](image)

Fig. 7.5. A current source converter (a) circuit diagram and hysteresis voltage control block diagrams (b) bipolar (c) unipolar.
7.3. Simulation Results

In order to validate the proposed topology and control algorithm, output current of a buck is controlled at 20 A (+/-0.15A) and the output voltage across a piezoelectric transducer is generated at different frequencies and voltage levels according to the controller. The inductor current is stable and is kept constant at 20A and the output current based on bipolar and unipolar are shown in Fig. 7.6(a) and Fig. 7.6(b), respectively. From these figures, it is obvious that it is possible to control the frequency and amplitude voltage of the converter in desired ranges.

The advantage of this topology is that the system can drive different high power ultrasound transducers as the output voltage is generated across the external capacitor (C_{ext}) regardless of input impedances of different piezoelectric transducers.
Fig. 7.6. Output voltage, output current and inductor current waveforms based on (a) bipolar and (b) unipolar modulations.

7.4. Test Results

To validate the simulation results, a current source converter is utilized to excite a high power ultrasound system. In this test, the input current ($i_L$) of the converter is controlled by a hysteresis control to control the inductor current between 1-1.5 A. The unipolar modulation technique is applied to control the output current. The amplitude of the output voltage measured across an ultrasound transducer is controlled between -40 V to 40 V. A digital signal controller (TMS320F28335) is applied to control the switching pattern signals. In this test, the switching frequency is adjusted to 41 kHz which is one of the resonance frequencies of the ultrasound transducer.

The experimental setup and results are depicted in Fig. 7.7 and Fig. 7.8, respectively.
Fig. 7.7. Experimental setup of current source converter.
7.5. Conclusions

In this paper a buck converter is used as an adjustable current source for a current source converter to drive high power piezoelectric transducers. As a control system two hysteresis controllers can be used. These controllers can operate independently or in sliding mode control. The first hysteresis current controller is to adjust the buck output current and the second hysteresis voltage controller is to generate high quality output voltage with adjustable magnitude and frequency. The simulation results show that the proposed topology and control system can drive high power ultrasound transducers with better performance and energy conversion through the high power transducers. The experimental results illustrate that the input and the output current as well as the output voltage are controlled in desired ranges.

References


Chapter 8

CONCLUSIONS AND FUTURE RESEARCH
8.1. Conclusions

The capability of the ultrasound systems in energy conversion is a growing demand for industrial and biomedical applications. A basic ultrasound system consists of two piezoelectric transducers and a power supply. Depending on the power range of the system, the applied ultrasound transducers can be low or high power. A high power ultrasound system was investigated in this research. Since the performance of a piezoelectric transducer is extensively related to its excitation, a proper excitation signal with low distortion should be generated because low quality excitation signal results in power dissipation. To generate a desired excitation signal with adjustable magnitude and frequency, several investigations have been undertaken in this research.

8.1.1. Modelling of High Power Ultrasound Transducer

A high power ultrasound transducer is one of the important parts of the high power ultrasound system for energy conversion. It can generate ultrasound waves in response to applied electrical energy or convert applied mechanical energy to electrical energy. As a piezoelectric transducer has several resonance frequencies, its impedance is investigated at different ranges of voltage and frequency in this research. In first investigation, the impedance of a high power ultrasound transducer is measured using a vector network analyser (R&S ZVL3). The main resonance frequency of the transducer is 78 kHz. Since a voltage range of the network analyser is limited (<2 V), another experimental test was carried out in higher voltage range (2 V - 30 V) to measure the ultrasound transducer impedance. In this test, a signal generator and a power amplifier (OPA 549) are used to generate a sinusoidal signal. The impedance of the ultrasound transducer is then measured dividing the voltage across transducer by the current through it.

Based on the basic electrical model of the ultrasound transducer (Van Dyke model), the ultrasound transducer can be modelled as RLC branches in parallel with a capacitor. Each resonance frequency of the ultrasound transducer can be modelled as an additional RLC branch in parallel with the basic electrical model. In this research, it is shown that at each resonance frequency, the output voltage of the system is proportional to the voltage across the resistor of the RLC leg at that particular resonance frequency. It means the resistor of the RLC leg at each
resonance frequency delivers power to the other side of the system. A new method is proposed in this research to detect resonance frequencies of the transducer. In this technique, the resonance frequencies are estimated according to relative minimums of the piezoelectric impedance in frequency domain. Also, as discussed in chapter 2, it is possible to adapt the fundamental frequency of a power supply based on the resonance frequency variation of the ultrasound transducer. The paper exploring this technique is published as a journal paper in *IET Science, Measurement & Technology, Vol. 6, No. 4, 2012*.

According to the test results, it is concluded that the ultrasound transducer is nonlinear because its impedance varied with the amplitude changes of the input voltage signal. For more investigation, superposition law is used to prove the nonlinearity of the ultrasound transducer. Based on this principle, the ultrasound transducer is excited, at first by two separate input sinusoidal signals and then by two simultaneous sinusoidal signals. A power amplifier is used to add two simultaneous input signals and from the test results, the ultrasound transducer is found to be nonlinear.

Since the high power ultrasound transducer can be used in different ranges of voltage and frequency, a high power excitation signal is required to drive the ultrasound transducer in higher ranges of voltage (> 30 V). In this regard, a two-level converter is implemented to excite the high power ultrasound transducer. To study the characteristics of the transducer at different frequencies, the switching frequency of the converter is adjusted to generate a square wave signal with the fundamental frequency of 39 kHz and 78 kHz. Also, this test is repeated in four stages and in each stage the amplitude of the input signal is changed. The nonlinearity of the ultrasound transducer was shown in the test results where its impedance is changed at different stages of this test. The test results are submitted as a journal paper for *IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control*.

### 8.1.2. Modelling of High Power Ultrasound System

As it is discussed in previous chapters of this thesis, a high power ultrasound system studied in this research consisted of two high power ultrasound transducers. One of them is used as a transmitter and converted the electrical energy to mechanical energy; another one plays a role of a receiver and converted mechanical energy to electrical energy. Two types of media are used to couple these transducers,
water and oil. The behaviour of the ultrasound system is studied in terms of voltage ratio of the system. The input voltage is measured across the transmitter and the output voltage is measured across the receiver. Based on the density of the medium, water and oil, the voltage ratio of the system is different. The amplitude of the measured output voltage decreases when oil is used as a coupling material. As the oil density is higher than water, intensity of the generated ultrasound waves attenuates so the measured voltage across the receiver is reduced.

To excite the transmitter, two types of excitation signals are generated, sinusoidal signal and square wave signal. To investigate the behaviour of the system, two individual sinusoidal signals with different fundamental frequencies (39 kHz and 61 kHz) and amplitudes (15 V and 30 V) are generated using a signal generator and a power amplifier (OPA 549). Based on the test results, the responses of the system are not compatible with the amplitude variation of the input signals even at same fundamental frequencies. For instance, the responses of the system to 15 V input signal and 30 V input signal at 39 kHz are almost same while at 61 kHz they are different. If it is a linear system, the output variations of the system should be same as the input changes otherwise this system is nonlinear. Considering this concept and based on the test results, it is concluded that the ultrasound system is nonlinear. For more clarification, superposition law is applied. According to this law, the sum of responses of a linear system to the individual inputs should be equal to the response of the system to the sum of the inputs. Considering this principle, the ultrasound system is nonlinear where the experimental results are not same.

In the next step, a single phase two-level converter is applied to drive the transmitter. The generated signal has a fundamental content and some components in its sidebands in the frequency domain. The effect of these sidebands (low quality signals) on the performance of the ultrasound system is investigated. To achieve this goal, the fundamental frequency of the input signal is adjusted to 39 kHz so its first sideband is at 78 kHz. Because of the first sideband at 78 kHz, some portion of the output power is delivered at this frequency while it is targeted to deliver whole power at 39 kHz. In some applications like biomedical ones, power delivery at undesired frequency can affect the lateral tissue when an ultrasound system is applied to treat an ill tissue.

The response of the system to input voltage variations is studied where the DC link voltage is adjusted to 50 V, 100 V, 200 V and 300 V. All input and output
voltage signals are normalized for better comparison. All normalized input voltage signals matches with each other while the output voltage signals mismatches due to nonlinearity of the system. Also, the increment in output voltages is not compatible with the input voltages increment. For example, the response of the system to 300 V input signal is much lower than its response to the 100 V. A comprehensive behaviour analysis of the high power ultrasound system is published in proceeding of ICIEA conference, Singapore, 2012.

8.1.3. High Power Excitation Signal

Multilevel converters are usually used to generate a high power signal. Generation of a high power and high quality signal is required for some applications such as a high power ultrasound system. Several modulation methods and control techniques are introduced to control the output signal of the converter.

One of the modulation techniques is conventional harmonic elimination method in which the output voltage levels are equal and switching angles are found out to eliminate low order harmonics. The number of eliminated harmonic by this technique is restricted by the number of the switching angles. Therefore, to eliminate more harmonics, more output voltage levels are required.

A new harmonic elimination method is proposed in this research in which the non equal output voltage levels along with the switching angles are calculated to eliminate more low order harmonics. This technique is applied for a four-level and a five-level converter. The simulation and experimental results proves the capability of this technique in eliminating more harmonics compared to the conventional harmonic elimination method. In case of four-level converter, five harmonics are eliminated using a new harmonic elimination method while just two harmonics are eliminated when a conventional technique is applied. Compared to conventional technique, five more harmonics are eliminated when the new technique is applied to a five-level converter. Outlines of this part of the research are accepted for publication (in press) in IET transaction on Power Electronic 2012.

A capacitive load in a voltage source converter suffers from generated current spikes due to higher voltage stress across it. The LC filters are used in some applications as a remedy of this problem. But in some applications like a sensory system in which an ultrasound transducer is utilized, the LC filter can change the behaviour of the transducer and affect the performance of the system.
As the ultrasound transducer has capacitive characteristics in almost all frequencies, generating a high power excitation signal using a current source converter can be a valuable option. To control the output voltage signal of this type of converter, DC current is chopped based on a modulation strategy. Hereof, a buck DC/DC converter is implemented and connected to a current source converter to drive the ultrasound transducer. The test results show the output current and voltage are controlled in desired range. Two hysteresis controllers are applied. A hysteresis current controller is used to adjust the buck output current and another hysteresis voltage control is utilized to generate a high quality output voltage with adjustable frequency and amplitude. Also, the unipolar modulation technique is applied to control the output current. The switching signals are controlled by a digital signal controller, TMS320F28335. The simulation and test results are published in proceeding of EPE conference, Serbia, 2012.

8.2. Future Research

This research study was focused on improving ultrasound excitation systems using a flexible power supply with adjustable voltage and frequency to drive high power piezoelectric transducers. In this regard, several excitation systems have been utilized to generate desired signals (low voltage and high voltage). Due to the existing limitations in this research such as frequency and voltage limitation of switching components, some suggestions for future research work are discussed below.

8.2.1. Modelling of High Power Ultrasound System

- The behaviour of the high power ultrasound system is investigated in terms of voltage ratio and it is concluded that it is a nonlinear system. Some investigations are required to study the effects of media, size and dimensions of the container and type of the piezoelectric transducer on the system nonlinearity.

8.2.2. High Power Ultrasound Transducer Excitation

- To drive a high power ultrasound system, a high power excitation signal is required otherwise low power signal cannot excite the high power ultrasound transducer properly and the efficiency of the system will be
decreased. In such a system the lifespan of the high power ultrasound transducer may be sacrificed by a high power excitation.

It can be targeted as a future research, to investigate and compare the efficiency of below systems:

- a system includes one transducer excited by a high power signal \( P \)
- a system includes \( N \)- transducer excited with a low power input signal \( P/N \)

From a quality point of view, increasing the number of output voltage levels decreases the number of the output harmonics. In such a case, the number of components, complexity and cost of the converter will be increased. Based on the proposed new modulation technique it is possible to improve the output quality with fewer components. To generate the desired DC voltage levels calculated from the new technique, DC/DC converter are used. The multi-output DC/DC converter is used in this research to generate four and five DC voltage levels. To achieve more output voltage levels, a multi output DC/DC converter for a multilevel converter should be investigated more to improve the quality of output signal and solve the problem of DC link capacitor voltage balancing.

Due to capacitive characteristics of the ultrasound transducer, the current source converter has a better effect on the performance of the ultrasound transducer compared to voltage source converter. The frequency of the output signal is limited to the maximum frequency of switching components. Therefore, in some applications like ultrasound systems in which high switching frequency is required, fast switching components should be applied. Development of a current source converter with close loop control and modelling of a current source converter can be targeted as future researches to generate a proper signal for the high power ultrasound system excitation.