SS 31:

Generative AI Models and Their Applications in Communication, IoT, Biomedical Engineering, and Cybersecurity

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Practical Demonstrations and Technological Insights for Ultrasound-Based Energy Harvesting for Biomedical Applications

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Abstract: This paper explores ultrasound-based energy harvesting using piezoelectric transducers, providing both theoretical insights and practical demonstrations. The primary objective is to assess the feasibility and efficiency of this technology for powering biomedical and other long-term, stable power-requiring devices. We investigate various system designs for ultrasound-based energy harvesting through both simulations and practical implementations. A piezoelectric transducer is utilized to convert ultrasound waves into electrical energy. Comparative analyses between simulated outputs and practical results are conducted to evaluate performance. Simulation results demonstrate the potential of different ultrasound-based energy harvesting designs, indicating varying degrees of efficiency and output. Practical demonstrations confirm these findings, with the piezoelectric transducer successfully generating a measurable output voltage. The comparison between virtual and practical outputs provides deeper insights into system performance and reliability.

Keywords: *Ultrasound-Based Energy Harvesting, Biomedical Applications, Piezoelectric Transducers, Energy Efficiency, Medical Devices, Simulation and Practical Implementation, Power Generation, Structural Health Monitoring*

1. INTRODUCTION

Energy harvesting involves converting ambient energy (mechanical vibrations, heat, or light) into a utilizable electrical energy. Several materials available in the market can generate a usable amount of energy. Still, in this paper, we are taking piezoelectric material as our systems' primary energy source. Piezoelectric materials play a crucial role in this field. Ultrasound-based energy harvesting utilizing piezoelectric materials represents an innovative approach to generating electrical power from ambient mechanical vibrations from ultrasound waves. Piezoelectric materials own a distinctive property: whenever they are subjected to mechanical stress or vibration, they give rise to electrical charges, which are converted into voltage. This principle builds the foundation of ultrasound-based energy harvesting systems, where piezoelectric transducers convert ultrasound waves' mechanical energy into utilizable electrical energy.

This ultrasound-based energy harvesting system strategy of using ultrasound waves to generate electrical energy is much more helpful than conventional wireless energy harvesting systems characterized by electromagnetic coupling. These ultrasound-based energy harvesting systems provide several advantages over conventional wireless energy systems. There are myriad benefits to ultrasonic energy harvesting technology, which, in turn, presents a very promising proposition for powering numerous devices. One significant benefit is that it is incredibly cost-effective. For applications such as IoT-based wireless sensors, ultrasonic systems' simple and cheap components are much preferable to other energy harvesting methods.

Furthermore, the efficiency of these systems is relatively high in converting ultrasonic energy to electrical power. That means these systems can be optimized for specific frequencies and conditions, providing long-term stable performance without environmental damage. Another major asset of ultrasonic energy harvesting is its scalability, which makes this solution easily deployable over various fields and applications.

It was another critical factor - the strength of the tech. Ultrasonic transducers are robust enough to be placed in a remote or harsh location while providing good results. They offer low-maintenance systems that provide stable power with hardly any downtime. Moreover, ultrasonic signals are more robust to environmental noise than other energy harvesting techniques, allowing for a stable power supply under noisy conditions. The low-cost, highly efficient devices are appealing because they can be deployed as scalable and maintenance-free ultrasonic energy harvesters. Additionally, its ability to function in harsh and harmful circumstances makes it an excellent choice for various applications.

Several key components are required to be involved in the ultrasound-based system. Many of those are listed here as:

- **Piezoelectric Transducers:** They are the primary energy source in ultrasound-based energy harvesting systems. These piezoelectric transducers are made from lead zirconate titanate (PZT) or polyvinylidene fluoride (PVDF), which exhibit piezoelectric properties. When subjected to some stress or pressure, it generates voltages that can be used.
- **Ultrasound Source:** Ultrasound Waves are generated using a dedicated source, which could be a piezoelectric transducer, a specifically designed ultrasound emitter, or an ambient source like machinery vibrations. These waves' frequency and intensity influence the productivity of ultrasound-based energy harvesting systems.
- **Energy Conversion Circuitry:** These are other essential components in ultrasound-based energy harvesting systems. There are typical requirements for rectifier circuitry for conversion of AC to DC voltage generated by piezoelectric transducers and storage components like batteries or capacitors to store the harvested energy for further use or later use.
- **Optimization and Tuning:** Optimization and tuning to match the system resonant frequency with the frequency of ultrasound waves. With this resonance, the efficiency of ultrasound-based energy harvesting systems increases effectively.

Application Integration: Ultrasound-based energy harvesting systems find application in various fields where a natural requirement of energy source is required with the least harm to nature. It can be implemented in biomedical operations, wireless sensor networks, and IoT devices.

2. CONCEPT OF PIEZOELECTRICITY

Piezoelectricity is quite a fascinating phenomenon where a particular material generates electrical charges in reciprocation to applied mechanical stress, vibrations, or pressure. "piezoelectricity" originates from the Greek word "piezein," which means to squeeze or press. This concept was first discovered by Pierre Curie and his brother Jacques Curie in the late 19th century. The fundamental principle behind piezoelectricity lies in the asymmetry of the crystal structure of certain materials, particularly crystals like quartz and Rochelle salt, and certain ceramics such as lead zirconate titanate (PZT). These materials have a non-centrosymmetric crystal structure, meaning their positive and negative charges are not symmetrically distributed within the crystal lattice. When an external mechanical force is applied to such a material, it distorts the crystal lattice, displacing positive and negative charges within the material. This displacement creates an electric dipole moment, leading to the generation of an electric field and, consequently, an electric voltage across the material.

Figure 1 depicts the mechanism of energy harvesting using a piezoelectric transducer made of lead zirconate titanate (PZT). When the PZT material is compressed, it generates electricity, which is captured by metal plates on either side. The generated voltage is a result of this compression, demonstrating the piezoelectric effect.

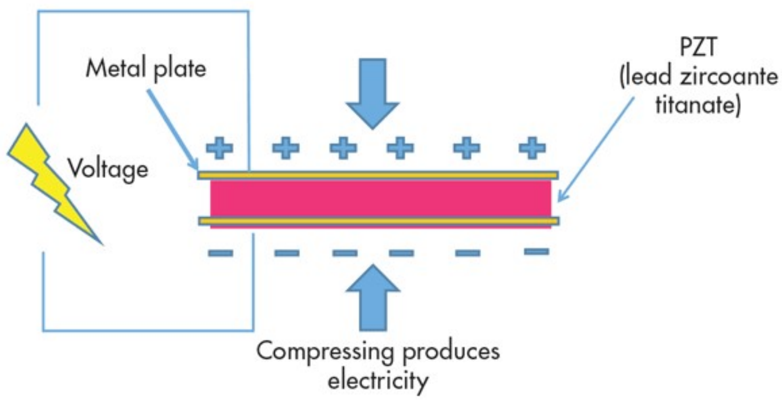


Figure 1. Concept of piezoelectricity

2.1 Requirements to use piezoelectric in ultrasound-based energy harvesting systems

First, we must understand what happens with our piezoelectric transducer or material. As soon as exterior force is applied to the material or transducer, positive and negative charged surfaces are created, pronounced as polar surfaces. After that, a piezoelectric potential is created, which is used to drive electrons in an external circuit, converting the provided mechanical energy (such as vibration and stress) into electricity. During the operation of the piezoelectric device or material, polar surfaces that have been created need to be maintained for continuous generation of electricity. For this purpose, Ultrasonic waves are widely used to induce or create stress on the piezoelectric material. Thus, the output resultant voltage generated by the piezoelectric transducer results in an AC voltage. The ultrasonic wave frequency is adjusted equal to the resonant frequency of the transducer, which in turn varies inversely according to its size. As specified in the above line, the voltage generated by the piezoelectric transducer is an AC voltage. Therefore, the system must efficiently convert AC to DC voltage so that the electronics system can work. Also, at the same instant, due to misalignment between the exterior generator and interior transducer or material, the amplitude of the output voltage generated will have some unpredictable variations. As a result, it is not best to feed them to electronic circuits. Therefore, the ultrasound-based energy system should consist of an AC-to-DC converter and a power converter, whose regulation can be done, i.e., the output voltage can be controlled to provide a fixed amount of DC voltage. Also, the output voltage supplied after conversion or regulation is much smaller, and hence, a boost converter is necessary to provide a much higher voltage to our systems. Several DC-to-DC boost converters are present in the market, like buck-boost converters, which are much more efficient and compact. Also, several designs can be implemented and used.

The remainder of the article is presented in the following order. The 2nd section gives information about the operating principles and topology of the conventional circuits used to convert or rectify AC signals produced by the piezoelectric device and their simulation/output with the help of a software program. Section 3 provides insight into the practical demonstration or experimental setup of ultrasound-based energy harvesting circuits and their production. Section 4 summarizes the conclusions.

3. RECTIFIER IMPLEMENTTION

This low-voltage, low-power voltage rectifier operates on a bulk-driven (BD) winner-take-all (WTA) circuit. It functions as both a half-wave and full-wave rectifier, employing a maximum selector approach. Despite its deficient power consumption, this technique operates effectively at frequencies in the range of several tens of kilohertz.

Figure 2 illustrate two different configurations of a BD-WTA (Bias Differential Winner-Takes-All) circuit. In the first configuration (left), Vin1V_{in1}Vin1 is a biased sinusoidal signal while Vin2V_{in2}Vin2 is a constant bias voltage, with VoutV_{out}Vout reflecting the dominant input. In the second configuration (right), an inverter is added to the Vin2V_{in2}Vin2 path, providing an inverted input to the BD-WTA circuit. Both setups aim to determine the output voltage VoutV_{out}Vout based on the input signals, demonstrating how the BD-WTA circuit handles varying input conditions.

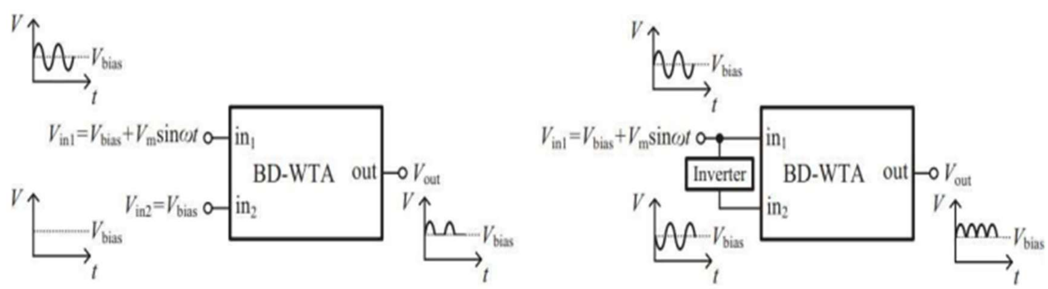
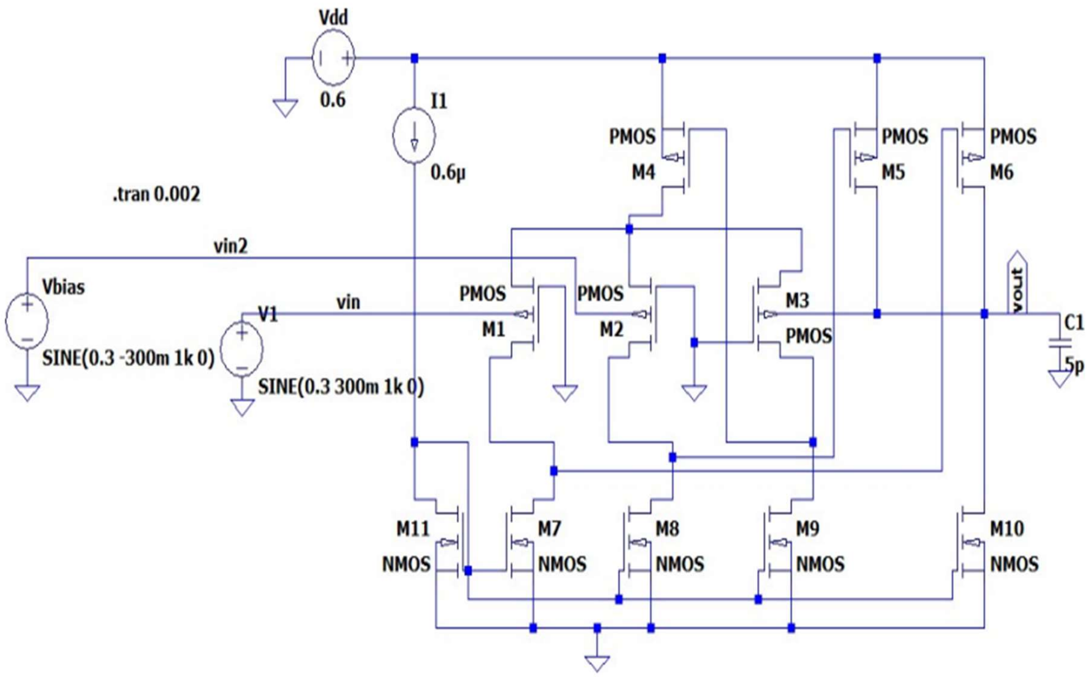


Figure 2. BD-WTA (a) half-wave (b) and full-wave rectifier



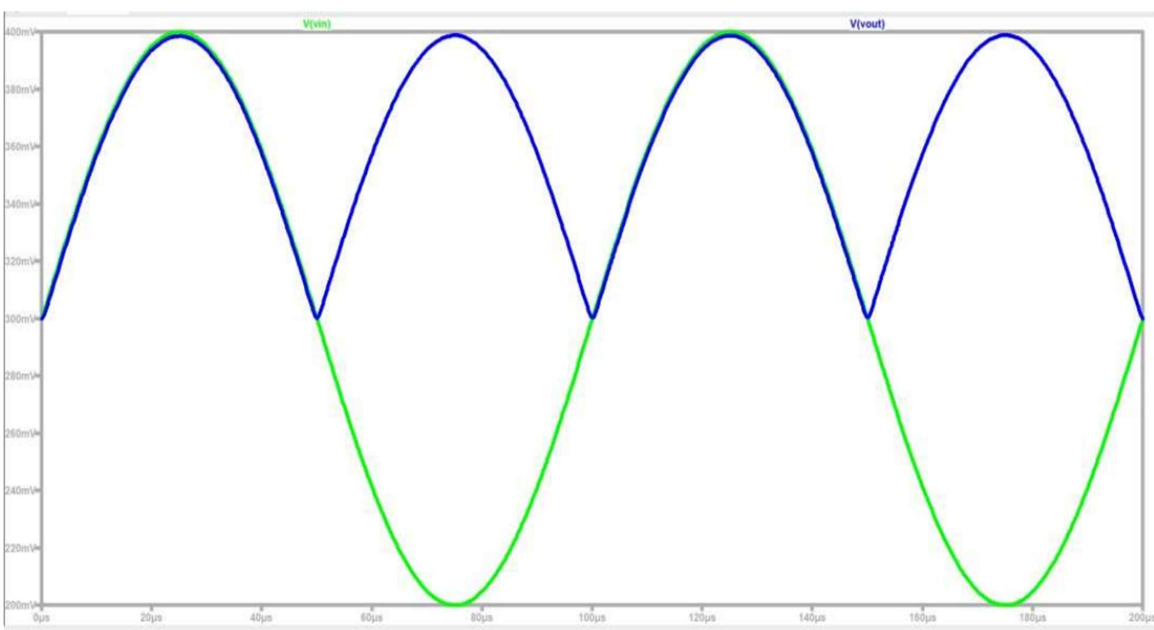


Figure 4. Simulation Results

Figure 3 present two setups of a BD-WTA (Bias Differential Winner-Takes-All) circuit. In the first setup, the circuit receives Vin1=Vbias+Vmsin (ωt)V_{in1} = V_{bias} + V_m \sin(\omega t)Vin1=Vbias+Vmsin(ωt) and Vin2=VbiasV_{in2} = V_{bias}Vin2=Vbias, resulting in an output VoutV_{out}Vout determined by the dominant input signal. In the second setup, an inverter is introduced between Vin1V_{in1}Vin1 and the BD-WTA circuit, altering the phase of the input signal before it reaches the circuit. This configuration also receives Vin2=VbiasV_{in2} = V_{bias}Vin2=Vbias, and the output VoutV_{out}Vout again reflects the dominant signal. These setups illustrate the circuit's response to different input conditions.

Figure 4 shows three sinusoidal waves labeled U(in1), V(in2), and V(out). The waves are offset from each other by approximately 120 degrees, forming a three-phase pattern.

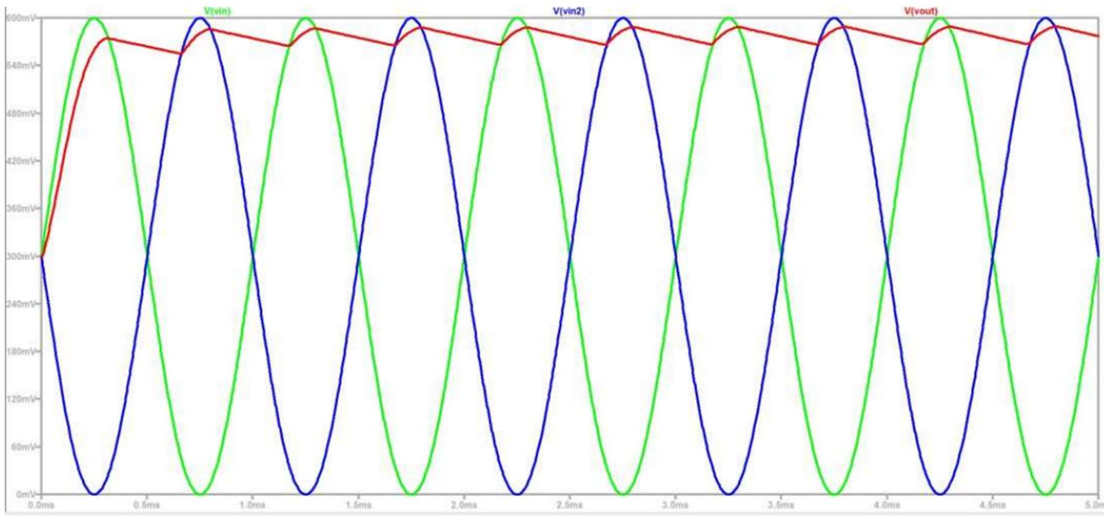


Figure 5 Simulation result with higher capacitance

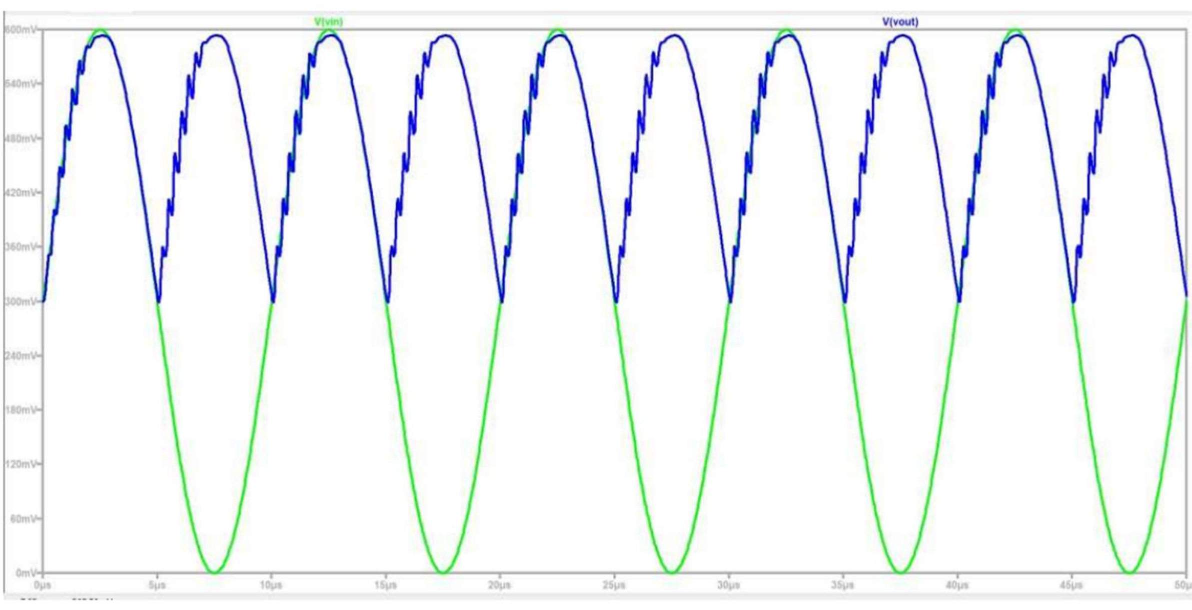


Figure 6 Simulation result with 10 KHz Frequency

Figure 5 shows two overlapping waveforms: V(out) and V(in). V(out) is a smooth sine wave in blue. V(in) is a stepped approximation of a sine wave in green. The waveforms are in phase and have the same frequency and amplitude. And , figure 6 depicts two overlapping waveforms: V(out) in blue and V(in) in green. V(out) is a distorted sine wave with high-frequency oscillations superimposed. V(in) is a smooth sine wave with lower frequency than V(out)'s main waveform. The two signals share the same fundamental frequency and phase.

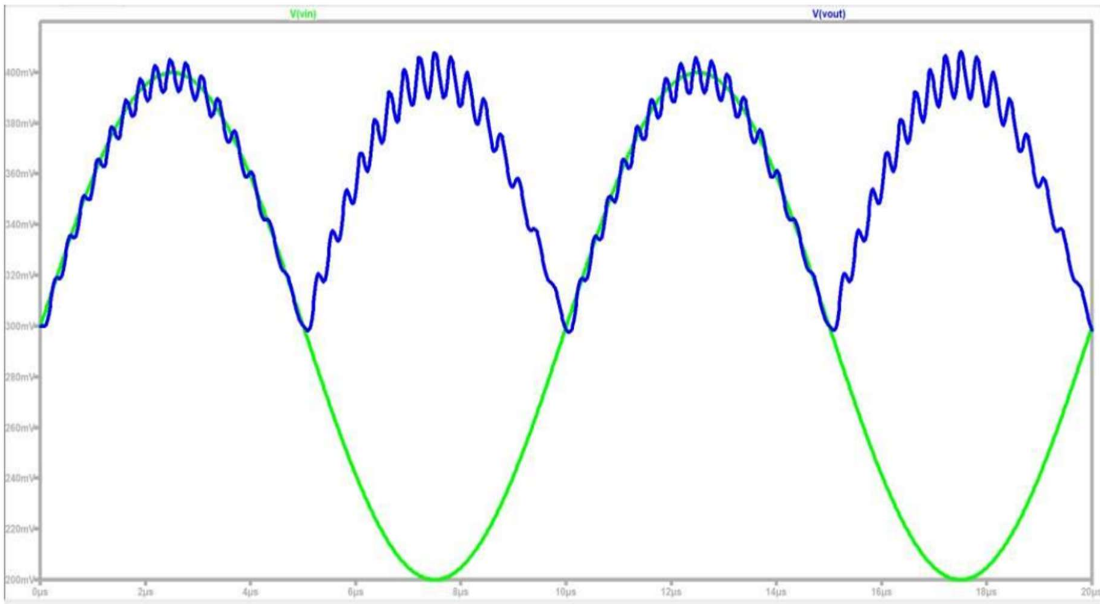


Figure 7 Simulated output voltage (green) and input voltage (blue) waveforms at 100 kHz

In Figure 5, the value of the capacitor is increased from 5pF in Figure 4 to 20nF in Figure 5. This increase in capacitance leads to a higher charging constant, which results in a more stable DC signal. With a larger capacitor, the charging and discharging cycles occur slower, providing smoother and more consistent DC output. This enhanced stability benefits applications requiring a reliable and steady power supply. As it is evident from Figures 4, 6, and 7, the proposed circuit works well in the range of a few kilohertz, and performance starts deteriorating with increasing frequency.

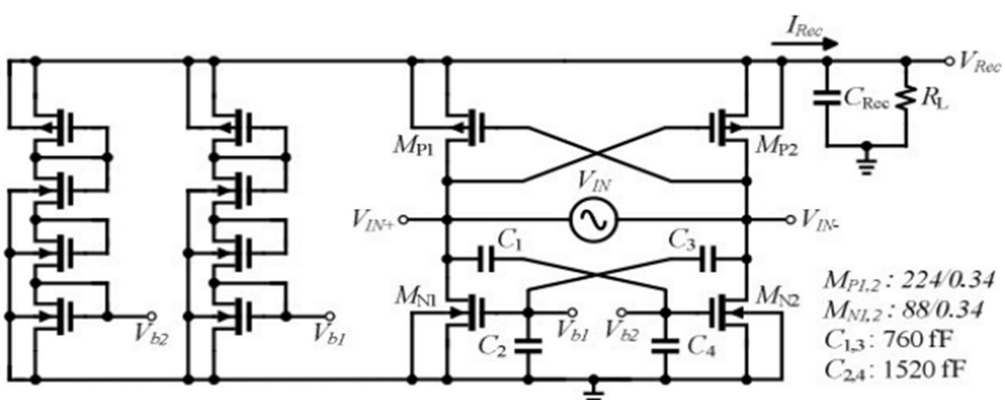


Figure 8 This circuit diagram illustrates the rectifier design, including key components like transistors (MP1, MP2, MN1, MN2), capacitors (C1, C2, C3, C4, C13, C24), and resistors

3.1 Passive Magnetic Rectifier / Passive CMOS Rectifier

The conventional cross-coupled architecture applies the whole input voltage between the gate and the source of all transistors. As a result, both NMOS and PMOS transistors often switch on or off at roughly the same time, forming a leakage channel from the load to the source. To reduce leakage currents, the rectifier should only switch on when the input voltage exceeds the load voltage. In the suggested design, the rectifier's turn-on/off voltage levels are regulated by delivering a separate bias voltage to the NMOS transistor. This method effectively reduces reverse leakage currents while increasing the cross-coupled rectifier's Power Conversion Efficiency (PCE).

Figure 8 shows a complex transistor-based configuration. Central section features cross-coupled transistors (Mp1, Mp2, Mn1, Mn2) with capacitors. Left side has two columns of stacked transistors; right side includes IRec, CRec, and RL. Figure 9 shows a complex MOSFET-based configuration. Left side has two columns of stacked PMOS and NMOS transistors (M11-M4, M9-M8). Center and right feature additional MOSFETs, capacitors, voltage sources, and output stage with C5 and R1.

Figure 10 show two configurations of a BD-WTA (Bias Differential Winner-Takes-All) circuit. The first setup processes a biased sinusoidal input (Vin1V_{in1}Vin1) and a constant bias (Vin2V_{in2}Vin2), outputting the dominant signal. The second setup includes an inverter for Vin1V_{in1}Vin1, altering its phase before input to the BD-WTA circuit, affecting the resulting VoutV_{out}Vout.

Figure 11 illustrate two BD-WTA (Bias Differential Winner-Takes-All) circuit configurations. The first setup processes a biased sinusoidal input and a constant bias, outputting the dominant signal. The second setup adds an inverter to the sinusoidal input path, affecting the phase and the resulting output.

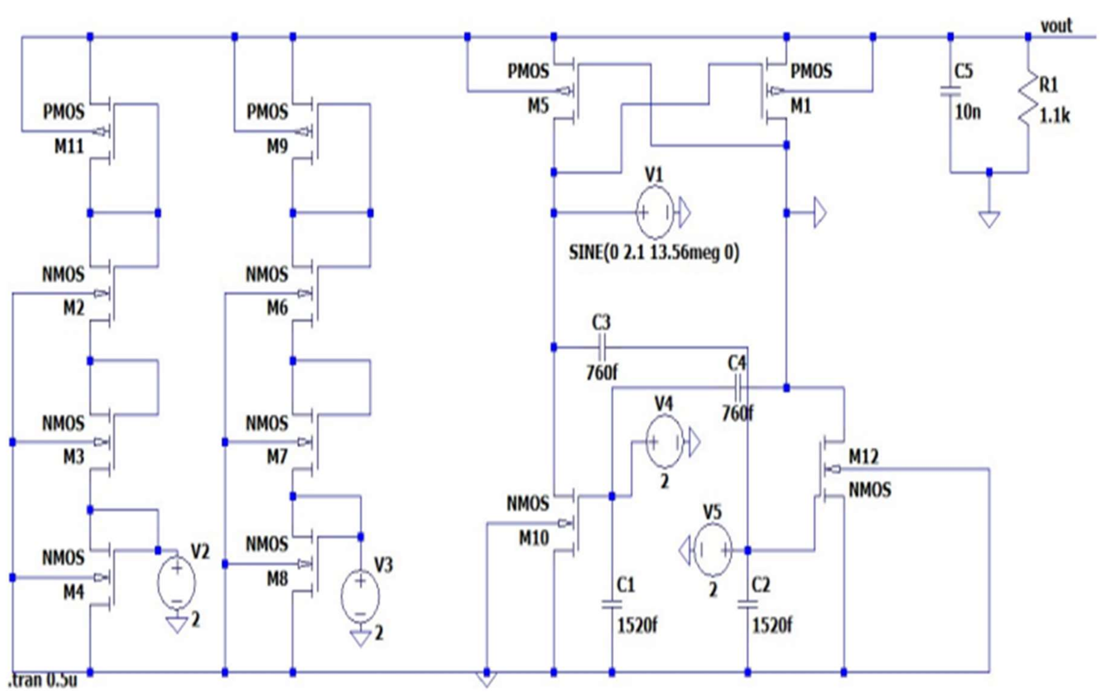


Figure 9 Circuit Diagram of the Proposed Voltage Doubler

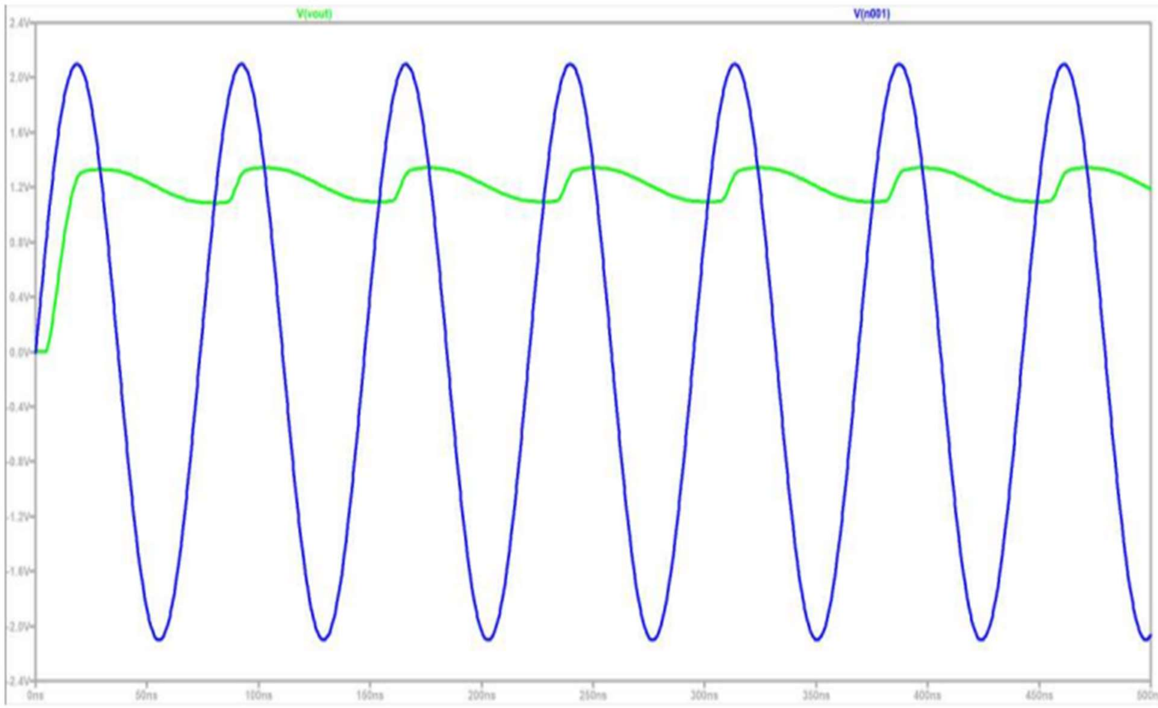


Figure 10 Simulated Input (Blue) and Output (Green) Voltage Waveforms

3.2 Active Piezo rectifier / Full-wave rectifier with Comparator

Here is an illustration of a full-wave active rectifier with a gate cross-coupled NMOS pair and active PMOS diodes that operate as switches [4]. This layout allows for minimal dropout voltage across the transistors, resulting in a high Power Conversion Efficiency (PCE). The active PMOS diode has a fast comparator with a common-gate input stage.

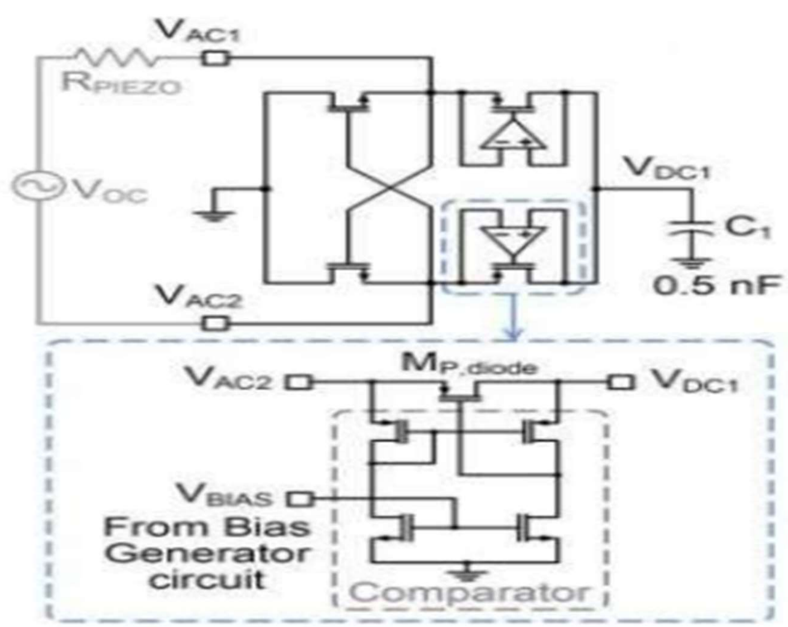


Figure 11 Rectifier design featuring a piezoelectric element (RPIEZO), transistors (Mp.diode), capacitors (C1), and a comparator.

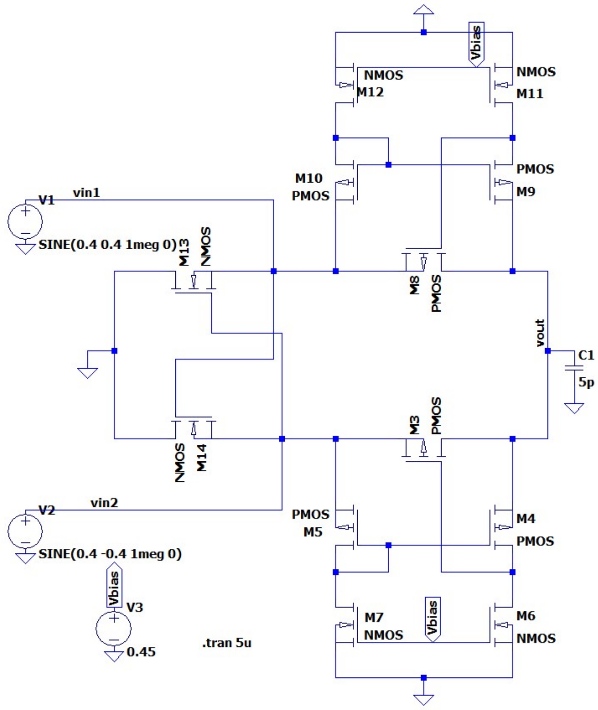


Figure 12 Circuit Diagram

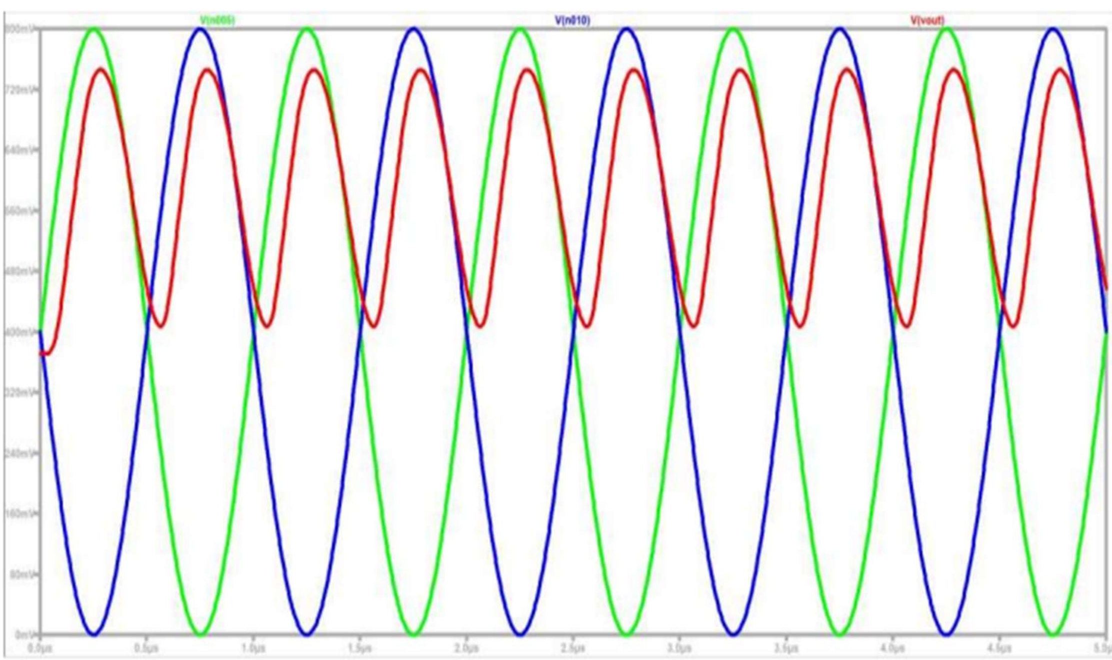


Figure 13 Simulation Result with lower capacitance

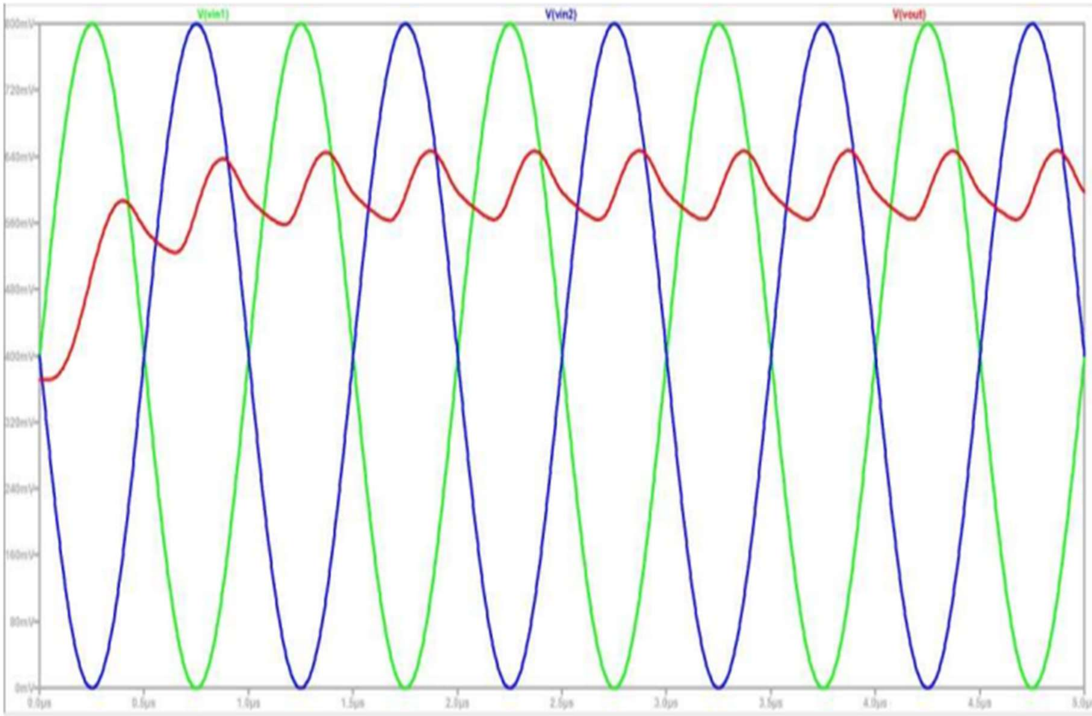


Figure 14 Simulation Result with higher capacitance

Figure 12 display BD-WTA circuit configurations. The first processes a biased sinusoidal input and a constant bias, yielding the dominant signal. The second includes an inverter for the sinusoidal input, altering the phase before output. Figure 13 Voltage and current waveforms of a buck converter, showcasing the relationship between input voltage (Vin), output voltage (Vout), and inductor current (Il). The waveforms demonstrate the switching behavior of the converter and the associated voltage and current ripple. Figure 14 Voltage waveforms of a three-phase system, illustrating the phase difference between the three phases (A, B, and C). The waveforms demonstrate the sinusoidal nature of the voltage and the balanced distribution of power across the phases.

4. PERFORMANCE COMPARISON

The rectifier topology used is determined by several factors, including the individual application, technology used, and design parameters. One technique for choosing the best rectifier architecture is first analyzing the input voltage range, as shown below. Body-driven circuits, such as microscale and in-body biomedical devices, provide a potential alternative for applications that need ultra-low input voltages (0.1V-0.6 V). This is because the threshold voltage of transistors in such conditions is generally high, and body-driven topologies successfully solve this issue. Furthermore, boost converters are usually necessary to modify the rectified voltage to levels typically needed to operate working blocks.

Passive rectifiers, such as cross-coupled and voltage doubler topologies, are great for applications with low input voltages (0.6-1.2V). In this voltage range, transistors perform well without needing extra circuits, retaining Power Conversion Efficiency (PCE). For applications with medium to elevated input voltages (greater than 1.2 V), active rectifier designs emerge as the preferred option for maximizing efficiency, particularly in power consumption, as measured by Power Conversion Efficiency (PCE).

The body-driven rectification described in [2] is the best method in favor of shallow input voltage ranges. This feat, nevertheless, is credited to the supply of an auxiliary power source with a voltage more significant than the input signal's amplitude. The circuit, similar to a comparator, outputs the most critical value of the two input signals. Despite its usefulness, this circuit has downsides and limits due to the need for extra supply, biased sources, and a body-driven method. While this method allows for functioning with extremely low voltages as input signals, it limits the highest possible amplitude values that may be handled.

On the contrary, data from [4] demonstrate that active topologies are unsuitable for low input voltage ranges, considering they own a Power Conversion Efficiency (PCE) of less than 60%. This poor power performance is due to auxiliary components' reduced speed and driving capabilities, such as comparators and bias generators, when transistors operate in the sub-threshold region. This confirms the previously established classification, given that the average threshold voltage of a conventional MOSFET is around 0.6V or 600mV.

Table 1 compares three different transducer setups for energy harvesting. Section 2.3 uses a piezoelectric transducer with a 180 nm process and passive rectifier topology, operating at 0.2 MHz, and has an input voltage range of 0.25-0.6 V, resulting in a maximum output voltage (VOUT,MAX) of 6.29 V. Section 2.1 also uses a piezoelectric transducer but with a 65 nm process and active rectifier topology, operating at 1 MHz, with an input voltage range of 0.6-1.1 V and a VOUT,MAX of 1 V. Section 2.2 utilizes a magnetic transducer with a 180 nm process and passive rectifier topology, operating at 13.56 MHz, and has an input voltage range of 1.6-3.6 V, resulting in a VOUT,MAX of 1.8 V.

Table 1. Comparison chart for different rectifiers

Section no.	**2.3**	**2.1**	**2.2**
Transducer	Piezo	Piezo	Magnetic
Process(nm)	180	65	180
Rectifier Topology	Passive	Active	Passive
Frequency (MHz)	0.2	1	13.56
Input Voltage (V)	0.25-0.6	0.6-1.1	1.6-3.6
VOUT,MAX(V)	6.29	1	1.8

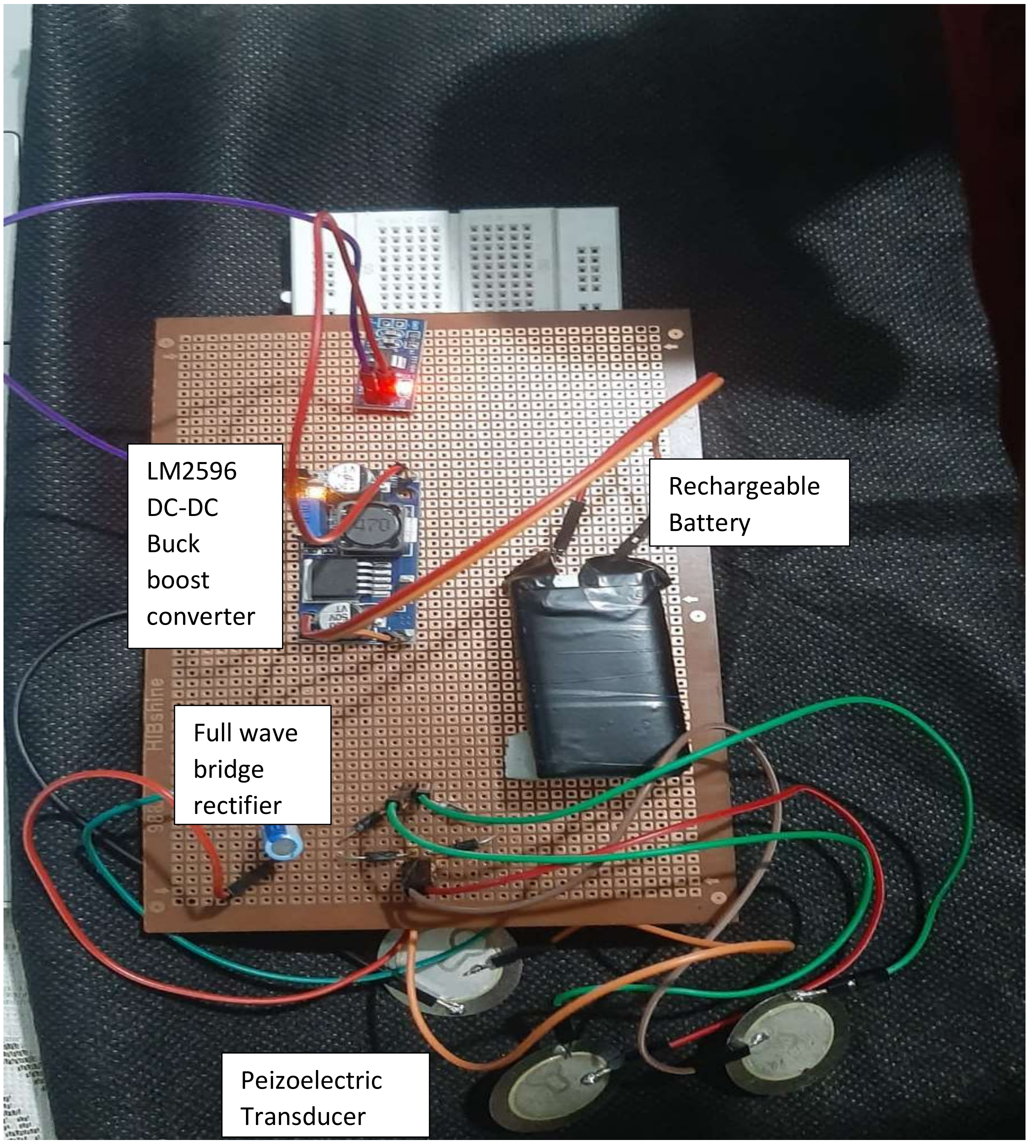


Figure 15 Setup for ultrasound-based energy harvesting circuit

5. PRACTICAL IMPLEMENTATION OF ULTRASOUND-BASED ENERGY HARVESTING CIRCUIT

A piezoelectric crystal has been used in the practical implementation of an ultrasound-based energy harvesting circuit. When ultrasound waves are emitted, they generate a voltage due to stress or mechanical force created by ultrasound waves. To implement it, it is necessary to convert an AC voltage proportional to the stress applied on the piezoelectric transducer to DC voltage for its usage in electronics systems. Also, there is a need for a DC-DC Boost Converter to boost the output produced by the rectifier. There is also a need for a rechargeable battery to store the voltage generated due to irregular voltage generation and a voltage regulator circuit that can regulate the voltage provided by the battery or the boost converter circuit or rectifier. The circuit for all these requirements is given in Figure 15.

In Figure 15, a full wave bridge rectifier is made using the conventional topology of the diode and ripple capacitor. From this capacitor, the voltage is given to the battery and to the buck-boost converter LM2596, which is connected to the battery with the help of a switch. Then, the output from the buck-boost converter is given to a voltage regulator circuit of 3.3 V.

5.1 Output Voltage levels

Firstly, ultrasonic waves are applied only to one piezoelectric transducer. When output is measured from the full wave bridge rectifier, there is a DC voltage of 0.30-0.32 V that is being produced, and that is fed to the buck-boost converter, which is turned off due to the voltage not reaching the level of input voltage it can start functioning. The battery is given this voltage, which will be charged.

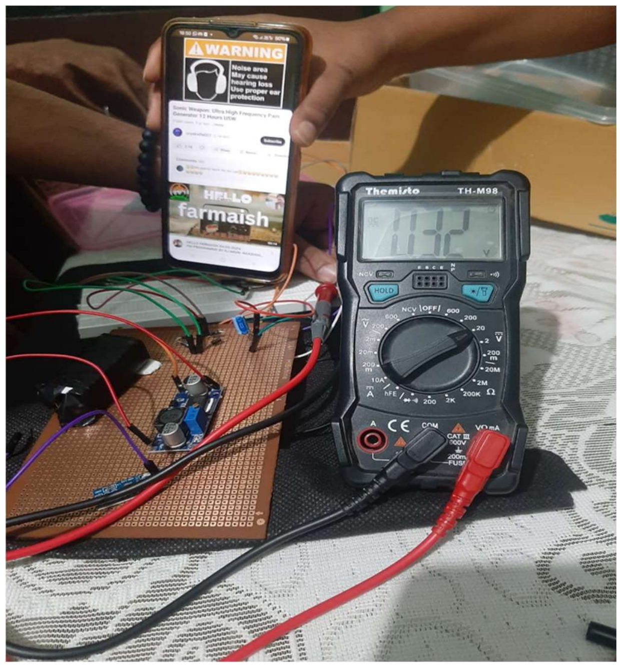


Figure 16 (a). DC voltage from ultrasonic waves application to a piezoelectric transducer

Secondly, when the ultrasonic waves of the same frequency are applied on all the transducers, there is the generation of voltage around 2.05-2.08 V, which is way more when we apply at one transducer and when its voltage is given to buck-boost converter it enhances it, and voltage regulator regulates it.

Figure 16 (a) and 16 (b) depicts a breadboard setup with various electronic components, including a multimeter for measurement, and a microcontroller board for control. The project appears to be in progress, with wires and components spread across the breadboard.

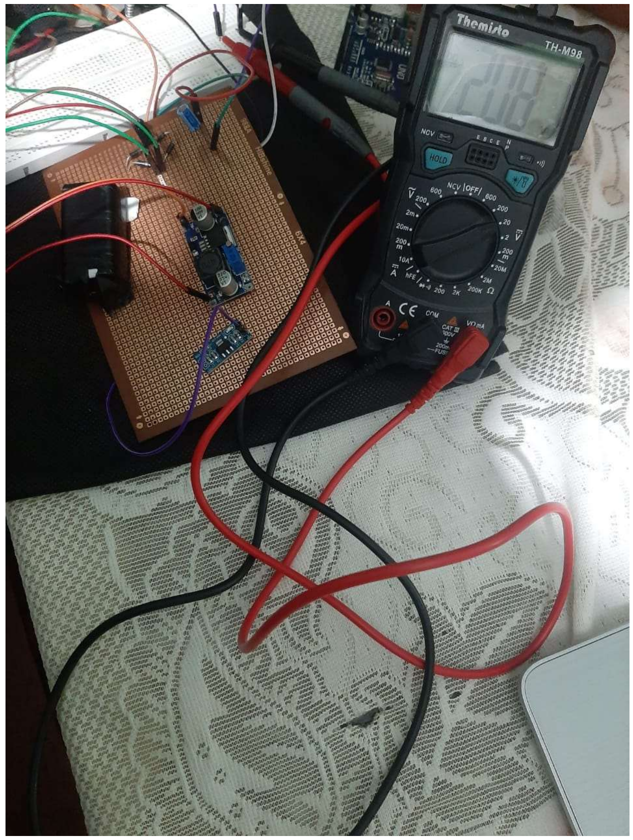


Figure 16 (b). Applying ultrasonic waves to all the transducers

6. CONCLUSION

Ultrasonic energy harvesting is a feasible method for transforming the mechanical vibrations of surroundings into electrical power. This novel technology utilizes the unique nature of piezoelectric materials to obtain this conversion effectively. The resulting power source is a high-efficiency energy supply that can be easily scaled and adapted due to the intellectual design of these systems. However, the practical implementation of tech is also essential to grasp a clearer picture and experience its complete utilization in the future and the present. Such verifications are a way to understand its key features, feasibility, and real-world applications in the practical world. The main steps in this demo also outline different technologies placed on these ultrasound-based energy harvesting systems, highlight their importance in this system, and present real-life world functioning applications.

Also, practical demonstration aids in understanding non-availability or defects in the deployment of systems and provides feedback that can validate effectiveness for further refinement. Such practical demonstrations will allow researchers, engineers, and innovators to showcase the technology's capabilities, which can also help facilitate cross-industry adoption. In the end, it is to work towards sustainable energy and overcome an increasingly pertinent issue in terms of global power generation.

7. FUTURE SCOPE

Energy harvesting based on ultrasonic power has infinitely more potential, and prospects for future development would be a flurry of activity beyond imagination. There are some titled future scope of this technology out-of-these endless used cases below :

Healthcare field: The healthcare sector has dramatically benefited owing to the rapid rise in customization requirements of those within and around the body and biochemical equipment. These devices are well suited for using an ultrasound-based energy harvesting system since these systems can be used to harvest the vibrations that are generated by body movements and power devices in a non-invasive way without having to pierce through any part of your body with only one goal of get rid excessive battery replacement. This can prove to be a revolution in the health sector.

Environmental Monitoring: The ease of deploying the systems in extreme conditions is due to their rugged design. So, this may be used in secret scenes to deploy these conditions, which are very tough for environmental monitoring. By collecting mechanical vibrations from natural sources like wind, water flow, etc, they emerged as an independent energy source for deployed ecological monitoring devices.

Advanced Technology: Next-generation technology like nanotechnology and IOT, which will result from the miniaturization of technology, requires a ruggedized, highly efficient source when, at the same time, its size should also be minimized to some extent so that it can compatible with this next-gen technology for which no solution provides best other than Ultrasonic energy harvesting. Also, using wireless sensor networks has become well-known.

Intelligent Infrastructure: The modern era is going under a boom in architecture, so it becomes essential to monitor these architectural components and save them from causing any mishappening. These systems can be used as the leading power source for monitoring devices of these architectures, which has never happened before in this field. This prevents the infrastructure from wearing out, and structural integrity can be monitored continuously without any accident.

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REFERENCES

[1] A. Ballo, M. Bottaro, and A. D. Grasso, "A Review of Power Management Integrated Circuits for Ultrasound-Based Energy Harvesting in Implantable Medical Devices," Applied Sciences, vol. 11, no. 6, p. 2487, 2021. doi: 10.3390/app11062487.

[2] F. Khateb and S. Vlassis, "Low-voltage bulk-driven rectifier for biomedical applications," Microelectronics Journal, vol. 44, pp. 642–648, 2013. doi: 10.1016/j.mejo.2013.04.009.

[3] J. Charthad, M. J. Weber, T. C. Chang, and A. Arbabian, "A mm-Sized Implantable Medical Device (IMD) With Ultrasonic Power Transfer and a Hybrid Bi-Directional Data Link," IEEE Journal of Solid-State Circuits, vol. 50, pp. 1741–1753, 2015.

[4] M. A. Ghanad and C. Dehollain, "A passive CMOS rectifier with leakage current control for medical implants," in Proceedings of the 2012 19th IEEE International Conference on Electronics, Circuits, and Systems (ICECS 2012), Seville, Spain, 2012, pp. 520–523.

[5] T.-H. Tsai, J.-H. Hong, L.-H. Wang, and S.-Y. Lee, "Low-power analog integrated circuits for wireless ECG acquisition systems," IEEE Transactions on Information Technology in Biomedicine, vol. 16, no. 5, pp. 907–917, 2012.
[6] W. Greatbatch and C. F. Holmes, "History of implantable devices," IEEE Engineering in Medicine and Biology Magazine, vol. 10, no. 3, pp. 38–41, 1991.
[7] J. Katic, "Highly-Efficient Energy Harvesting Interfaces for Implantable Biosensors," Doctoral Dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, 2017.
[8] M. B. Nandish and B. Hosamani, "A Review of Energy Harvesting From Vibration using Piezoelectric Material," International Journal of Engineering Research and Technology, vol. 3, no. 2, p. 1607, 2014.
[9] A. B. Amar, A. B. Kouki, and H. Cao, "Power Approaches for Implantable Medical Devices," Sensors, vol. 15, pp. 28889–28914, 2015.
[10] R. V. Taalla, M. S. Arefin, A. Kaynak, and A. Z. Kouzani, "A Review on Miniaturized Ultrasonic Wireless Power Transfer to Implantable Medical Devices," IEEE Access, vol. 7, pp. 2092–2106, 2019.
[11] H. Basaeri, D. B. Christensen, and S. Roundy, "A review of acoustic power transfer for bio-medical implants," Smart Materials and Structures, vol. 25, no. 12, p. 123001, 2016.
[12] A. Ballo, M. Bottaro, A. D. Grasso, and G. Palumbo, "Regulated Charge Pumps: A Comparative Study utilizing Verilog-AMS," Electronics, vol. 9, no. 6, p. 998, 2020.
[13] A. Denisov and E. Yeatman, "Ultrasonic vs. Inductive Power Delivery for Miniature Biomedical Implants," in Proceedings of the 2010 International Conference on Body Sensor Networks, Singapore, 2010, pp. 84–89.
[14] Y. Zhou, C. Liu, and Y. Huang, "Wireless Power Transfer for Implanted Medical Application: A Review," Energies, vol. 13, no. 11, p. 2837, 2020.
[15] D. Jiang, B. Shi, H. Ouyang, Y. Fan, Z. L. Wang, and Z. Li, "Emerging Implantable Energy Harvesters and Self-Powered Implantable Medical Electronics," ACS Nano, vol. 14, no. 6, pp. 6436–6448, 2020.
[16] J. Zhao et al., "Self-Powered Implantable Medical Devices: Photovoltaic Energy Harvesting Review," Advanced Healthcare Materials, vol. 9, no. 15, p. 2000779, 2020.
[17] P. M. Kumar et al., "The Design of a Thermoelectric Generator and Its Medical Applications," Designs, vol. 3, no. 4, p. 22, 2019.
[18] J. Selvarathinam and A. Anpalagan, "Energy Harvesting From the Human Body for Biomedical Applications," IEEE Potentials, vol. 35, no. 4, pp. 6–12, 2016.
[19] A. Ballo, A. D. Grasso, and G. Palumbo, "A Subthreshold Cross-Coupled Hybrid Charge Pump for 50-mV Cold-Start," IEEE Access, vol. 8, pp. 188959–188969, 2020.
[20] Y. Yang, G. D. Xu, and J. Liu, "A Prototype of an Implantable Thermoelectric Generator for Permanent Power Supply to Body Inside a Medical Device," Journal of Medical Devices, vol. 8, 2013.
[21] M. Meng and M. Kiani, "Design and Optimization of Ultrasonic Wireless Power Transmission Links for Millimeter-Sized Biomedical Implants," IEEE Transactions on Biomedical Circuits and Systems, vol. 11, no. 1, pp. 98–107, 2017.
[22] R. Das, F. Moradi, and H. Heidari, "Biointegrated and Wirelessly Powered Implantable Brain Devices: A Review," IEEE Transactions on Biomedical Circuits and Systems, vol. 14, no. 3, pp. 343–358, 2020.
[23] G. L. Barbruni, P. M. Ros, D. Demarchi, S. Carrara, and D. Ghezzi, "Miniaturised Wireless Power Transfer Systems for Neurostimulation: A Review," IEEE Transactions on Biomedical Circuits and Systems, vol. 14, no. 6, pp. 1160–1178, 2020.
[24] A. Ibrahim, M. Meng, and M. Kiani, "A Comprehensive Comparative Study on Inductive and Ultrasonic Wireless Power Transmission to Biomedical Implants," IEEE Sensors Journal, vol. 18, no. 9, pp. 3813–3826, 2018.
[25] K. Agarwal, R. Jegadeesan, Y. Guo, and N. V. Thakor, "Wireless Power Transfer Strategies for Implantable Bioelectronics," IEEE Reviews in Biomedical Engineering, vol. 10, pp. 136–161, 2017.
[26] A. Arbabian et al., "Sound Technologies, Sound Bodies: Medical Implants with Ultrasonic Links," IEEE Microwave Magazine, vol. 17, no. 12, pp. 39–54, 2016.
[27] C. Shi et al., "A 0.065-mm3 Monolithically-Integrated Ultrasonic Wireless Sensing Mote for Real-Time Physiological Temperature Monitoring," IEEE Transactions on Biomedical Circuits and Systems, vol. 14, no. 3, pp. 412–424, 2020.
[28] A. Manbachi and R. S. C. Cobbold, "Development and Application of Piezoelectric Materials for Ultrasound Generation and Detection," Ultrasound, vol. 19, no. 4, pp. 187–196, 2011.

[29] M. A. Karami and D. J. Inman, "Ultrasound Energy Harvesting Using Piezoelectric Materials," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 59, no. 3, pp. 556–562, 2012. doi: 10.1109/TUFFC.2012.2272.
[30] J. Bae, S.-W. Kim, and B. Han, "Ultrasound Energy Harvesting with Bulk PZT," Journal of Intelligent Material Systems and Structures, vol. 26, no. 5, pp. 562–569, 2015. doi: 10.1177/1045389X15592477.
[31] N. Saeidi and M. Packirisamy, "Ultrasound Energy Harvesting: A Review," Sensors, vol. 14, no. 10, pp. 19209–19242, 2014. doi: 10.3390/s141019209.
[32] P. Fiorini and V. Ferrari, "Piezoelectric-Based Ultrasound Energy Harvesting: State of the Art and Challenges," Micromachines, vol. 9, no. 11, p. 570, 2018.