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Sustainable energy harvesting system for low-power underwater sensing devices

Sahana Salagare[1], Pattipati Naga Sudha[1], Karthik Palani[2]
[1]Department of ECE, K.S. Institute of Technology, Affiliated to Visvesvaraya Technological University, Belagavi, India
[2]Department of ISE, Cambridge Institute of Technology, Affiliated to Visvesvaraya Technological University, Belagavi, India

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ABSTRACT

In marine scientific research, ocean monitoring is crucial where the battery-powered sensor devices are placed under the water to collect different information like temperature, pressure, and turbidity in underwater sensor networks (UWSNs). Thus, keeping these devices active for longer periods is challenging. In the last decades, the piezoelectric transducer (PZT) material has been used widely for constructing more environmentally friendly energy harvesting systems. The PZT harvester offers a promising solution by eliminating the need for batteries for running devices in the future with less maintenance. The PZT harvester allows the system to generate higher voltage to run low-power devices. This paper designed and developed a new renewable energy harvester system using PZT transducers for running different types of underwater sensor devices like temperature, turbidity, and obstacle sensors. The proposed PZT-based energy harvester employs a two-stage amplification model for generating higher voltage and current to run multiple devices. The sensing information collected from these sensors is transmitted to the cloud which is later utilized for analysis and decision-making. Experiment results show the proposed PZT-based energy harvester can generate a voltage of 13 volts (V) and a current of 43.3 milliampere (mA) equivalent to 562 milliwatt (mW) which is very good to run multiple low-power underwater sensor devices.

Corresponding Author:

Sahana Salagare
Department of ECE, K.S. Institute of Technology, Affiliated to Visvesvaraya Technological University
Belagavi-590018, Bengaluru, India
Email: pms.nie1@gmail.com

1. INTRODUCTION

Modern advances in technology have contributed to increasing sensor device self-reliance substantially lowering the amount of energy required to operate them [1]. Utilizing affordable renewable energy sources, sensory motes network lifespan could be increased [2]. A growing approach for sustaining underwater wireless networks (UWSNs) is energy harvesting, in which each sensing mote has its power source, lowering operational and battery costs. Independent energy generators should be created capable of dealing with the UWSN environment and other applications of a similar nature. Numerous power production methods have been examined to provide electricity for the UWSN motes, each of which has a distinct set of functioning principles and elements and a distinctive combination of advantages and disadvantages [3]. The two main categories of clean energy producers are semi-submerged equipment, which typically functions within the outermost layer of the water, and fully immersed equipment, which functions below the surface of the water [4].

Two major obstacles to the effective operation of energy sources in underwater conditions appear to be the persuasive characteristics of the marine atmosphere (this includes the impact of waves, weather, flora, the climate, and navigating) and the problems created by microbes, an occurrence comprised of micro and macro-organisms growing on the hardware interfaces. The structure is significantly impacted by bacteria growth, which also reduces equipment performance and lifetime. The advantages of deploying equipment on the seafloor include its simple design, inexpensive cost of operation, and availability of an extensive variety of technological possibilities, including the use of wind, solar, piezoelectric, and others. The drawbacks involve their susceptibility to pollution and wave influences [5], [6]. They can also interrupt marine flow and demand an isolated region or farms to install.

The fact that underwater motes are unlikely to be subjected to direct sunlight or the effects of tides is one of their major advantages. The disadvantages include the inability to use both solar and wind power, the potential for algae to form within the apparatus, the risk of damage from fishing paths, and the fact that membrane clogging issues are common. The systems in question can make use of general harvesting strategies given their broad spectrum of objectives [6], [7]. The benefits and drawbacks of various methods for harvesting energy utilized in underwater circumstances are discussed in the literature survey section. By presenting a two-phase amplifier-facilitated piezoelectric-based renewable energy system, this work aims to alleviate the restriction of the current renewable energy system [8] employing piezoelectric transducers (PZT) [9] and [10].

The significance of research work are as follows. The work introduces a two-step amplifier model for generating higher current and voltage. The proposed PZT-based energy harvesting system can efficiently power multiple underwater sensor motes. The underwater sensor device sends the packet periodically and event-driven to the cloud; the data collected are later analyzed to perform different decision-making.

The organization of the paper are as follows: section 2, studies various current renewable systems that have been used to power underwater wireless networks. Section 3 shows the working architecture of the proposed PZT-based energy harvesting system. In section 4 provides the experiment study of the proposed PZT-based energy harvesting system. The last section discusses the benefits and limitations of the proposed PZT-based energy harvesting system.

2. LITERATURE SURVEY

This section presents a survey of various recent energy harvesting methodologies designed for underwater wireless sensor network environments. Rigourd *et al.* [11] PZT materials were readily accessible in the market to create an electromagnetic power converter for the marine setting. They employed no amplifier circuits or submerged devices when they generated the energy. Zou *et al.* [12], a prosthetic flexible nanogenerator was utilized to draw mechanical power from the movement of humans in an aquatic environment. The prototype took advantage of both the triboelectrification process and electrostatic inductive concepts generated by running water. In a closed circuit, the equipment could produce a maximum potential voltage of 10 volts. A low-cost power generator was invented in [13] employing a small piezoelectric sensor in the shape of a sphere. An outcome of 3 volts is obtained once the design has been built through simulations; nevertheless, no real-world experimentation is performed. Jang and Adib [14], a piezoelectric power generator was invented. Acoustic waves are delivered towards a PZT, which causes vibrations and stores the resulting electricity. The prototype produces about 1.8 V.

Abdellatif *et al.* [15], a solar-powered technology was utilized to power a radio-frequency modem and to collect sensory data at low cost in the UWSNs environment; subsequently, the system only had a limited UWSNs coverage area. Dynamical induction methodology was utilized in [16] for fueling the self-driving vehicle and for underwater information gathering, yet the prototype only functions within extremely limited transmission ranges. An autonomous internet-of-underwater things (IoWTs) was built [17] for the establishment of multimedia streaming applications under the water, nonetheless, it uses a greater amount of electricity. Gereb *et al.* [18] addressed the significance of minimizing the size of components and running the machine utilizing batteries that can be recharged for providing hydroacoustic transmission applications. Although the prototypes do not generate any power, the focus is placed on tracking and lowering the loss of energy. Considering its use in aquatic wearable motes, tiny, water-resistant pressure monitoring devices with great efficiency were developed [19]. The device produces 10 mW of power. It functions primarily from a narrow transmission distance, but it’s appropriate for aquatic wearable applications.

The most effective strategy to energize a network of sensors in the marine environment, according to [20], is underwater kinetic energy harvesting. This approach produces adequate energy for the motes and light emitting diodes (LEDs). PZTs have been employed for developing a self-powered triboelectric nanogenerator [21] for monitoring mechanical motions, and search, and rescue operations in aquatic environments. Kargar and Hao [22], developed a drifted PZT and used it in a simulated scenario to measure wave height and duration across the marine surface. Faria *et al.* [23] describes the construction of a device that uses linear microwaves in frequency ranges of 0.1–4 hertz (Hz). When the rate of 0.4 Hz is taken into consideration, the system possesses the ability to create 7.77 millijoules/second. Zhou *et al*. [24] to improve data rates in UWSNs, an aquatic scandium-doped aluminum-nitride piezoelectric with greater-frequency microelectromechanical circuit hydrophone prototype is designed for monitoring acoustic pressure gradient. The concept concentrates mainly on studying and tracking dolphins' cries to support the protection of these creatures. Similarly, Chiu *et al.* [25], [26] demonstrated that within an aquatic setting the resultant electricity is dependent upon the deepness of the seafloor and that energy produced is lower close to the seafloor than at the surface; they produced a current of 5.8 mW and voltage of 1.5 V.

Zhou *et al.* [27] modeled PZT pulse-jet actuator using the concept of jellyfish [28] to generate energy to run underwater devices. A total of 6 PZT pulse-jet actuator is constructed sideways to form an antihydropressure tiny underwater autonomous robotic device. Shi *et al.* [29] a higher bandwidth using high-frequency microelectromechanical systems (MEMS) vector hydrophone to detect pressure in an underwater environment using scandium-based aluminum nitride PZT. Xiao *et al.* [30] studied the impact of temperature on piezoelectric outcomes. Zhang *et al.* [31] embedding the PZT into the wall of underwater autonomous robots and turbulence characteristics impacting drag reduction is studied; similarly, the impact of velocity and direction on the performance of underwater vehicles have been studied in [32]. Kaya and Alkoy [33] a flex-tensional V-shaped transducer through the structuring of the identical composition of metal and ceramic caps for representing structures like seashells. Mansouri and Ganji [34] designed micromachined ultrasonic PZT can improve the electromechanical coupling effect, quality, and sensitivity by employing a slot-based model considering both the transmission and reception process. The model aids in reducing stiffness, creating piston-like motion, and increasing vibration amplitude; thereby, reducing thermoelastic loss. However, future applications [35] in the underwater environment require the model to run multiple underwater devices at the same time in a more autonomous manner with low cost and high energy efficiency [36]. The proposed model is motivated to implement an energy harvesting mechanism employing a PZT by the considerable advantages of adopting a piezoelectric-based energy transducer for many different applications in an underwater situation. The power provided by a PZT can be enhanced by creating an efficient amplification design, according to a thorough study of applications and energy harvesting methods in [37].

3. PROPOSED DESING AND IMPLEMENTATION

This section presents an effective energy harvesting system using PZTs for running multiple UWSN devices. The architecture of the proposed PZTs-based energy harvesting system is shown in Figure 1. The detailed working process of the proposed energy harvesting model using PZTs is discussed in a forthcoming sub-section.

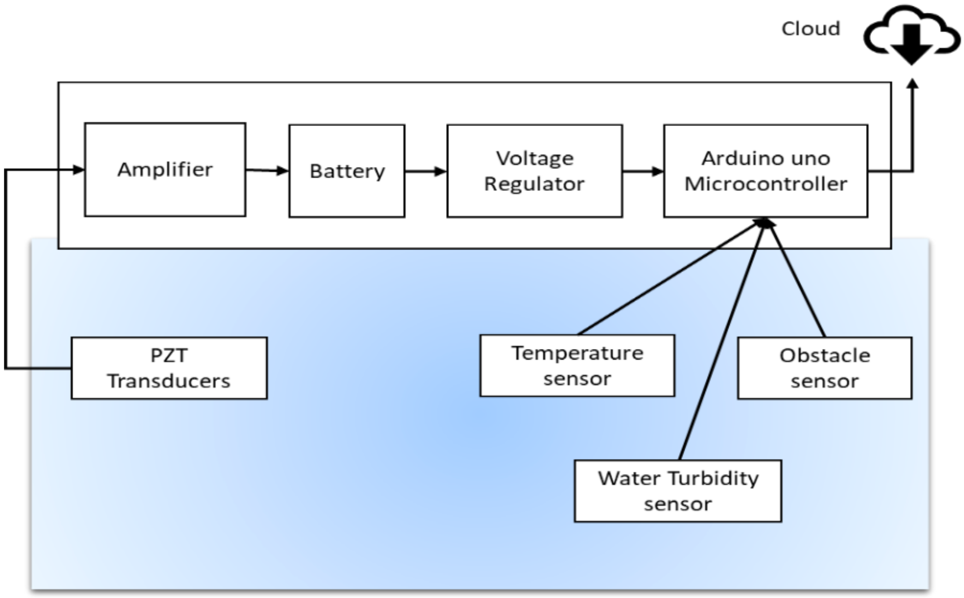

Figure 1. Proposed PZTs-based energy harvesting system

3.1. Piezoelectric transducer output

The work first places 20 PZTs under the large water tank with a depth of 5 meters (m) with 119,700 kilopascal (Kpa) pressure. The PZTs by converting pressure i.e., mechanical energy into electrical energy. Whenever these PZT experience pressure within their surface they generate electricity. Initial measurement shows the voltage ranges between 2 millivolts (mv) to 1 V. The study also shows that as depth increases the pressure increases which in turn increases the overall voltage. However, the measured output is very low to run underwater devices considering a depth of 5 m in the swimming pool.

3.2. Amplifier stage output

The output generated by the transducers is sent to an amplifier module. The amplifier module is composed of two phases to increase the voltage and power generated to run multiple underwater devices. The study in [37] shows that the charge amplifier offers a simple and effective way of generating enough power to charge the battery and run multiple underwater devices. The block diagram of the 2-phase amplifier module is described in Figure 2 and the output voltage generated is adequate for running multiple underwater devices for many hours.

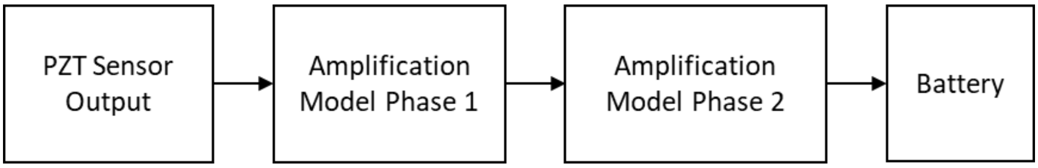

Figure 2. Block diagram of amplification stage

The amplification process of phase 1.
Amplifier phase 1:

$$Gain = 1 + \frac{R_f}{R_1} \tag{1}$$

$$V_0 = V_{in} * Gain \tag{2}$$

$$= V_{in} * \left(1 + \frac{R_f}{R_1}\right) \tag{3}$$

then,

$$V_0 = V_{in}(1 + 100) = V_{in} * 101\,V,\ when\ R_f = 100K\Omega\ \&\ R_1 = 1K\Omega \tag{4}$$

the amplification process of phase 2 is as follows:
Amplifier phase 2:

take $R_{f1} = 10K\Omega\ \&\ R_1 = 1K\Omega$

3.3. Block diagram of implementation module

The block diagram of the proposed energy harvesting system is shown in Figure 3. The output from the PZT is passed into the amplifier circuit. The proposed model employs a two-phase amplifier circuit to increase the voltage and power generation to run multiple underwater devices. The power generated is stored in the battery. Then, the regulated voltage is passed into the Arduino uno microcontroller to run multiple underwater devices. The entire setup is placed inside a waterproof box that can handle the pressure of the water surface. In this work, we have considered three different sensors like temperature, turbidity, and obstacle sensor. The information collected is stored in a cloud platform for conducting further analysis. The experiment to study the efficiency of the proposed model is given in the next section.

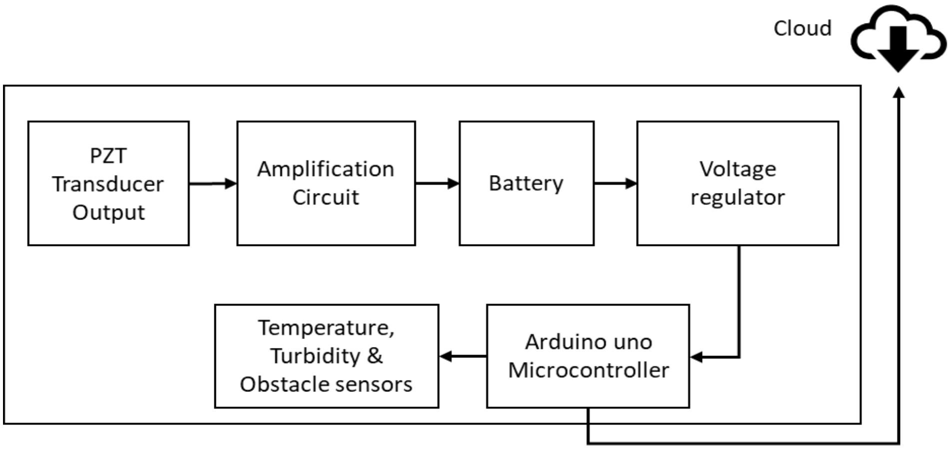

Figure 3. Block diagram of proposed energy harvesting system

4. RESULTS AND DISCUSSIONS

In this section, an experiment is conducted to study the efficiency of the proposed system to run multiple underwater devices. The work considers a total of 20 piezoelectric sensors, a 2-phase amplifier module, one lead acid battery with a capacity of 12 V and 1.3 ampere-hour (Ah), an Arduino Uno microcontroller, and multiple underwater sensors like temperature, turbidity, and obstacle sensors. The performance of the proposed energy harvester system placed under the water is measured in terms of voltage, current, and discharge time to run multiple underwater devices. Figure 4 shows the testbed where the proposed energy system is placed autonomously. Figure 5 shows a close-up view of the energy harvester system placed inside the waterproof box. Figures 6 and 7 show the placement of different sensors like PZT, temperature, turbidity, and obstacle sensors under the water. Figure 8 shows the initial measurement state of the energy harvester model. Figure 9 shows the generated voltage and energy outcome of the proposed energy harvester system.

Figure 4. An energy harvester is placed in the water tank

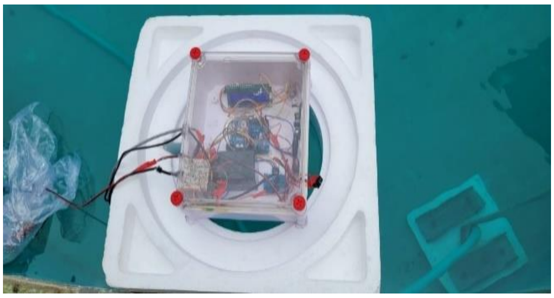

Figure 5. Closer view of the proposed energy harvester system

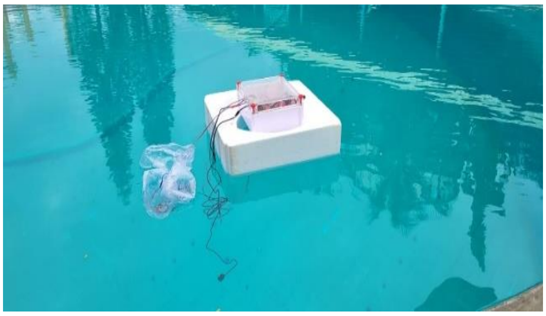

Figure 6. PZT sensor is placed under the water tank

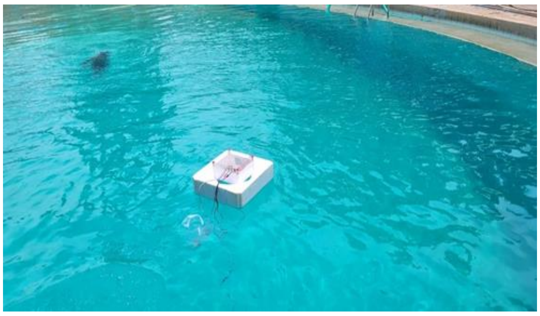

Figure 7. Temperature, turbidity, and obstacle sensors are placed under the water tank

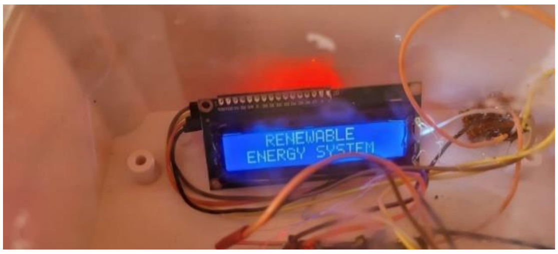

Figure 8. The initial state of the system

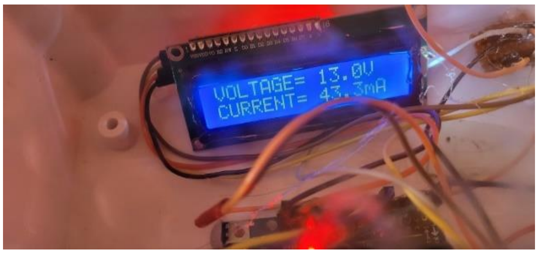

Figure 9. Voltage and current are generated after obtaining output from the PZT

4.1. Energy harvesting analysis

The experiment results show that the proposed PZT-based energy harvesting system for underwater applications can generate an output voltage of 13 V and current of 43.3 mA; thus, the overall power generated is computed as (5).

$$Power = Voltage \times Currnet$$
$$Power = 13 \times 43.3 = 562 \text{ mW} \tag{5}$$

The power generated is stored in the battery with a capacity of 12 V and 1.3 Ah. The overall time taken to charge the battery to its full capacity is measured as (6).

$$Charging\ time = \frac{Battery\ capacity}{charging\ current}$$
$$Charging\ time = \frac{1.3\ Ah}{43.3\ mA} = 30.02 \text{ hours} \tag{6}$$

The work runs three underwater devices such as temperature sensors, turbidity sensors, and obstacle sensors with 150 mW, 5 V, and 30 mA takes discharge time using (7).

$$Discharge\ time\ per\ device = \frac{1.3 \times 12}{150} = 104 \text{ hours} \tag{7}$$

Discharge time for three devices with same rating it will be:

$$Discharge\ time\ per\ device = \frac{1.3 \times 12}{3 * 150} = 34.67 \text{ hours} \tag{8}$$

4.2. Data analysis in the cloud

This section studies the analysis of data collected from different sensors. Figure 10 shows the temperature measured in Celsius using temperature sensors; the results show the temperature varies between 27 degrees to 29 degrees Celsius. Figure 11 shows the obstacle measured in centimeters using an obstacle sensor; the results show the obstruction varies between 0 to 678 cm. Figure 12 shows the turbidity measured in millimeters using a turbidity sensor; the results show the turbidity varies between 2,000 to 4,000 nephelometric turbidity units (NTU). Figure 13 shows the voltage measured; the results show the voltage varies between 13 to 20 V. Figure 14 shows the current measured; the results show the current varies between 43.3 to 66 mA.

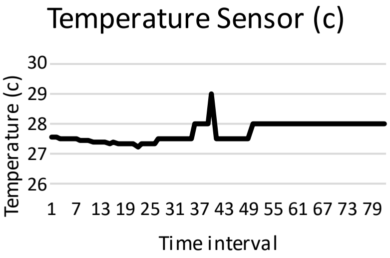

Figure 10. Temperature measurement

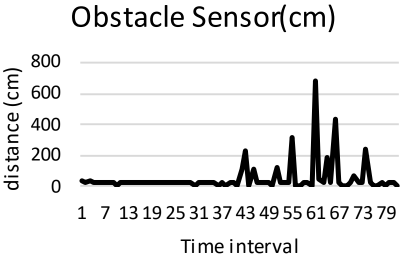

Figure 11. Obstacle sensor measurement

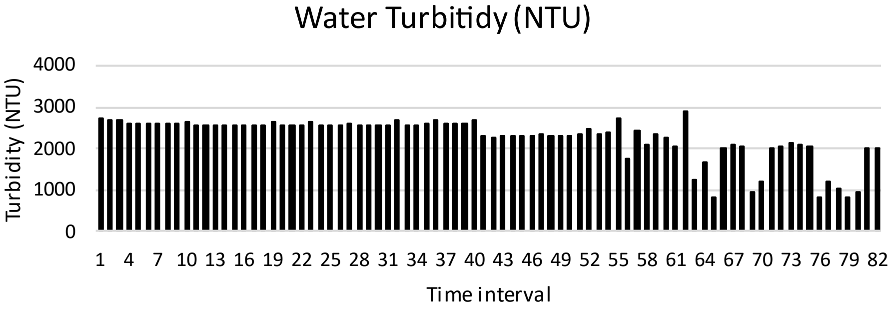

Figure 12. Water turbidity measurement

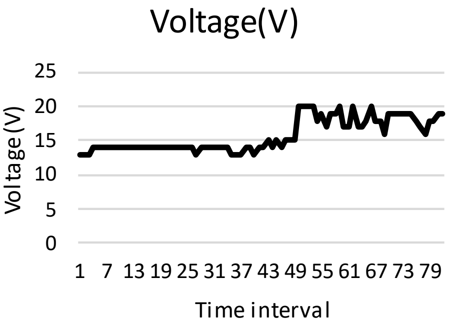

Figure 13. Voltage measured

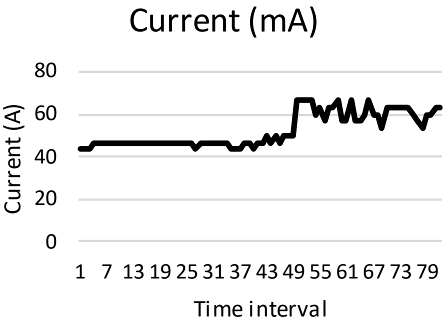

Figure 14. Current measured

4.3. Comparative study

This section compares the results of the proposed and existing PZT-based energy harvesting system. The voltage and energy generated using the proposed and existing PZT-based energy harvesting system are graphically shown in Figures 15 and 16, respectively. The existing PZT-based energy harvesting system [37] can generate a maximum voltage of 10.6 V and a current of 10.1 mA; the existing model can run only one temperature sensor device in an underwater environment. On the other side, the proposed PZT-based energy harvesting system can generate a voltage of 13 V and a current of 43.3 mA; the proposed model can use three underwater devices namely temperature, turbidity, and obstacle sensors. Thus, the proposed model improves voltage generation by 18.47% and current generation by 76.52%.

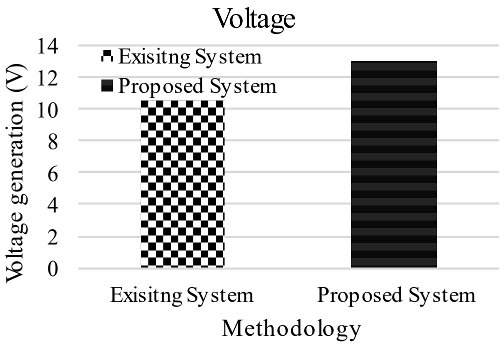

Figure 15. The voltage is generated after obtaining output from the PZT

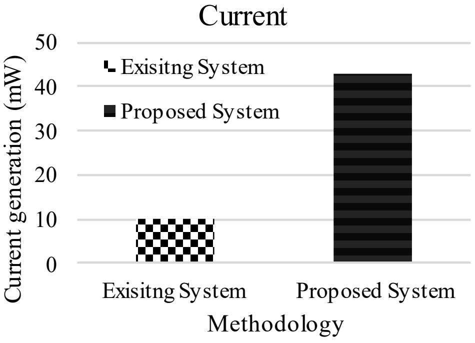

Figure 16. Current generated after obtaining output from the PZT

5. CONCLUSION

The research presented here demonstrates how essential is the need to increase the lifespan of UWSNs. To extend the lifespan of networks and enable potential intelligent applications, developing effective systems for generating electricity is crucial. Renewable power systems for UWSNs are designed using a variety of power harvesting techniques, including solar, electromagnetic, wind, and piezoelectric energy, among others. To solve the problem in this research, a two-stage method for current and voltage amplifying was incorporated into an innovative power harvesting technology using PZTs. The results of the study demonstrate that, at the maximum depth of 5 m, the proposed renewable energy system can generate a maximum voltage of 13 V and a current of 43.3 mA. The electricity produced is adequate for operating numerous low-power underwater instruments including temperature, turbidity, and obstacle sensors. Future work would consider more detailed analysis to study the impact of velocity and speed on the proposed energy generation model considering different water sources, terrain, and depth. Alongside, how the working model can be used to support different kind of sensor device in more efficient manner must also be studied.

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BIOGRAPHIES OF AUTHORS

Sahana Salagare received B.E. (E&C) degree and M.Tech. degree in Information and Communication Engineering from Vishweshwaraih Technological University (VTU), Belagavi in 2010. Currently pursuing Ph.D. degree in Wireless and Communication at Electronics and Communication Research Centre, K.S Institute of Technology Bengaluru which is affiliated to VTU Belagavi. She has teaching experience of 9 years in various Engineering Colleges. Her research interest includes wireless communication, underwater communication, underwater sensor network and presented various papers in many international journal and conferences. She attended many national and international workshops, FDPS and seminars in her academic journey. She reviewed many national and international papers. Her research focus is to explore various energy harvesting techniques for low power underwater devices that would play a very important role in today’s underwater research field. She can be contacted at email: pms.nie1@gmail.com.

Dr. Pattipati Naga Sudha completed B.E. (E&C) from Vijayanagar Engineering college Bellary under Gulbarga University and M.Tech. Digital Electronics from B.V.B College of Engineering Hubli under and secured third rank in M.Tech. to VTU Belagavi in 2002. Persued Ph.D. in wireless communication with thesis titled speech compression and error correction for mobile communication and awarded during December 2013. She has teaching experience of 23 years in various engineering colleges. Her research interest includes wireless communication, underwater communication, underwater sensor network, and digital signal processing. She can be contacted at email: koolpms22@gmail.com.

Dr. Karthik Palani completed B.E. (E&C) from Periyar Unibversity in 2004 and and obtained M.E. in Applied Electronics in 2006 from Satyabhama University. Persued Ph.D. from Dr. MGR Educational University in 2013. He has teaching experience of 16 years in various engineering colleges. His research interest includes wireless communication, underwater communication, underwater sensor network, image processing, and digital signal processing. He presented various papers in many international conferences including IEEE. He published many papers in various international journal and attended many national and international workshops and seminars in her academic journey. He can be contacted at email: prabhu.vijay23@gmail.com.