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Progress in Piezoelectric Material Based Oceanic Wave Energy Conversion Technology

MAHBUBUR RAHMAN KIRAN[1], OMAR FARROK[2], (Member, IEEE), MD. ABDULLAH-AL-MAMUN[2], MD. RABIUL ISLAM[3], (Senior Member, IEEE), AND WEI XU[4], (Senior Member, IEEE)

[1]Department of Electrical and Electronic Engineering, Green University of Bangladesh, Dhaka 1207, Bangladesh
[2]Department of Electrical and Electronic Engineering, Ahsanullah University of Science and Technology, Dhaka 1208, Bangladesh
[3]School of Electrical, Computer and Telecommunications Engineering (SECTE), University of Wollongong, Wollongong, NSW 2522, Australia
[4]State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Corresponding author: Wei Xu (weixu@hust.edu.cn)

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ABSTRACT Recently, electrical engineers are paying great attention to develop oceanic wave energy conversion technologies based on the piezoelectric materials because of their excellent conveniences. Piezoelectric oceanic wave energy converters (OWECs) have several benefits over the others such as its small size, lightweight, no requirement of using intermediate device as well as having less negative impacts on the oceanic environment. Various review and research papers focus on the piezoelectric devices, their operation and application for oceanic energy conversion. But, to the best of the authors' knowledge, none of the existing research or review papers present detailed scheme of piezoelectric device based power generation covering all the relevant topics as depicted in this review. This article focuses different aspects of piezoelectric device based oceanic wave energy conversion technology including prospect, historical development, classification, operating principle, configuration, arrangement, model, processing, post-processing, and their test setups. In addition, technical challenges, future direction of research and critical review are also illustrated. It is assumed that, this article would play a significant role for the future development of piezoelectric OWECs and the researcher working in this field.

INDEX TERMS Energy conversion, oceanic wave energy, piezoelectric material, piezoelectric generator, renewable energy, wave power.

I. INTRODUCTION

Electrical energy generation from renewable energy sources (RESs) is becoming popular in recent decades to meet the increasing energy demand. RESs are good enough for the environment comparing fossil fuel based energy sources. Although, fossil fuel is the main source of electricity generation in the globe, but it is estimated in [1] that, by the year 2040, the use of energy sources based on fossil fuel would be reduced to 4%. Then the rest of required energy would be provided by the RESs [1]. As per the report of the Intergovernmental Panel on Climate Change (IPCC) in 2014, the level of sea water in 2010 will increase by 0.2 m approximately by the year 2050 [2]. Consequently, both the land and the islands would be reduced significantly. While burning fossil fuel, carbon di-oxide (CO_2) gas is produced and it is highly responsible for environmental pollution [3].

On the other hand, the demand of energy in 2040 would be double compared to that of in 2016 [4]. For the generation of clean and sustainable energy, RESs such as solar [5], wind [6], oceanic wave energy (OWE) [7], and geothermal energy [8] have already got significant attention. Among all the RESs, OWE is conceived with the highest potentiality of producing electrical energy [9]. For that reason, the development of highly efficient wave energy converter (WEC) technology has become one of the concerning issues.

Most of the oceanic wave energy conversion technologies are based on the electrostatic, electromagnetic, or piezoelectric properties [3]. In an electrostatic principle based system, the kinetic energy is transferred which is produced by

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vibrational motion of devices overcoming the electrostatic forces between the devices. The simulation work in [10] presents an energy harvester which is designed and developed based on the methodology of converting the vibration into electricity. The frequency of input vibration was 120 Hz and the power density was 116 μW/cm^3. The concept of electrical power generation by electromagnetic induction was discovered by great scientist Michael Faraday in 1831. Several WECs are presented in [11] in which rotational and linear electrical generators are described. The generator mostly operates by the principle of electromagnetic induction. It was semi-submerge type and oscillates following the oceanic wave which in turn drives hydraulic motors to drive electrical generators for the generation of electrical energy. The length and weight of the harvester was 180 m and 1350 t respectively. The output power was obtained about 750 kW [12].

A comprehensive review on wave-to-wire models for various WECs is presented in [13]. Direct drive WEC (DDWEC) offers high energy conversion efficiency because, the losses in the intermediary parts, mechanical or hydraulic arrangements are not used. Different types of linear generator and magnetic coupling machine also known as snapper can be included in the category of direct conversion technologies for OWE. Piezoelectric and triboelectric transducers can also be considered for direct drive system. Tubular and flat type linear generators are also under research for the development of efficient design of DDWECs [14]. The later class of converters can produce shear stress up to 10 times more compared to that of those in traditional electrical generators with very low loss [15]. An optimized planar linear generator is proposed in [16], which is capable of utilizing several modes of OWE conversion. Optimal design of the generator is developed based on parameters of the electrical equivalent circuit and the properties of oceanic wave. A permanent magnet linear generator is designed and proposed in [9] that considers split translator secondary stator windings. The proposed generator minimizes translator's weight to improve dynamics of the translator motion.

Piezoelectric materials are also used to generate electricity [3], [17]. Piezoelectric materials are sustainable source of electricity that can be extracted from different RESs such as OWE [18]–[21], wind energy [22] etc. It is implemented on various devices such as microphones, load cells, power excavator etc. Excellent properties such as greater energy density, ability of natural inverse energy conversion, and simplicity in designing construction were found from that power excavator [23]–[25]. It is easy to construct energy harvesting devices from micro and nano-scaled malleable piezoelectric materials [26]–[28]. To meet the global energy demand, several technologies have been developed for converting OWE into electrical energy in recent time [29]. Submersible technologies have been developed in [30] for OWE conversion.

Piezoelectric materials convert strain energy into electrical energy without any intermediate operation [31], [32]. They are already being used in wind power generation [33], [34] and OWE extraction [18], [19], [35], [36]. A small power WEC using flexible piezoelectric device was designed and presented in [37], [38] considering the kinetic energy of oceanic waves. The piezoelectric devices were placed near the surface of the ocean water. These devices were carried by a floating member to produce electricity from the energy of oceanic waves. Another energy harvester was designed with 28 μm polyvinyldifluoride (PVDF) piezoelectric material and was experimentally verified. The operating frequency was 10 Hz and maximum output electric voltage was 1.1 V [39]. A well-designed energy extractor was proposed in [40] which produced electricity by compressing the piezoelectric plate. It has better efficiency and the frequency of resonance is lower. A Prototype was experimentally verified which produced 300–400 μW output power with 200 and 250 Hz vibrational frequencies [40].

From the literature review it is found that, it is possible to generate micro-watt power scale electricity from 0.5 m/s wave velocity [41]. A newly developed piezoelectric material based wave energy harvester (WEH) is proposed in [30]. It is structurally connected to a floating buoy and experimentally verified for maximum 169 V output voltage at no load condition (100 MΩ). It is possible to harvest significant amount of electrical energy with machines by vibration conversion provided that shock absorbers, etc. are properly utilized [42]. A wind power plant was designed and developed based on piezoelectric bimorph [43]. It was practically validated for 7.5 mW with wind velocity of 10 mi/h and a connected load of 6.7 kΩ.

To improve the efficiency of piezoelectric material based WECs, researchers are paying considerable attention. An advanced WEC associated with piezoelectric sensor is designed and experimentally tested in [2] for 12.35 mW output power at 20 Hz operating frequency. It is observed that, energy harvesters based on piezoelectric materials provide higher conversion efficiency. Large scale power generation (kW range) from wind power and OWE is under both the research work and prototype implementation [32], [44]. Soundpower company has designed and commercialized an electric power generator with a vibration motion producer [45]. The piezoelectric material based WECs require comparatively lower maintenance cost and offers versatile applications [46]. Well-designed piezoelectric WECs incorporate the piezoelectric floats [18] and cantilevered beams [19], [35]. Theoretical and practical investigations were carried out for the improvement of design and successful implementations of piezoelectric [47], electromagnetic [48], and electrostatic [49] energy conversion techniques. The operation and performance of a piezoelectric device was analyzed for energy production in [50]. It was placed on highway bridge including a movable load. The estimated consummate power of oceanic wave can exceed 50 kW/m of the wave front. The production of electricity from the kinetic energy of oceanic wave is considered as a promising alternative to meet the global energy demand [21]. It is investigated that, piezoelectric devices even of nano scale size may contribute to produce electricity from vibration and stress. They will play an important role to build future smart cities with good health, clean environment, self-powered monitoring devices, and resource administration for economic progress [51].

General mechanism of power generation by piezoelectric devices are highlighted in [1] under different deformation conditions. There is brief illustration of the mathematical modelling, limited information on experimental tests of piezoelectric WECs, and lack of suggestions about the post-processing of the generated electrical energy. Different methodologies of ocean energy conversion using piezoelectric devices with prototype tests are discussed in [3] where only one mathematical model is included without elaboration. Besides, processing of materials for manufacturing piezoelectric harvesters and strategies for conditioning the produced power are not depicted. Various WEC methodologies are illustrated in [11] that includes linear generator along with piezoelectric WECs. But no mathematical model, material processing, and test setup are not presented.

One of the motivational aims of this review article is the limitation of available publications on the promising piezoelectric material-based wave energy conversion technologies. In this context, authors' contribution of this article includes the finding of the advantages as well as shortcomings of the existing review on piezoelectric WECs and recommendation of possible solutions to the challenges. After studying available literatures on piezoelectric energy converters for oceanic waves, an elaborate presentation on the state of the art of renewable energy, prospects of OWE, and piezoelectric devices is outlined. In addition, the physics of piezoelectric harvesters introducing the charge coefficients, strategies of material processing, mathematical modeling, different configurations for OWE conversion, post-processing of harvested energy, and experimental tests are included in this article. Recommendations are provided for the development of this wave energy conversion system through proper discussion in most sections of the review. Finally, in the discussion and conclusion section, critical review for different situations are presented for piezoelectric WEC. All the topics as presented in this review are not found together in the existing reviews including [1], [3], [7], [11], [17], [27], [47], and [48].

II. PROSPECT OF OCEANIC WAVE ENERGY AND EXISTING WECs

At present, the generation of electrical power from renewable and sustainable energy resources is one of the uppermost primacies in many counties. The European Union (EU) and the USA have established their policies regarding the increment of RES based power stations. The aim is to meet the gradually increasing energy demand as well as to mitigate the problematic issues associated with global warming and environment pollution. Being one of the prominent sources of renewable energy, the OWE is available almost all time with highly predictability [52].

The estimated worldwide OWE potentiality is approximately 2 TW [53]. Based on the available resources nearby the UK shoreline, the expected OWE can provide 50 TWh/year that can fulfill approximately 14% of the entire electrical energy demand in UK [54]. In China, the projected extractable OWE is about 21.79 GW. The European World Energy Council and Commission reported the exploitable OWE as 120–190 TWh/year for offshore and 34–46 TWh/year for near-shore sites [55], [56]. Considering the geographical locations, the potentiality of OWE in Europe can be summarized in Table 1.

TABLE 1. Owe potential in few countries in europe [55], [56].

Nation	OWE potential (TWh/year)	
	Near shore	Offshore
Germany	0.3–0.5	0.9–1.4
Greece	1–2	4–7
Denmark	2–3	5–8
Italy	3–5	9–16
Spain	3–5	10–16
France	3–5	12–18
Portugal	4–6	12–18
Ireland	7–11	21–32
UK	14–21	43–64

According to the policies set by most nations in the world in 2015, the projected range of electrical power production from RES is 30% increased by 2030 [54]. China has a plan to meet 15% of the total electrical energy demand of the country from RES especially from the OWE. The worldwide energy potentiality of OWE is approximately 8,000–80,000 TWh/year [57]. The oceanic energy potentiality of the USA mainland shelf edge is about 2,640 TWh/year. It is equivalent to 64% of total electrical power production in 2010 and it has been assessed by Electric Power Research Institute (EPRI) in the USA. It is evaluated that there is 16% of OWE of the world is obtainable in European countries. It is reported that, oceanic power density averages up to 100 kW/m at offshore and 50 kW/m of wave front near the shoreline [57]. The oceanic energy extraction has been improving for 35 years [58].

The untapped oceanic energy can be harvested by implementing some physical experiences such as salinity, temperature grade, natural tides, sea waves, and marine currents [59]. OWE is mainly converted to a systematic mechanical energy in linear [9] or revolving form by using a WEC [60]. Most of the mega-scale WECs include the electrical generators for extracting the kinetic energy of the oceanic waves. In general, the electromagnetic harvesters include the conducting coils and magnets which make the system heavy. Based on the location where the fixing is executed, WECs can be categorized into off-shore [61], near-shore [62], and onshore [63]. Four vigorous types of the WECs are oscillating water column (OWCs) [64], point absorber [65], surface attenuator [66], and overtopping device [67]. Advanced power take-off devices for seizing OWE contain hydraulic rams which is fundamentally a water pump, hydroelectric turbines, air turbine, and linear electrical generator [68].

Among different types of WECs, the leading WECs are Power Buoy [14]- developed by Ocean Power Technologies corporation, USA, Pelamis [69]- designed by Pelamis Wave Power, UK, Oyster WEC- manufactured by Aquamarine Power, UK, Wave Dragon [70]- by Erik Friis-Madsen, Denmark, and AWS-III- proposed and commercialized by AWS Ocean Energy, UK. The direct drive WECs are incorporated with linear generator [71] and thus it offers the convenience of simplicity in design. The control techniques required for converters to improve quality of the generated power, are comparatively complicated than that of indirect drive systems [72]. The latest methodologies for OWE harvesting associate the categories of WECs, electrical generators, control methods, sites of arranged controller, characteristics of sea waves, power conversion techniques, and the pragmatic validation [73]. Another new technology of harvesting OWE is getting popularity because of its excellent performances for the generation of electricity from mechanical energy. It avoids the use of traditional electrical generators due to some shortcomings under low frequency conditions by implementing the triboelectric generators. The concept of electricity production using triboelectric generator was first introduced in 2012 [74]. The important conveniences compared to the traditional electromagnetic generator topologies that can be offered by the triboelectric generators are improved power density, reduced size and weight, less manufacturing costs, as well as better efficiency (may reach 70%) [75], [76]. Due to the lightweight characteristics, the triboelectric generators are more suitable to the rough and casual nature of the oceanic waves. The electric current in a triboelectric generator is produced by alternating polarization field generated by the charge carriers created under surface polarization phenomena. The operating principle of the triboelectric generation is based on the combination of electrostatic induction and triboelectrification effect. The triboelectric charges of opposite polarity with equal quantity, are induced on the surface of two dielectric elements when a physical interaction is made between the elements. Under the application of mechanical vibration, electrical potential difference is generated. To stabilize the electric field, electrostatic induction is occurred. The operation process is a comparative parting and/or gliding between the two dielectric elements instigated by kinetic energy of the oceanic waves, which produces electrical voltage difference between the electrodes attached to one of the dielectric devices.

In spite of the availability of OWE, the energy harvesting at very low frequencies (<5 Hz, e.g.) has become a crucial issue (at present) to the power engineers. For such type of low frequency electricity generation, triboelectric generators are more efficient compared to the conventional electromagnetic generators. In order to substantiate the concept of electricity generation from kinetic energy of water by implementing the triboelectrification methodology, numerous prototypes have been tested [77]–[81]. An advanced system structure for triboelectric generator based wave energy harvesting unit is proposed in [82] which can be contributed to the improvement of the output power quality. Primarily it is projected that an electrical power of 1.15 MW can be harvested with the proposed system covering an oceanic area of 1 km^2. A water resistant wave energy harvesting system is designed incorporating non-interacting attractive dynamism between the braces of magnetic devices to control the transportable part of the triboelectric generator [82]. The design and manufacturing processes of a floating buoy based wave energy harvesting unit including cylindrical shaped triboelectric generators are presented in [83]. An OWE extractor composed of single floating unit, liquid solid interaction based triboelectric generator, and polytetrafluoroethylene tube (8×10 cm), can produce 1000 nC charge, current of 40 μA, and voltage up to 400 V [81]. High impedance and low service durability are the disadvantages of triboelectric generator based WECs.

III. POWER DENSITY OF PIEZOELECTRIC MATERIALS

In this section, different types of piezoelectric materials are compared in terms of their structural properties and performances in OWE applications. Piezoelectric materials can be used for electricity generation because of its structural properties. The structural configuration of the piezoelectric crystal such as crystal film, is associated with single crystals and exhibits the inherent transduction characteristics. In case of ceramic type piezoelectric devices such as barium titanate ($BaTiO_3$) and AlN, plethora of small scale quartzes are arbitrarily oriented and under the application of electric potential exhibit piezoelectric properties [47], [84]. The lead-free piezoelectric composite ceramic $(K,Na)NbO_3$–$KTiNbO_5$ is developed and its characteristics are discussed in [85] along with the microstructure. Alkaline niobate ceramics $(K,Na)NbO_3$ offer mainly improved microstructure piezoelectric properties and a comparatively high Curie temperature. The existence of too much voids in a sintered piezoelectric composite reduces its chemical constancy, robustness, and exhibits insulation damage throughout polarization. Because, electric field is generated at the voids. Dielectric materials can be used to fill in the voids which in turn mitigate the drawbacks of the lead-free composites.

The idea of soft and hard lead-free piezoelectric material is explained in [86] according to donor and acceptor customized PZTs, respectively. Similar to PZT, improved characteristics are observed for the $(Na,Bi)TiO_3$-$BaTiO_3$ and ternary system with $(K,Bi)TiO_3$ piezoelectric composites. The results of a lead-based piezoelectric to anti-ferroelectric conversion under less than Curie temperature restrict their applications. The polymers of piezoelectric materials are being attracted significant interest because of the conveniences as intrinsic elasticity, simplicity of processing, excellent mechanical strength, as well as proper suited for energy excavation [87], [88]. Figure 1 illustrates the experimental results of piezoelectric device based oceanic energy harvester [89].

The testing was performed including sheet and knit type flexible piezoelectric devices (FPEDs) made of polyvinylidene fluoride (PVDF) material. Different types of configuration were selected for the arrangement of the energy harvesting units. It is reported that, a maximum electrical

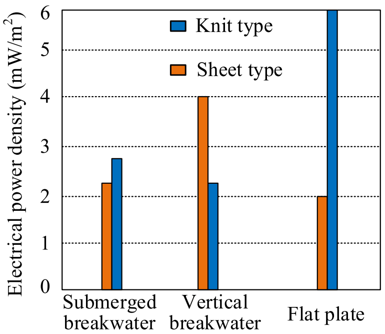

FIGURE 1. Comparison of electric power density between different types of coastal and sea configurations.

power density of 6 mW/m^2 was obtained by knit type FPED with a flat type structure. The knit type incorporates different evacuations inside the internal structure of the PVDFs to produce low oscillation created by cross drizzle towards them. Sheet type piezoelectric device produces the highest power density of 4 mW/m^2 during vertical breakwater conditions. The lowest available power per square-meter of the oceanic area was approximately 2 mW produced by sheet type harvester. Properties of several piezoelectric devices are enlisted in Table 2. The comparison of generated electric power density by five different FPEDs at offshore and nearshore locations, are graphically represented in Figure 2 [31].

TABLE 2. Properties of different painted piezoelectric devices.

Device	Substrate thickness (mm)	Substrate density (kg/m^3)	Material	Young's modulus (MPa)	Stiffness, EI (Nm^2)
$FPED_1$	10	1250	Silicone	3.2	0.096
$FPED_2$	15	1250	Silicone	3.2	0.309
$FPED_3$	20	1250	Silicone	3.2	0.699
$FPED_4$	12	1190	PVC	3.1	2.650
$FPED_5$	15	1190	PVC	3.1	6.360

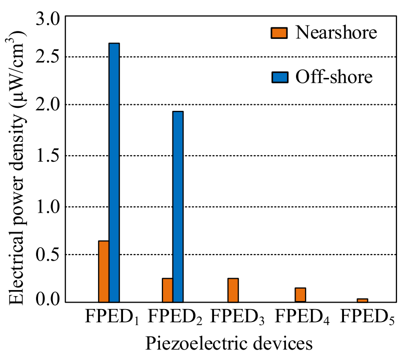

FIGURE 2. Comparison of electric power extracted by several FPED at nearshore and offshore locations.

The first two devices $FPED_1$ and $FPED_2$ are made of silicon material and have stiffness of 0.096 and 0.309 Nm^2, respectively. They can generate comparatively more electrical power at offshore location than that of at the nearshore [1]. The maximum produced electrical power density for nearshore location is approximately 0.65 μW/cm^3. It is decreasing exponentially to the minimum power density (around 0.05 μW/cm^3), obtained by the fifth device $FPED_5$, which is made of polyvinyl chloride (PVC) material and has stiffness of 6.36 Nm^2. The generated power by the device at offshore location is approximately zero.

IV. CONFIGURATIONS OF PIEZOELECTRIC DEVICES AS ENERGY CONVERTERS

The effectiveness of piezoelectric energy harvesters depends on the degree of freedom of the deformation, which in turn influences the coefficient of piezoelectric materials as enlisted in Table 3. Because of simplicity in design infrastructure of piezoelectric devices, most of the cases the effect of d_{31} is implemented. Design of piezoelectric devices considering d_{14} and d_{15}, is complex despite having large value of coefficients. Figure 3 illustrates the process of generating electricity using the coefficient, d_{15} of the piezoelectric material.

TABLE 3. Different charge constants of piezoelectric materials.

Piezoelectric coefficient	Estimated magnitude (pC/N)	Frequency of application in research
d_{14}	10–18.9	Low
d_{15}	6–9	Low
d_{33}	3–6.5	Medium
d_{31}	1–2.5	High

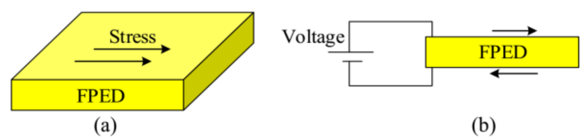

FIGURE 3. Graphical representation of the configuration of piezoelectric material and applied force: (a) 3D and (b) cross-sectional view.

The typical effect of d_{15} is greater compared to the effect of d_{31} and d_{33} in case of PZT material. It is analyzed that piezoelectric device performs well as an energy harvester during the application of cutoff stress to it [90]. The energy production of piezoelectric device in a two-stage operation process is depicted in Figure 4 [3], [21]. The energy harvesting device is mounted on the metal plate and supported by a vertically placed structure. In this configuration, the vibratory sections are excited by the force exerted by low-velocity water waves. The positive outcome of this structure is the increasing resultant vibration frequency. That is done by the two separated piezoelectric devices with low frequency highly changing oscillation of the floating buoy. It is analyzed that, a floating buoy of 7.62 cm diameter can contribute to produce 0.06 mW to 0.18 W electric power [21]. The deformation process of piezoelectric energy harvester due to the applied force exerted by fluid is illustrated in Figure 5 [91]. In order to increase the

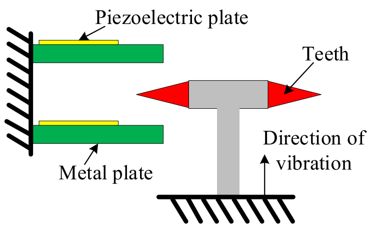

FIGURE 4. Schematic arrangement of 2-stage energy harvester.

electrical power generation, several segments of piezoelectric layer can be used as shown in Figure 5 (a).

In this case, PVDF is used as the piezoelectric material and adjacent energy harvesting units are separated by silicon layer. This configuration is called dual core type flexible piezoelectric device and it generates electric field when stress is applied that causes the deformation. A single core type piezoelectric transducer is also depicted in Figure 5 (b). The transducer is made of one PVDF layer and two silicon layers. The generated electric field lines in both cases (dual core and single core) are indicated by arrows in the piezoelectric layer. The deformation process of piezoelectric diaphragm due to force exerted by fluid flow is illustrated in Figure 6 [1], [92]. In the figure, the maximum pressure is denoted by P_{max}. The flexible diaphragm is vibrated by the pressure generated from the liquid flow. The complete scenario is like a wave carpet swimming on the oceanic waves. In this system, if a layer of piezoelectric material is merged with the diaphragm, electrical voltage is produced between the terminals of the electrodes connected to the diaphragm.

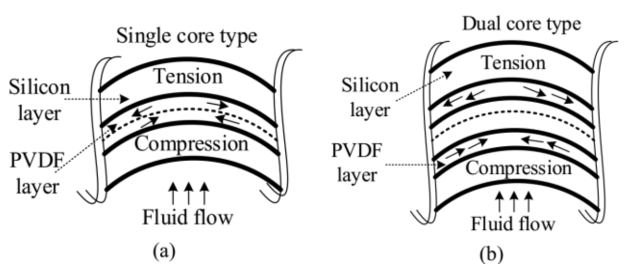

FIGURE 5. Depiction of inner stress field in FPED caused by a liquid force: (a) Single core type and (b) dual core type.

It is possible to generate electrical power in watt scale using the most prominent PVDF material-based harvesters. Most of the application areas include the power supply to the sea monitoring appliances such as robots, different sensing devices as well as floating harbors. Use of multiple piezoelectric material based WECs can improve the relative energy conversion efficiency of the harvesting systems. This methodology is verified by an experimental set up with electric potential of 2.2 V and power of 0.2 μW by applying a stressing pressure of 1.196 kPa with 20 Hz vibrational frequency. A piezoelectric WEC with floating and sinking configuration is depicted in [93]. The energy harvester is made of a semi-submerged type structure which can vibrate according to the dynamic oscillation of the oceanic wave. The cantilever plates are attached to the semi-submerged member for continuously forming and deforming of the piezoelectric device due to the exerted force of water flow.

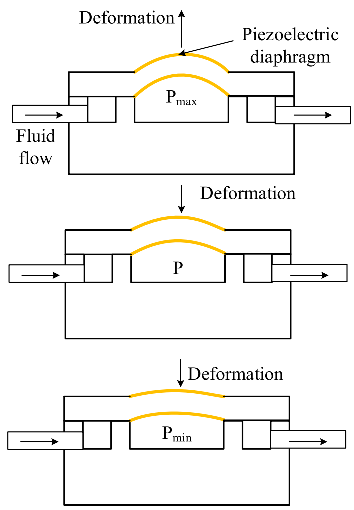

FIGURE 6. Illustration of the deformation process of piezoelectric devices.

The electric voltage is generated by converting the stress provided to the piezoelectric transducer by utilizing the characteristics of the device material. A low cost piezoelectric WEC is developed in [94] including disk type piezoelectric strips. The oscillating motion of the sea water rotates the cylinder that incorporates the piezoelectric disks. The whole cylinder is connected to the seabed through a flexible cord. A pendulum, subjected to the cylinder rotation, is placed inside the cylinder in such a way that it can contribute to the deformation of the piezoelectric strips. The kinetic energy of the wave motion is converted into electrical power by piezoelectric disks.

A floating type oceanic WEC incorporating piezoelectric bar made of lead zirconatetitanate material is illustrated in Figure 7 [36]. A vertical lever is attached to the bar. It contributes to magnify the force exerted by oceanic wave. In order to convert the oscillation of the waves into vibrations, a mass-spring configuration is utilized. In this system, two piezoelectric members connected to the mass, produce electrical power by converting and magnifying the kinetic energy of the waves. Displacement of the oceanic waves on the sea surface is denoted by v which is a function of the position, x and time, t. The peak amplitude and the wavelength of the wave are denoted by A, W, respectively and l, w denote the length and width of the energy extractor, respectively.

At the time when the whole energy transducer is limited by the anchor or other type of fixing to keep the dynamics of the waves, the position becomes approximately equal to the x_1 as presented in Figure 7. The system associates the floating buoy connected to the seabed by connecting rod [30]. Figure 8 and 9 show the process of energy extraction mechanism from OWE using piezoelectric materials by utilizing the heaving and pitch motion.

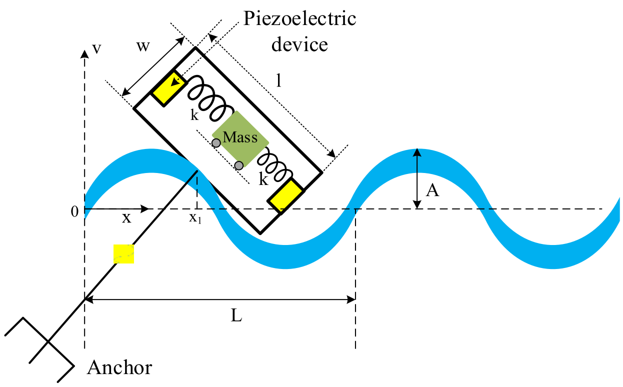

FIGURE 7. Schematic depiction of the flexible energy harvester on sea waves.

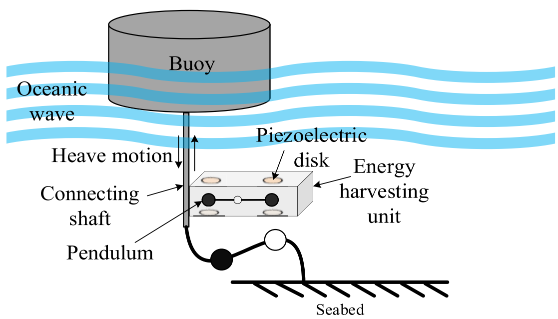

FIGURE 8. Illustration of heaving motion type oceanic energy extraction system.

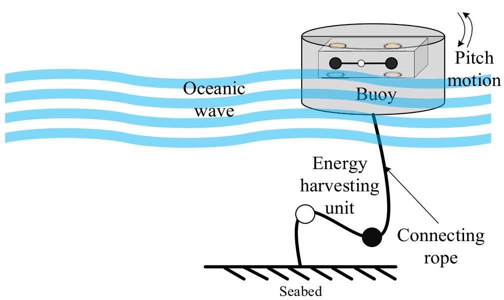

FIGURE 9. Illustration of pitching motion type oceanic energy extraction system.

The converter shown in Figure 8 includes piezoelectric device which is fixed to the connecting rod. Due to the heaving motion of the buoy, rolling motion is produced in the piezoelectric device by dragging either sides of the chassis. Therefore, electrical energy is produced by transferring the mechanical motion of the pendulum to the disks. For the energy harvester shown in Figure 9, the buoy hosts the complete chassis including the piezoelectric units. The pitching motion of the float contributes to the generation of electrical energy. An ocean energy harvesting device is designed using PZT piezoelectric material and the operation process of the converter is figuratively explained in Figure 10 [30]. The whole system mainly has four piezoelectric disks and one balance type pendulum.

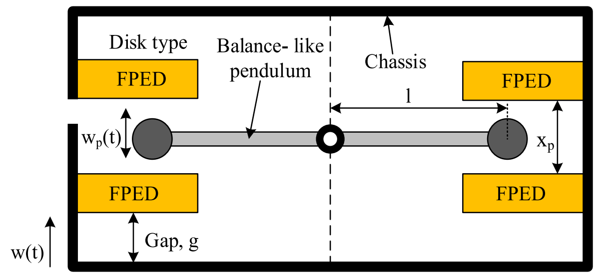

FIGURE 10. Methodology of balance-like physical pendulum harvester.

The separation distance between two vertically placed piezoelectric plates is denoted by x_p. All the components are enclosed inside a rectangular box made of brass material. $w(t)$ and $w_p(t)$ are the velocity of the rectangular chassis and the pendulum, respectively. The water enters inside the box and hits the left part of the pendulum. The balls of the pendulum start oscillating and touch the PZT disks and thus vibrate the disks. Finally, electricity is produced due to the deformation of the energy harvesting disks. An advanced methodology of WEC using piezoelectric material is designed in [37] as illustrated in Figure 11.

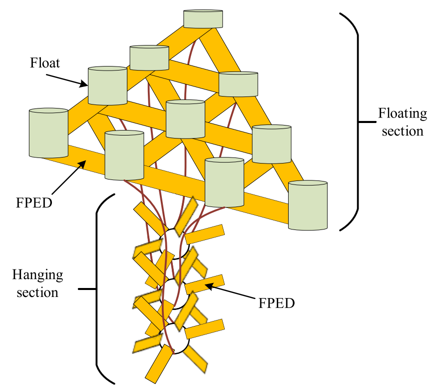

FIGURE 11. Schematically design of EFHAS.

The complete system mainly consists of one floating unit and one hanging structure. Hence it is known as elastic floating unit with hanging structure (EFHAS). All the floating sub-sections are interconnected by flexible piezoelectric devices. The hanging structure consists of three vertically placed FPEDs and three horizontally arranged FPEDs. In general, the kinetic energy caused by the surface wave can be extracted by the floating unit. The horizontal unit of the hanging structure has the capability of generating electricity from the OWE by utilizing the effect of heaving motion. On the contrary, the vertically hanging unit produces electricity from both vortex and current energy. The important advantage of this process for harvesting ocean energy, is the feasibility of producing electrical energy from very low wave forces. The generated unbalanced electrical power is made stable using intermediate rectifier circuits. A scheme of hybrid wind-ocean farm is presented in Figure 12. Wind turbines contribute to extract wind energy and the OWE is harvested by the EFHAS [37] type piezoelectric WEC. It is evaluated that, the EFHAS helps the offshore wind power plant to be protected from the dynamic power of the oceanic waves. The floating section is further carried out under testing process in a water tank environment as illustrated in Figure 13 and 14 [37].

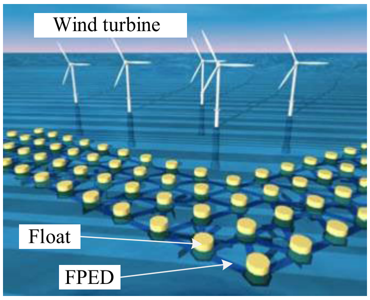

FIGURE 12. Ocean energy farm including offshore wind turbines [37].

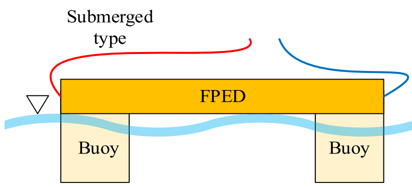

FIGURE 13. Submerged type segregated floating structure of EFHAS.

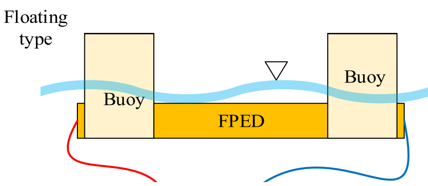

FIGURE 14. Floating type segregated structure of EFHAS.

The applied oceanic wave has the wavelength of 1 m and the amplitude is 0.077 m. The electric performance of two floating units including floats of 115 mm height and 85 mm width, are evaluated. The submerged type harvester has piezoelectric device mounted on the body of floaters. In both cases (floating and submerged units) the floaters are fixed to the bottom of the tank through connecting rods. The FPED is made of PVDF material and it is dual core type in structure. To get satisfactory electricity production, the length of the PVDF layer is chosen from 0.1 mm to 0.5 mm and it is suggested not to choose greater than 0.5 mm for obtaining better deformation of the device.

An OWE extraction system was discussed in [95] using sheet of piezoelectric material as the energy harvester which is presented in Figure 15. The system is studied considering

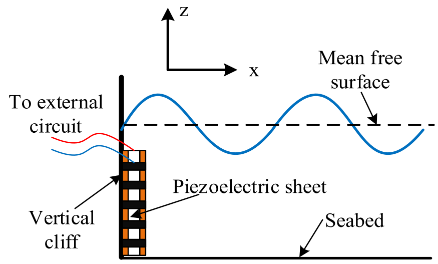

FIGURE 15. Hydrodynamic-piezoelectric harvester configuration.

an oceanic environment, a vertically placed piezoelectric thin plate, and an external circuitry. When oceanic wave passes through the sheet, it causes the stress of the harvester and due to the characteristics of the piezoelecric transducer, electrical voltage is generated which is further transferred to the external circuit. The most important conveniences that can be obtained by this kind of energy conversion schemes are: (1) harvesting the applicable electrical energy and (2) the oscillations caused by overflowing loads.

V. MATHEMATICAL MODELLING OF PIEZOELECTRIC WAVE ENERGY CONVERTERS

The methodologies of wave energy extraction using piezoelectric devices are mathematically modeled in this section to characterize the performance factors. The wave dynamics, deformation of the harvesting devices, generated electric charge, voltage, and power are expressed by mathematical equations. The geometric depiction of FPED with supporting beams, is represented in Figure 16 [31], where x_1 and x_3 denote the length of the paint of piezoelectric layer from the edges of the beams to the edges of piezoelectric area.

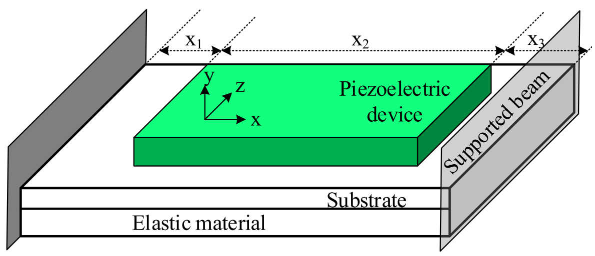

FIGURE 16. Modeling a painted FPED.

The length of the active FPED is represented by x_2. The purpose of this kind of footstep is to mathematically analyze the performance of the FPED for electricity generation. There is a coating of electrode material on the painted piezoelectric area and this type of coating has small thickness which is provided to the adjacent layer. The vibration at neutral position of the under dammed beam can be expressed as:

$$\frac{\partial^2 M(x,t)}{\partial x^2} + m(x)\frac{\partial^2 w(x,t)}{\partial t^2} = F_e \quad (1)$$

$$w(x,t) = w_r(x,t) + w_b(x,t) \quad (2)$$

where $M(x, t)$ is the internal moment of the supporting beam at the cross-sectional point, $m(x)$ denotes the mass of the piezoelectric device for per unit length, $w(x, t)$ represents the diagonal strain, and the force exerted by the flow of fluid, is denoted by F_e. The transverse strain, $w(x, t)$, is a combination of the displacement of the beam relative to the base, $w_r(x, t)$ and the displacement of the base, $w_b(x, t)$ as expressed by (2). The effect of $w_r(x, t)$ is greater than that of $w_b(x, t)$ and hence $w(x, t)$ can be regarded as $w_r(x, t)$. The internal moment of the beam can be expressed as:

$$M(x, t) = EI(x)\frac{\partial^2 w_r(x, t)}{\partial x^2} + \varepsilon V(x, t) \tag{3}$$

where the stiffness of the piezoelectric material is denoted by $EI(x)$, $V(x, t)$ is the generated voltage across the electrodes connected to the piezoelectric device, and ε is the permittivity of the particular deformation of the device. The governing equation for evaluating the mechanical properties of the piezoelectric device can be obtained by substituting (3) into (1) as:

$$\frac{\partial^2}{\partial x^2}\left[EI(x)\frac{\partial^2 w_r(x, t)}{\partial x^2} + \varepsilon V(x, t)\right] + m(x)\frac{\partial^2 w_r(x, t)}{\partial t^2} = F_e \tag{4}$$

The transient generated voltage in differential form can be represented as follows:

$$C_p\frac{\partial V(t)}{\partial t} + \frac{V(t)}{R_l} = \sum_{q=1}^{\infty} E_p d_{31} t_p b_p \left[\frac{\partial W_q(x)}{\partial x}\right]_{x_1}^{x_1+x_2} \left(\frac{d\eta_q}{dt}\right) \tag{5}$$

where the internal capacitance of the piezoelectric device is denoted by C_p, R_l is the resistance of the resistive load connected across the external terminal of the device, E_p, d_{31}, t_p, and b_p are the constant of Young's modulus of elasticity, coefficient, separation distance between the middle of the piezoelectric layer and the neutral level, and width for particular piezoelectric device, respectively. $W_q(x)$ and η_q denote the normalized eigenvectors and the coordinates in time domain, respectively. Equation (5) describes that, the output voltage is subjected to the mechanical behavior of the piezoelectric device, C_p, R_l, and modal effect of the beam. The generation of electricity by applying mechanical stress in different directions to the piezoelectric device, is shown in Figure 17 [3].

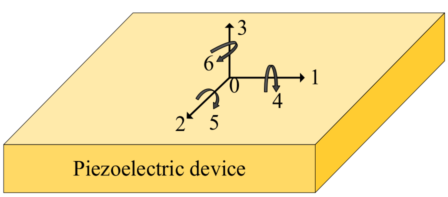

FIGURE 17. Illustrations of piezoelectric coefficients.

The relation among the displacement of electric field, the strength of the field, and the mechanical strain can be expressed as [35]:

$$\begin{aligned} S_p &= E_p\sigma_p + d_{pk}E_k \\ D_i &= d_{ip}\sigma_p + \varepsilon_{ik}^T E_k \end{aligned} \tag{6}$$

where the subscripts, $i = 1, 2$, and 3, denote the coordinate axes and d_{pk} denotes the piezoelectric material constant which can be derived from the stress matrix as [96]:

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{'11}^T & \varepsilon_{'12}^T & \varepsilon_{'13}^T \\ \varepsilon_{'21}^T & \varepsilon_{'22}^T & \varepsilon_{23}^T \\ \varepsilon_{31}^T & \varepsilon_{32}^T & \varepsilon_{33}^T \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{7}$$

S_p defines the inputted strain in the p direction, σ_p is the applied mechanical stress, D_i is the displacement of the electric field along i axis, E_k is the produced electric field along k axis, E_p presents the Young's modulus constant inside a static electric field, ε_{ik}^T is the coefficient of dielectric material for certain deformation. A dynamic model of a piezoelectric energy harvester is developed in [97] considering the system depicted in Figure 18. In the configuration, the vibration of the end mass caused by some other mechanical means, creates the deformation of the piezoelectric bimorph which in turn produces alternating electrical power.

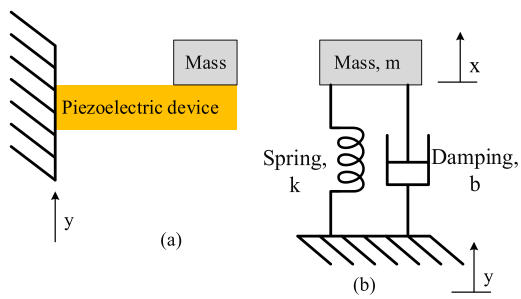

FIGURE 18. (a) Piezoelectric energy harvesting system, (b) Spring-mass-damper model.

The harvester as shown in Figure 18 (a), can be presented by the model interpreted in Figure 18 (b) in which m denotes the mass and b, k are the damping coefficient and stiffness of the bimorph, respectively. The displacement of the end mass and the piezoelectric beam are presented by x and y, respectively. The dynamics of the piezoelectric device can be expressed as:

$$F = m\frac{d^2\delta}{dt^2} + b\frac{d\delta}{dt} + k\delta \tag{8}$$

where F is the applied force to the dynamic structure and δ denotes the relative displacement of the end mass with respect to the piezoelectric bimorph. If the impedance of the mechanical load becomes equal to $b + j((k/\omega) - \omega m)$, maximum electrical power can be achieved using the harvester [97]. The natural frequency of resonance of the mechanical system is $\omega = \sqrt{k/m}$ at which the amplitude of the mechanical input impedance is the minimum. The possible largest produced electrical power due to the application of a sinusoidal mechanical excitation of amplitude, F_m can be derived as:

$$P_m = \frac{F_m^2}{8b} \tag{9}$$

From (9), the maximum generated power does not depend on the vibrational frequency of the mechanical system and is solely subjected to the peak value of applied force and the damping of the bimorph. Experimental configuration of a piezoelectric WEC is schematically sketched in Figure 19 [19].

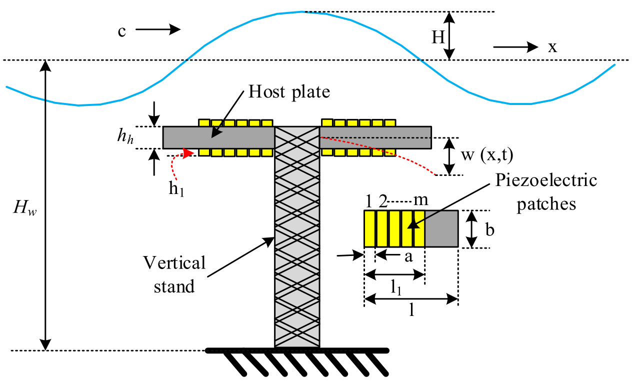

FIGURE 19. Arrangement of a piezoelectric energy harvester.

The horizontally arranged piezoelectric cantilever plates are mounted on the vertically placed static structure under the water. The oceanic wave hits the piezoelectric device and the kinetic energy produced from the transverse motion of the waves is converted into electricity. H, c are the height and velocity of the oceanic wave flowing in the x direction, respectively, L is the total length of the energy converter, H_w is the distance from the bottom of the sea to the middle point of the wave amplitude. The deformation of the piezoelectric device due to the exerted force of the waves is denoted by $w(x, t)$, h_h is the height of the host plate and h_1 is the difference between the lower edges of the plate and the patch unit. The complete piezoelectric plate is a combination of several piezoelectric segments each of having length a and width b. The generated electric charge, Q and voltage, V by the each of the piezoelectric segments can be expressed by

$$\begin{cases} Q = \dfrac{-e_{31}b(h+h_1)}{2} \\ \displaystyle\sum_{n-1}^{\infty}\left(\left.\frac{dW_n(x)}{dx}\right|_{(x-ia)} - \left.\frac{dW_n(x)}{dx}\right|_{(x-(i-1)a)}\right) q_n(t) \end{cases}$$
$$\begin{cases} V = \dfrac{-e_{31}(h+h_1)}{2C_p} \\ \displaystyle\sum_{n-1}^{\infty}\left(\left.\frac{dW_n(x)}{dx}\right|_{(x-ia)} - \left.\frac{dW_n(x)}{dx}\right|_{(x-(i-1)a)}\right) q_n(t) \end{cases} \tag{10}$$

where C_p is the capacitance per unit width of the piezoelectric device, W is the eigenvector, and q_n is for the generalized coordinates. Another model of wave energy harvesting system is proposed in [18] by using piezoelectric cantilever plates attached to a floating buoy. The buoy is flexible to keep track of the dynamics of oceanic wave in medium and deep sea environment. The size of the buoy is optimized considering the impacts of the shapes on the produced electrical power. The electrical output performance of the energy harvester can be modeled in terms of the electric charge and voltage as (19) where ω_n is the oscillating frequency of the piezoelectric plates and τ is the simulation time. Simulation results bring to light that it is possible to produce a maximum power of 24 W by utilizing the energy harvesting process. Figure 20 represents the hydro-mechanical modeling of the piezoelectric material based oceanic WEC [46].

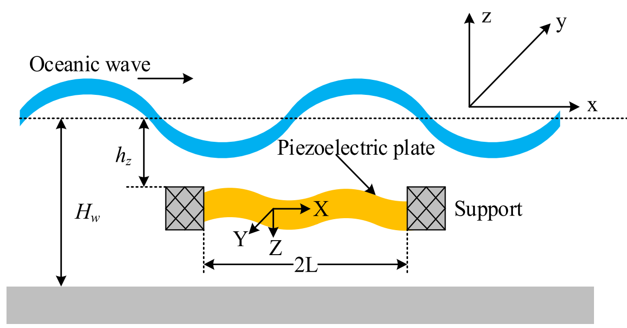

FIGURE 20. Modeling of a piezoelectric oceanic energy harvesting unit.

During the modeling bimorph type piezoelectric plate is considered and placed under the sea water. The global reference frame for the system is denoted by (x, y, z) and coordinate system for the bimorph is defined by (X, Y, Z). The length of the plate is $2L$ and it is located at h_z distance from vertical neutral point of the wave. The depth of the seabed from the water surface is chosen as H_w. The vibrational motion of the bimorph plate due to the kinetic energy of the waves, can be mathematically modeled as:

$$\frac{\partial^2 M_{XX}}{\partial X^2} - I_b \frac{\partial^2 W}{\partial t^2} = q \tag{11}$$

where M_{XX} is the moment of internal deformation of the plate, $W(X, t)$ is the displacement in vertical direction, I_b refers the density of the surface of the plate, and q is for surface load active in vertical direction. M_{XX} and I_b can be expressed as:

$$M_{XX} = \int_{-d_b/2}^{d_b/2} \sigma_{XX} Z dZ \tag{12}$$

$$I_b = \int_{-d_b/2}^{d_b/2} \rho(Z) dZ = \rho_o h_o + 2\rho_p h_p \tag{13}$$

where $h_b = h_o + 2h_p \ll L$, overall height of the plate, σ_{XX} is the applied stress to the bimorph, ρ_p and ρ_o denote the

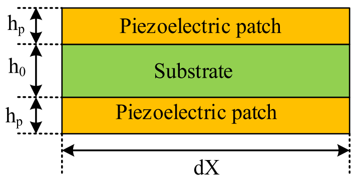

FIGURE 21. Illustration of the piezoelectric bimorph.

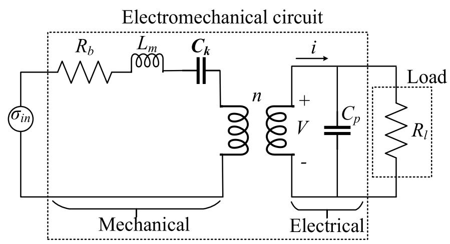

FIGURE 22. Electrical equivalent circuit of piezoelectric energy harvester.

density of the bimorph material and the substrate between two piezoelectric layers, respectively as shown in Figure 21.

h_0 and h_p are the height of the piezoelectric layer and intermediate substrate layer, respectively. The generated electric charge, Q can be expressed relating the electric potential, V, and the capacitance of the piezoelectric bimorph, C_p as:

$$Q = -\theta \frac{\partial^2 W}{\partial X^2} - C_p V \tag{14}$$

where θ is the coupling factor of piezoelectric bimorph plate. The essential boundary condition that must be satisfied to get satisfactory performance of the piezoelectric energy harvester is stated as:

$$W(\pm L, t) = \left. \frac{\partial W(X,t)}{\partial X} \right|_{X=\pm L} = 0 \tag{15}$$

When the bimorph plate is plunged into oceanic water, the waves exert the surface load, q, as the exciting force to the plate which causes the vibration and finally electricity is produced. The electromechanical representation of a piezoelectric transducer for generating electrical energy from mechanical vibration, is demonstrated in Figure 22 [98]. The applied stress is represented by, σ_{in} and R_b is the damping of the device, L_m is the mass of the transducer, and the stiffness is denoted by $1/C_k$.

By applying mesh analysis to the mechanical part of the circuit, the stress can be expressed as:

$$\sigma_{in} = R_b \frac{dS}{dt} + nV \tag{16}$$

where S denotes the strain, n is transformer's turns ratio, and V denotes the generated voltage. From Ohm's law, the voltage can be expressed as:

$$V = iR_l \tag{17}$$

where R_l is the external load connected to the harvester and i denotes the load current which can be defined as:

$$i = awl_e d_{31} E_p \frac{dS}{dt} \tag{18}$$

where a, w, l_e, d_{31}, and E_p are the constant which vary from 1 to 2 according to the wiring of the transducer, width of the harvester, length of the electrodes connected to the harvester, piezoelectric material coefficient, and coefficient of Young's modulus for the harvester, respectively. Now, the strain can be expressed relating R_l and i as:

$$\sigma_{in} = R_b \frac{dS}{dt} + niR_l \tag{20}$$

By substituting (19), as shown at the bottom of the page, into (20), the external load can be related to the mechanical part of the circuit as:

$$\sigma_{in} = R_b \frac{dS}{dt} + nR_l(awl_e d_{31} E_p \frac{dS}{dt}) = R_b \frac{dS}{dt} + n\alpha_p R_l \frac{dS}{dt} \tag{21}$$

$$\sigma_{in} = (R_b + n\alpha_p R_l)\frac{dS}{dt} \tag{22}$$

where $\alpha_p = awl_e d_{31} E_p$ is the modulus of the piezoelectric harvester. Equation (20) explains that R_l must be adjusted by the mechanical energy scaling by a multiplier of $n\alpha$ and this result is one of the most essential benefactions for the energy conversion process.

VI. PROCESSING OF PIEZOELECTRIC DEVICES

The properties of piezoelectric materials were first invented by great physicists Pierre Curie and Jacques Curie in 1880 [99]. Most available types of piezoelectric materials are PVDF and PZT which are required to be processed to make the energy harvesters. The processing of piezoelectric

$$\begin{cases} Q = \dfrac{-e_{31} b(h+h_1)}{2} \displaystyle\sum_{n-1}^{\infty} \left(\left.\frac{dW_n(x)}{dx}\right|_{(x-ia)} - \left.\frac{dW_n(x)}{dx}\right|_{\{x-(i-1)a\}} \right) \frac{\int_0^i w_n(x)dx}{\rho b h \omega_n B_n} \int_0^t p(\tau)\sin\omega_n(t-\tau)d\tau \\ V = \dfrac{-e_{31}(h+h_1)}{2C_p} \displaystyle\sum_{n-1}^{\infty} \left(\left.\frac{dW_n(x)}{dx}\right|_{(x-ia)} - \left.\frac{dW_n(x)}{dx}\right|_{\{x-(i-1)a\}} \right) \frac{\int_0^i w_n(x)dx}{\rho b h \omega_n B_n} \int_0^t p(\tau)\sin\omega_n(t-\tau)d\tau \end{cases} \tag{19}$$

material such as PVDF incorporating elastic materials such as silicon, resin, rubber as well as textile is described in Figure 23 [31]. Flexible PZT based energy extractors can produce up to 200 V at open circuit and 35 μA current at short circuit condition by providing biomechanical flexing and relaxing movement [99].

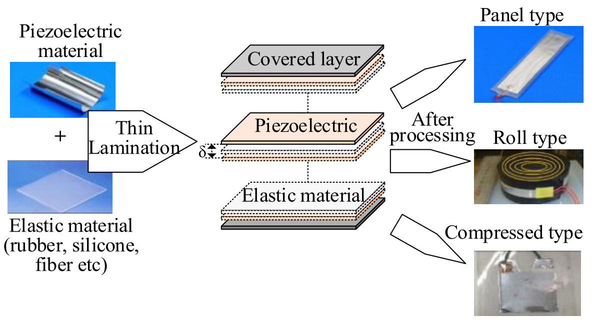

FIGURE 23. **Processing of FPED.**

The PZT materials are combined with appropriate proportions in order to make multi-layer piezoelectric device. The adjacent layers of piezoelectric material and the elastic material are attached together by using very thin lamination layer. A certain separation, δ is kept between the two adjacent piezoelectric layers to make a bimorph structure. The final stage of the device is obtained through different processing operations. The usable piezoelectric device may be of panel type, roll type, and compressed type depending on the design requirement [100]. Figure 24 describes the process of painting a piezoelectric device by using spray through a nozzle.

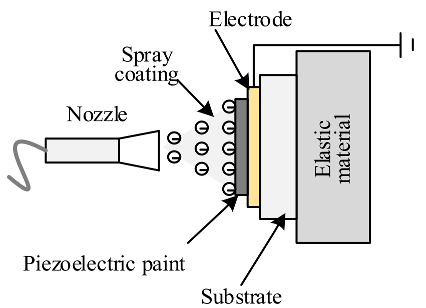

FIGURE 24. **Processing painting type of FPED.**

The design of a piezoelectric device can be optimized by considering the number of piezoelectric layer and the separation, δ including proper selection of elastic material. The efficiency of the piezoelectric device in terms of electric power harvesting may be improved by employing elastic material which has high elasticity property [101]. The interfacing layer between the piezoelectric layer and the elastic layer may cause the reduction of output voltage because of the cutoff stress during the deformation of the device. Between the piezoelectric material and the elastic material, a layer of substrate and an electrode are placed. The produced electricity is received through the copper electrode. The coating process is done on the layer of piezoelectric material through direct spraying of electric charge.

Depending on the grade of deformation and weather-beaten conditions caused by the oceanic waves, the flexible piezoelectric device including the painted layers can be used as the electrical energy producer from the OWE. The top and side views of the unimorph stage of the flexible piezoelectric device associated with the painted layer and proper lamination are shown in Figure 25 [31].

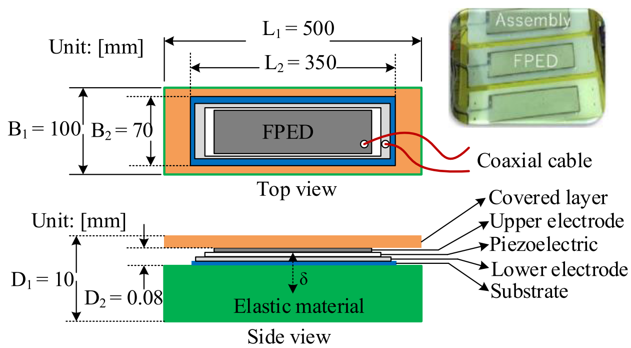

FIGURE 25. **Laminated configuration of a painted FPED.**

The lower electrode made of copper painting on the poly phenylene sulfide, is coated with piezoelectric paint. The upper lower electrodes are separated by the painting layer of piezoelectric material. The elastic material and the lower copper electrode are separated by proper layer of resin substrate. For the safety purpose, the covering layer is placed on the upper electrode to overcome the unpredictable forces that may be caused by oceanic wave. The piezoelectric layer is denoted by D_2 which is 80 μm in this case and D_1 of 10 mm, denotes the complete section from the bottom of elastic layer to the top of the covering layer. The length of whole painted piezoelectric device L_1 is 500 mm and the width B_1 is 100 mm, while the piezoelectric paint layer covers the area of 24,500 mm^2 (length L_2 is 350 mm and width B_2 is 70 mm).

The generated electricity by the piezoelectric device is provided to the external circuits through coaxial cables. The 3-D geometric view of a piezoelectric energy harvester is shown in Figure 26 [3], [41]. The device is mainly consisted of two layers of piezoelectric material PVDF and a layer of foam material. The piezoelectric device is subjected to deformation because of the mechanical stress caused by the flow of water.

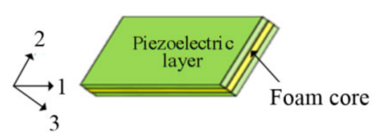

FIGURE 26. **Piezoelectric harvester: green PVDF, yellow foam core.**

The possible electrical power generation by a piezoelectric device under deformation process can be expressed as:

$$P = \frac{V^2}{2R_l\left[1+\left(\frac{CR_l}{\omega}\right)^2\right]} \tag{23}$$

where V is the output electric voltage, C, R_l, and ω are the internal capacitance of the piezoelectric device, the externally connected resistive load, and the operating frequency of the generator, respectively. The model is simulated and 1 mW electrical power is obtained by the device operating at 10 Hz frequency [41].

VII. POST-PROCESSING OF GENERATED ELECTRICAL ENERGY

The generated electrical power from a piezoelectric transducer is alternating in nature with low amplitude and frequency. Post-processing must be performed to make it usable for electrical load. Several researchers suggested to employ multistage power conversion techniques to store the harvested power using energy storage devices as elucidated in this section. The general process of producing electricity using piezoelectric transducer is given in Figure 27 including an electrical equivalent circuit of the energy harvester [102].

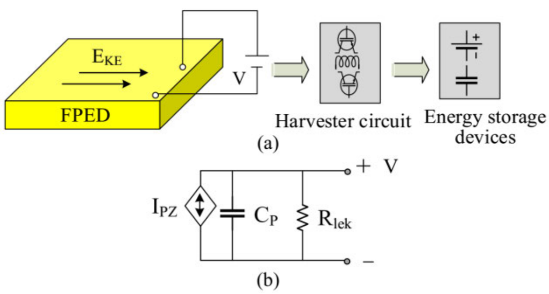

FIGURE 27. Piezoelectric harvester: (a) circuit with energy storage and (b) electrical equivalent model.

The applied kinetic energy, E_{KE} causes the deformation of the transducer and electricity, V is produced due to the piezoelectric effect of the device, as shown in Figure 27 (a). An intermediate electrical system made of transistors, transfer the produced electrical energy to a capacitor or battery. The whole piezoelectric material based energy converter can be represented by an electrical circuit as shown in Figure 27 (b), considering an ac current source, I_{PZ} and a parallel impedance of piezoelectric capacitance, C_P, and the leakage resistance of the device, R_{lek}. The output voltage, V is further rectified to get pure dc voltage to charge an energy storage device. A typical implementation of piezoelectric transducer to charge an energy storage device by the generated electrical energy, is shown in Figure 28 [91].

At the first stage, mechanical vibrations are created in the piezoelectric device by kinetic energy and due to the characteristics of the material, alternating electric voltage is generated across the device. To transfer the generated electrical

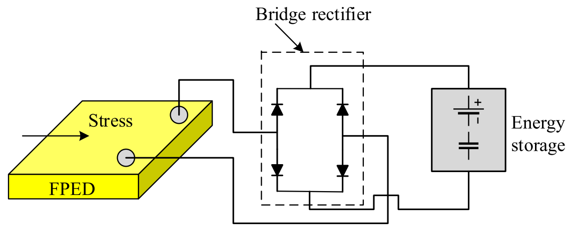

FIGURE 28. Design of energy storage system including FPED.

energy to an energy storage, an intermediate stage of energy conversion (ac-dc) is employed. In this case, a full wave bridge rectifier is used to perform ac to dc power conversion in the system. An energy harvesting technique using piezoelectric generator is designed and the comparison between the proposed and traditional harvester is shown by block diagram as shown in Figure 29 [98]. When mechanical stress is applied to the harvester, alternating electricity is produced and due to the low generated voltage, it is amplified by the dc-dc converter circuit. The biasing of the converter circuit by external power source reduces the conversion effectiveness of the system illustrated in Figure 29.

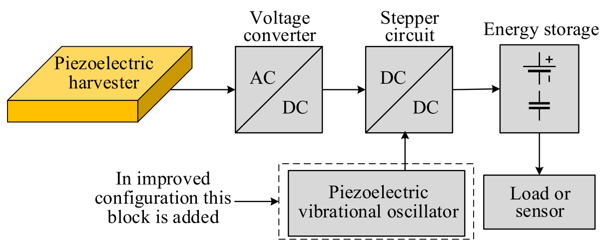

FIGURE 29. Energy harvester design piezoelectric oscillator.

To improve the efficiency of the harvesting scheme, the external biasing is avoided, and an oscillator is employed. This oscillator produces sinusoidal signal of required voltage and frequency for the dc-dc converter. An experiment is carried out and approximately 90% efficiency is offered with 300 μW electrical power for 1.2 MΩ external resistive load. The verification system of the proposed recycling concept is schematically depicted in Figure 30. A new energy recycling technique is proposed to increase the overall electrical energy production capacity of a piezoelectric based energy harvester [103].

The purpose of energy recycling is to avoid the loss of the stored charge by grounding. The experiment is carried out considering forces exerted by traveling waves. In general, the regulator includes rectifier circuits which converts the alternating output voltage of the piezoelectric device into smooth dc. The rectified voltage is given to the variable delay circuit. Clock pulses are generated from the output waveforms of the harvester. Energy reusing concepts are implemented in the digital delay circuit to recover the energy in the form of pulse train having frequency equal to that of shaking the transducer. Before applying the pulses to the piezoelectric

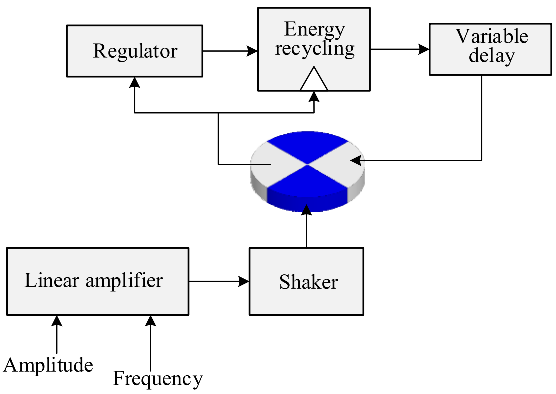

FIGURE 30. Block diagram of energy recycling system.

device again, an intermediate phase shift circuitry is used to analyze the phase difference of different signals from different electrodes. In this methodology, no external power supply is required for the delay circuit. The proposed energy reusing concept can capture 10% more electrical energy compared to that includes no energy recycling system.

VIII. EXPERIMENTAL TESTS OF PIEZOELECTRIC WAVE ENERGY CONVERTERS

The transduction characteristics of piezoelectric energy harvesters were verified by experiments in several research articles. Some of these conducted tests for analyzing the deformation of devices under certain strain or vibration and some also includes the employment of the harvesters as WECs. an experimental set up is performed in [30] to evaluate the deformation of piezoelectric device for applying certain amount of stress which is drawn in Figure 31.

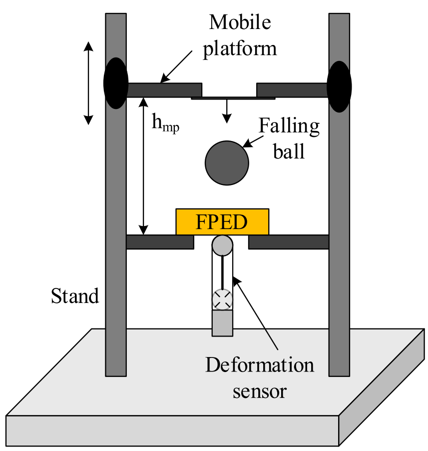

FIGURE 31. Experimental set-up for piezoelectric device.

The crucial purpose of this test is to govern and estimate the maximum amount of kinetic energy that can be applied to the piezoelectric energy harvester at a time. The testing system includes a fixed structure which hosts the piezoelectric disk on its base and the disk is assisted by the horizontal beams. A metal ball of specific mass is allowed to fall from the height directing the disk from the movable stand which can shift in vertical direction along the chassis. When the ball hits the disk, mechanical vibration is created in it. A linear variable differential transformer probe (Mahr 1300) which needs the estimating force of 0.75 N at the neutral, is used to estimate the deformation.

The actual deformation of the device can be estimated by Mahr Millitron which is coupled to the deformation sensor. Figure 32 shows the schematic diagram of experimentation based on laboratory of piezoelectric cantilever [37]. The purpose of this test is to characterize the effectiveness of electrical energy production of the energy harvester after applying certain amount of stress. The comparable density of the 100 mm long rectangular shaped bluff body ranges from 0.8 –1.2 mm. The maximum magnitude of the vibration is 77 mm and duration of the oscillation period is 0.8 s.

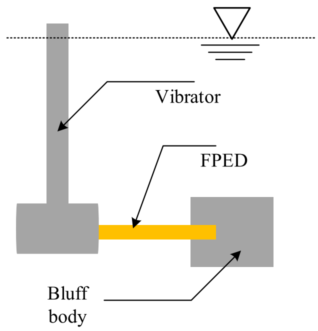

FIGURE 32. Test platform for vibration test of cantilever with a bluff body.

The volume of the cantilever plate is 17×10^3 mm^3 having length of 340 mm, width of 100 mm, and thickness of 5 mm. It is found that, the lower density of the bluff body can increase the rate of electrical power generation up to 50 % more compared to that of its unit density. An experiment was done in a laboratory to find deformation of piezoelectric device due to applied vibration. It is schematically shown in Figure 33 [91], [101]. The whole set up includes an artificial vibration producer on which the oscillation frequency depends. A small thick plate of flexible piezoelectric device and laser displacement meter are also available to observe the deformation in a personal computer with an intermediate

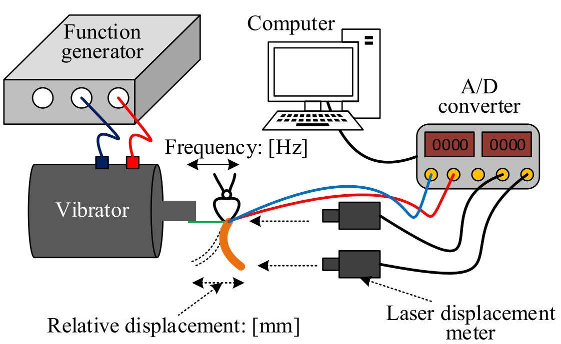

FIGURE 33. Experimental setup of vibration test.

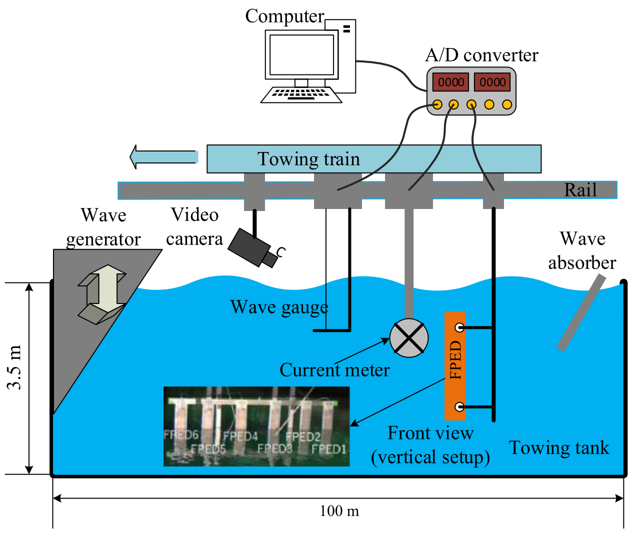

FIGURE 34. Experimental platform in towing tank test.

signal conversion by analog to digital converter. The generated electricity can also be measured by connecting external cables between the energy harvester and signal converter.

Figure 34 shows the practical implementation of the FPED for testing electrical performance of the device in an environment which is done in a laboratory [31]. The dimensions of the towing tank are considered as the length of 100 m, width of 8 m, and the depth of 3.5 m. The energy harvesters were being braced in both the vertical and horizontal directions by the strong frames and the jigs attached to the tank. To estimate the speed and height of the waves, the dynamic velocity meter and the wave gauge are used.

As for recording the scenario of the strain of FPEDs, a video camera is used directing to the device. A computer set up is established including an analog-to-digital signal converter with a preset 1 kHz sampling frequency to check and save the generated voltage. Most importantly, the artificial wave is created by the wave generator placed upper portion of the tank. The external terminals of the electrodes were connected to a data logger (model: NR-HV04, made by KEYENCE corporation) and the voltage is analyzed under open circuit condition. The maximum output voltage is found about 2.16 V by applying water waves having wave height of 0.15 m and velocity of 0.30 m/s in this experiment.

Figure 35 illustrates experimental platform for generating electricity by utilizing the effects of piezoelectric materials. In this test system, artificial water waves are produced by the wave maker and energy harvesting device is placed at the center of the water tank [91]. The wave gauge estimated 90 mm wave height and maximum output voltage is close to 9 V. Wave gauge is used to measure the wave height. When the waves hit the piezoelectric device, mechanical vibration is created inside it which in turn causes its deformation. Electric field is created across the piezoelectric device due to this kind of deformation. The length of the wave tank is about 8 m and there is a wave suppressor having length of 1.7 m.

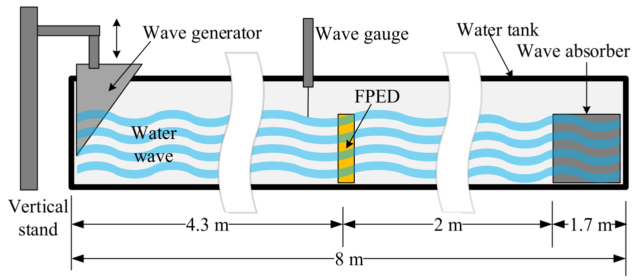

FIGURE 35. Experimental arrangement of wave energy harvesting using piezoelectric device.

The generated electric field in the experiment is illustrated in Figure 36. After analyzing the result is obtained by a method based on particle which is known as smoothed particle hydrodynamics (SPH) method. The analysis is carried out considering the regular water wave. The maximum generated electric potential is found at the bottom side of the piezoelectric device and it is 0.002 V. It implies that, more stress is provided by the waves to the lower part of the device compared to upper portion. Figure 37 presents the experimental set up view of the Eel structured piezoelectric WEC.

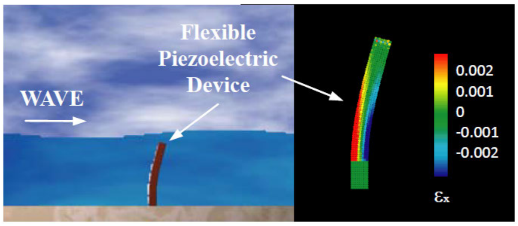

FIGURE 36. Evaluation of numerical result of deformation and internal strain field of the FPED caused by regular oceanic wave [91].

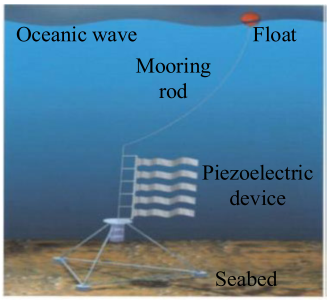

FIGURE 37. Eel structure piezoelectric energy harvester [3], [20].

This kind of WEH include Eel type generator to produce electricity from the kinetic energy available in the oceanic wave. The produced power can be utilized for the application of sea monitoring device without wire connections. In general, Eel generators cause the deformation of piezoelectric device by using the continuous downward motion of the flowing waves and thus creating an artificial Eel waves pattern. The output electrical power produced from such Eel swimming can be expressed as:

$$P_e = \frac{\eta_1 \eta_2 \eta_3 A \rho v^3}{2} \tag{24}$$

where η_1, η_2, and η_3 are the efficiencies of the hydrodynamic conversion, piezoelectric device, and the production of electrical energy, respectively. The cross-sectional area of the Eel structure is denoted by A, ρ is the specific mass density of water, and v is the speed of the flowing water. Batteries are used during the experiment to store the produced energy.

The advantages of Eel generators are the low cost consumer, flexible to scale in shape which significantly influence the power generation capability of the device. In addition, this type of energy harvester has the capability to recharge the energy storage devices used as distributed sources and greatly contributes to improve the life quality of water surrounded areas. A prototype of piezoelectric material based WEC is developed as shown in Figure 38. The model was designed to improve the energy conversion efficiency of the device (considering the effect of d_{13} coefficient) in which the piezoelectric plates are arranged in both the horizontal and vertical directions. It is practically come out that, if the number of piezoelectric plate is increased, more electrical power would be harvested.

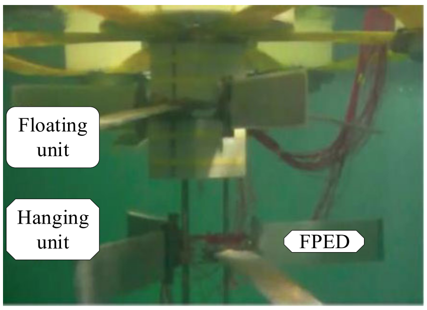

FIGURE 38. Configuration of a floating and hanging structure FPED in water [3], [38].

The experimental configuration includes both floating structure (top portion) and hanging structure (middle portion). Figure 39 presents the investigation of floating type piezoelectric oceanic WEC [38]. The complete set up includes a triangular shaped floating structure in which the floats are interconnected by flexible piezoelectric device, cameras for capturing the operation, and wave gauge to measure the wave properties such as height and wavelength.

Connecting rods were used to fix the floating unit to the bottom of water tank. In the experiment, two waves having time period of 0.8 and 1.0 s were considered as the excitation forces. About nine cases were analyzed with wave height, H/W ranging from 0.013 to 0.12. The height of the float located at the center of the floating structure and wavelength of water waves are denoted by H and W, respectively.

The deformation process having six degrees of freedom is observed from the video recording and it was analyzed using 3-D particle tracking velocimetry method. After evaluating the electrical performance of the energy harvester, it is suggested that power generation can be increased by governing the draft of the water flow for various wave properties. Figure 40 presents the geographical area of the field test of piezoelectric devices as WECs, which was organized in the northern site of Okinawa Island in Japan [31].

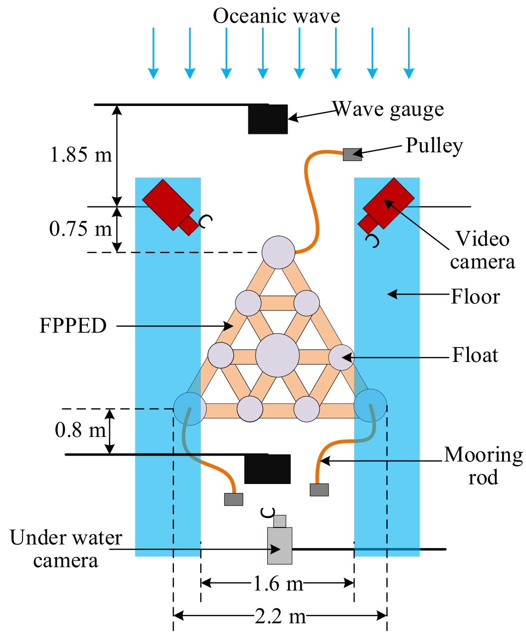

FIGURE 39. Experimental platform of a floating WEC.

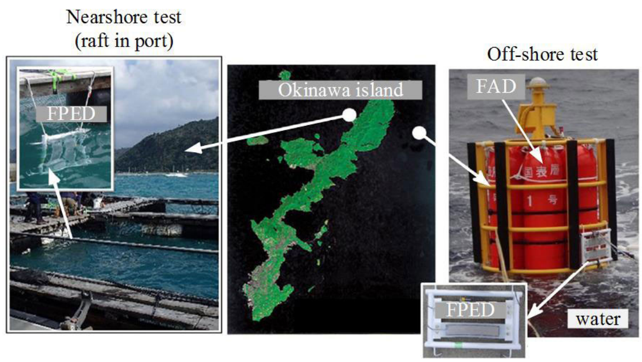

FIGURE 40. Field test of FPED at nearshore and offshore sites in the northern part of Okinawa Island in Japan [31].

TABLE 4. Experimental results of several piezoelectric WEH.

Structure of piezoelectric devices	Material	Voltage (V)	Power (mW)
Disk [2]	PZT	11.24	12.350
Flexible diaphragm [1], [92]	PVDF with silicone layer	2.20	0.0002
Flexible plate (FP) [1]	PVDF	1.15	–
FP [31]	PVDF	2.16	–
FP [91]	PVDF	9.00	–
Disk [30]	PZT-4	3.30	–

The experiment is performed at two locations, (i) the first and second test were conducted in the nearshore fishing port area (on 19th to 20th January in 2016) and (ii) the third test is done on 21st January in 2016 in offshore which is (20 km away from shoreline) location. The FPEDs are arranged close to the water surface on an aquaculture raft in the first and second setup. For the third experiment, the FPEDs were resolutely placed to a fish aggregating

TABLE 5. Survey of existing piezoelectric owe converters.

Types piezoelectric OWE converter	Installation area	Characteristics and outcomes
Piezoelectric prototype device as power generator [30]	Attached to floating buoy	Made of PZT-4 based piezoelectric disks. Maximum output voltage 3.3 V with low output power.
Spray coated energy harvester [31]	Flow-induced vibration in ocean and wind environments.	Painting type flexible piezoelectric device consisted of PZT material. Robust in construction and can be operated under harsh sea environments. Highest output 2.16 V. Can be used for operating wireless sensors.
Piezoelectric coupled buoy generator [18]	Attached to floating buoy in middle and deep ocean	The converter is built with a number of piezoelectric cantilever beams. Float construction is optimized to obtain maximum efficiency with output power up to 24 W for 1 m length of beams.
Transverse wave piezoelectric harvester [19]	Under the sea surface	Designed with two horizontal piezoelectric plates for maximum 30W power under 10.6 m of oceanic depth and wave height of 21.2 m.
Eel structure ocean power generator [20]	Oceans and rivers	Prototype was developed using piezoelectric polymer, PVDF. Due to the characteristics of PVDF, the Eel generators are relatively less costly, simple in construction, and can produce power of watt range.
Longitudinal wave piezoelectric generator [35]	Under oceanic surface	Developed with piezoelectric patches. A maximum power of 55 W was observed under pragmatic situations with 3 m oceanic depth and 2 m of wave peak. Output power can be increased by optimizing the size of cantilevers.
Mass-spring piezoelectric energy converter [36]	Midway and deep oceanic surface	Mathematical model of the converter is developed using Lagrangian-Euler technique. A 100 kg mass-spring structure produced the highest electrical power of 103 W under the magnitude of 2 m of oceanic wave.
Submerged piezoelectric harvester [95]	Attached to vertical cliff	The converter was designed with piezoelectric sheets and implementing linear wave theory. An external electrical circuit is also proposed to condition the generated power. A piezoelectric array was developed considering series connection of individual sheets to increase the output voltage and power.
Floating piezoelectric converter [38]	Offshore ocean surface	The harvester incorporates triangular floating structure. Camera is used to observe the six degree of freedoms of flexible piezoelectric sheets. The electrical power can be increased by controlling the draft of the water flow for different wave parameters.

TABLE 6. Output statistics of several piezoelectric energy converters.

Energy source	Piezoelectric material	Output power (mW)	Output voltage (V)	Year	Ref.
Wind	PZT, PVDF	0.004	2.04	2010	[22]
	PVDF	0.600	36.4	2011	[33]
	PZT	0.00033	9.00	2016	[34]
Mechanical vibration	Bimorph	7.500	2.5	2005	[41]
	PVDF	NA	1.10	2001	[39]
	PZT-5A	0.400	NA	2006	[40]
Oceanic wave	PVDF	0.0002	2.20	2015	[1]
	PZT	12.350	11.24	2018	[2]
	PZT-4	NA	3.30	2013	[30]
	PZT	NA	2.16	2017	[31]
	PZT-4	24,300	NA	2015	[18]
	PZT-4	30,000	NA	2014	[19]
	PVDF	1,000	2.00	2001	[20]

device. Several experimental results of piezoelectric material based WEHs are summarized in Table 4.

It is connected to synthetic sea constructions making an environment approachable network that helps fishes to be protected and nourishing locations. The fish aggregating device lifts on the sea surface and it is connected to the seabed by 1000 m chain and fiber rope. The generated voltages produced by the FPEDs are measured and saved by a remotely placed data logger. The deformation of the FPED is sensed by using accelerometers which are capable to move in three directions. In the field experiment, maximum 1.55 V is obtained.

IX. DISCUSSION

In this review, the advancement of piezoelectric material-based OWE conversion technologies is explained in an explicable way. The prospects of highly promising OWE and the historical development of different energy conversion technologies are highlighted in section II. Besides the electromagnetic principle, piezoelectric effect is getting countable attention for developing WECs. The technical survey of existing piezoelectric OWE conversion technologies are summarized in Table 5. Table 6 represents the output voltage, power statistics of piezoelectric energy converters. For harvesting the oceanic energy using piezoelectric devices,

TABLE 7. Different technologies of oceanic energy harvesting using piezoelectric materials.

Types of energy source	Method of harvesting	Materials	Power scale	Implementation areas	Challenges	Suggestions
Water current	Flow based vibrations	PVDF	(mW – W)	Supplying power to moving underwater appliances such as robots	Low energy conversion efficiency	Passive control methodologies, employment of multiple devices
Wave motion	Heaving and pitching structures	PZT	(mW)	Supplying power to sensors used for ocean surveillance, salinity measurements	Large difference between the frequencies of the wave and PZT vibration	Conversion of low frequency to high frequency, deploying of field forces instead of impact forces in two stage configurations
	Structures attached to seabed	PVDF/PZT	(mW – W)	Supplying power to nearby offshore platforms, seismic activity monitoring	Complex mechanical design and material selection process	Negotiation between electromechanical combination and required elasticity and power
	Flexible diaphragm on sea surface	PVDF	(μW–mW)	Power supply to nearby ocean structures and floating harbors	Very large area consumption for the accommodation of waves with multiple frequencies and directions	Employment of various piezoelectric components, external harvesting circuits developed to evade termination impacts in the harvested power
Waves impact forces	Sloshing	PVDF	μW	Power supply to ocean assemblies, wave load dampers on structures such as offshore assemblies and ships	Low energy conversion efficiency	Manufacturing new piezoelectric ingredients with higher degree of flexibility
Water force	Heaving balance pendulum	PZT	μW	Powering the very low voltage electrical loads	Medium energy conversion efficiency	Implementation of array structure may improve the power scale
	Flag structure	PVDF	μW	Powering the very low voltage electrical loads	Improved efficiency compared to the others	Implementation of array structure may improve the power scale

several methodologies have been developed as summarized in Table 7. The challenges and possible solutions to the respective problems have also been included in the table.

The flexible piezoelectric plate or beam are subjected to deformation which can contribute to generate electrical energy. After studying the physics of piezoelectric phenomenon, several charge coefficients of focused materials have been found which can play important role for designing effective energy harvesters. The power density of available piezoelectric materials has been explained in section III. The knit type piezoelectric devices have higher energy generation capacity compared to the sheet type. Based on geographical location the offshore area is favorable for producing more electrical power compared to nearshore installations. Different configurations of piezoelectric material-based OWE conversion strategies are included in section IV.

The methodology of heaving and pitch motion can cause reasonable deformation of piezoelectric beams due to the sinusoidal nature of oceanic waves. The elastic floating unit with hanging structure is also convenient for the flexible configuration. To design an effective piezoelectric WEC, the mathematical models with electrical equivalent circuit are integrated in section V. Piezoelectric coefficients and constant of Young's modulus of elasticity are considered for developing the expressions of electrical charge, voltage, and power. Post-processing strategies of the generated low frequency electrical power with piezoelectric WECs include the ac-dc-ac conversion stages. EFHAS and Eel structures were observed with good results in sea environment.

Durability of piezoelectric device depends on tensile strength of the materials and the level of stress provided by oceanic waves. In comparison to PVDF, PZT offers lower tensile strength and because of which the later materials unable to withstand very high stress [1]. Because of high tensile strength, reduced stiffness, and high ductility properties, PVDF materials are becoming feasible for applications where elasticity is required. PZT materials are conceived with higher piezoelectric coefficients, low flexibility and fragility which restrict their usage to few designs in the oceanic environment. Piezoelectric materials, particularly PZT was experimented in [104] for their maximum efficiency, life span and stability in diverse circumstances.

X. CONCLUSION

Piezoelectric materials are conceived with the characteristics of producing electrical potential under an applied deforming force and vice versa. In this article, the prospects along with the developments of the highly promising oceanic wave energy conversion systems using piezoelectric materials, are focused. Different types of electrical energy conversion methodologies such as electromagnetic, electrostatic, piezoelectric as well as triboelectric concepts are discussed, and the relative comparisons are outlined. In addition, various piezoelectric devices are introduced with their characteristic effects, processing techniques, and arrangement methodologies for the harvesting of OWE.

For designing highly effective oceanic energy harvester using piezoelectric devices, several significant mathematical models are included and analyzed. It is found that, the piezoelectric effect for using d_{13} is possible to implement by simple design concepts, but the power production level is low. On the contrary, it is expected to obtain improved power by employing the d_{33} and d_{15} effects and hence it is advised to develop the converters based on piezoelectric material by utilizing its effects. Among the available structures, the combination of hanging and floating arrangement of piezoelectric devices, is more promising to produce electrical power from oceanic wave energy than that of using any other arrangements. Multiple units of Eel constructions can be cascaded to achieve higher electrical power compared to the traditional concepts. The harvested low frequency ac power must be converted before feeding it to the electrical appliances. Further, storage battery or devices can be used to store the energy and ac loads can be powered through an inverter circuit.

APPENDIX

Nomenclature

A	Wave amplitude
b	Damping of piezoelectric harvester
C_p	Capacitance of piezoelectric device
c	Wave velocity
cm^3	Cubic centimeter
D	Electric field displacement
d	Piezoelectric coupling coefficient
h_o	Height of piezoelectric plate
h_z	Distance from vertical neutral point of the wave
E_p	Young's modulus
F_e	Fluid force
H	Wave height
H_w	Depth of the seabed from the water surface
Hz	Hertz
h_{mp}	Height between mobile platform
i	Load current
kg	Kilo-gram
kPa	Kilo-pascal
kW	Kilo-watt
L_m	Mass of the piezoelectric transducer
l	Length of piezoelectric harvester
M	Internal moment of piezoelectric beam
MPa	Mega-pascal
MW	Mega-watt
W	Mili-watt
$M\Omega$	Mega-ohm
n	Turn ratio of transformer
nC	Nano-coulomb
P_m	Maximum electrical power
P_{max}	Maximum pressure on piezoelectric diaphragm
Q	Electric charge
R_l	Load resistance
S	Mechanical strain
t	Time
TWh	Tera-watt hour
V	Electric voltage
W	Wavelength of wave
w	Width of piezoelectric harvester
x	Displacement
x_p	Distance between piezoelectric plates
μA	Micro-ampere
μW	Micro-watt
$\%$	Percentage
δ	Relative displacement
σ_p	Applied mechanical stress on piezoelectric device
θ	Coupling factor of piezoelectric bimorph plate
ω	Frequency of piezoelectric generator
η	Efficiency of energy conversion

Acronym

AWS	Archimedes wave swing
$BaTiO_3$	Barium titanate
DDWEC	Direct drive wave energy converter
EFHAS	Elastic floating unit with hanging structure
EPRI	Electric power research institute
FPED	Flexible piezoelectric device
IPCC	Intergovernmental panel on climate change
OWEC	Oceanic wave energy converter
OWE	Oceanic wave energy
OWC	Oscillating water column
PVDF	Polyvinylidene fluoride
PZT	Lead zirconate titanate
PVC	Polyvinyl chloride
SPH	Smoothed particle hydrodynamics
WEC	Wave energy converter
WEH	Wave energy harvester

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MAHBUBUR RAHMAN KIRAN received the degree in electrical and electronic engineering (EEE) from the Rajshahi University of Engineering and Technology (RUET), Bangladesh, in December 2017. He has been working as a Lecturer at the EEE Department, Green University of Bangladesh (GUB), Dhaka, Bangladesh, since September 2019. He has contributed to nine published technical papers, including two journals, one book chapter, and six international conference proceedings. His research interests include electrical machine design and optimization, grid integration of renewable energy sources, power electronics, and electronic instrumentation. He has been awarded the Best Poster Award and the Best Paper Award from the 5th IEEE Region 10 (2017) and ICEMS 2019 international conferences.

OMAR FARROK (Member, IEEE) received the Ph.D. degree from the Department of Electrical and Electronic Engineering (EEE), Rajshahi University of Engineering and Technology (RUET), Rajshahi, Bangladesh, in 2016.

Since 2016, he has been a Distinct Associate Professor with the Department of EEE, Ahsanullah University of Science and Technology (AUST), Dhaka, Bangladesh. He has authored or coauthored more than 60 technical papers in the international journals and conference proceedings, including 10 IEEE TRANSACTIONS/journal articles. His research interests include oceanic wave energy converter, linear electrical generator, magnetic material, electrical machine and drive, renewable energy systems, electromagnetics, and power electronics.

Dr. Farrok is a Life Fellow of the Institution of Engineers, Bangladesh (IEB). He received Four Best Paper Awards from the IEEE ICEMS, Sydney, NSW, Australia, in 2017, ASEMD, Tianjin, China, in 2018, ICEMS, Harbin, China, in 2019, and PEEIACON, Dhaka, in 2019. He is elected as the Chair, the Co-Chair, and nominated as a member of several technical committees formed by the Bangladesh Government under the Ministry of Industries and others. He was registered with the board of Bangladesh Professional Engineers Registration Board (BPERB), as a Professional Engineer (P.Eng.), in 2017.

MD. ABDULLAH-AL-MAMUN received the B.Sc. degree from the Department of Electrical and Electronic Engineering (EEE), Ahsanullah University of Science and Technology (AUST), Dhaka, Bangladesh, in 2017, where he is currently pursuing the M.Sc. degree. He worked as a Lecturer at the Department of EEE, Sheikh Fazilatunnesa Mujib University, Jamalpur, Bangladesh, and Uttara University, Dhaka. He joined the Department of EEE, AUST, as a Lecturer, in January 2019. He is continuing his profession at AUST. His research interests include power systems, renewable energy, and electrical machine designing. He has authored or coauthored three technical articles. He had been awarded with dean's list of honor for his academic excellence.

MD. RABIUL ISLAM (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the University of Technology Sydney (UTS), Sydney, NSW, Australia, in 2014.

He was appointed as a Lecturer at RUET, in 2005, where he promoted to a Full Professor, in 2017. In 2018, he joined the School of Electrical, Computer, and Telecommunications Engineering (SECTE), University of Wollongong (UOW), Wollongong, NSW, Australia. His research interests include power electronic converters, renewable energy technologies, power quality, electrical machines, electric vehicles, and smart grids. He has authored or coauthored 160 papers (including 46 IEEE TRANSACTIONS/IEEE journal articles) in international journals and conference proceedings. He has written or edited four technical books published by Springer. He received several funding from Government and Industries, including the Australian Government ARC Discovery Project 2020 (A Next Generation Smart Solid-State Transformer for Power Grid Applications). He has served as a Guest Editor for the IEEE TRANSACTIONS ON ENERGY CONVERSION, the IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, and *IET Electric Power Applications*. He has been serving as an Editor for the IEEE TRANSACTIONS ON ENERGY CONVERSION and the IEEE POWER ENGINEERING LETTERS and an Associate Editor for IEEE ACCESS.

WEI XU (Senior Member, IEEE) received the B.E. and M.E. degrees from Tianjin University, Tianjin, China, in 2002 and 2005, and the Ph.D. degree from the Institute of Electrical Engineering, Chinese Academy of Sciences, in 2008, all in electrical engineering.

From 2008 to 2012, he was a Postdoctoral Fellow with the University of Technology Sydney, the Vice Chancellor Research Fellow with the Royal Melbourne Institute of Technology, Japan, and a Science Promotion Society Invitation Fellow with Meiji University. Since 2013, he has been a Full Professor with the State Key Laboratory of Advanced Electromagnetic Engineering, Huazhong University of Science and Technology, China. He has more than 100 articles accepted or published in the IEEE TRANSACTIONS journals, 2 edited books published by Springer Press, 1 monograph published by China Machine Press, and 120 invention patents granted or pending, all in the related fields of electrical machines and drives. His research interest includes design and control of linear/rotary machines.

Dr. Xu is a Fellow of the Institute of Engineering and Technology (IET). He will serve as the General Chair of the 2021 International Symposium on Linear Drives for Industry Applications (LDIA 2021) and the 2023 IEEE International Conference on Predictive Control of Electrical Drives and Power Electronics (PRECEDE 2023), Wuhan, China. He has served as an Associate Editor for several IEEE TRANSACTIONS journals, such as the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and so on.