scientific reports

Check for updates

OPEN

Design and dynamic emulation of hybrid solar-wind-wave energy converter (SWWEC) for efficient power generation

Aryan Manan Jariwala[1], Santanu Kumar Dash[2]✉, Umesh Kumar Sahu[3]✉ & Saichol Chudjuarjeen[4]

As research into wave energy converters progresses and new developers enter the field, there arises a growing requirement for a standardized modelling approach. This article presents a novel design and dynamic emulation for a hybrid solar-wind-wave energy converter (SWWEC) which is the combination of three very well-known renewable energies: solar, wind and wave energy. Photovoltaic (PV) panels and vertical axis wind turbine (VAWT) are installed on top of the floating WEC that harness the energies from the sun and wind respectively. The SWWEC is designed with a point absorber capture system. An electrical motor is used to dynamically emulate the performance of the SWWEC under real world conditions to drive the DC generator. The present paper shows the importance and necessity of the required control schemes for the proper control of generator side converters which is present in the offshore marine substation and the most required grid connected onshore converters. The better switching signal generation for the converter control and generated harmonics elimination techniques are also presented in the paper. Outcomes of the present study are discussed and verified.

Keywords Power generation, Renewable energy, Solar-wind-wave energy converter, Wave energy

List of symbols

Symbols

A	Area, m^2
a	Radius of cylinder, m
a	Amplitude of wave, m
B	Arbitrary constant
b	Damping coefficient, kg/s
c	976 Wm^{-3} s^{-1}
D	Damping coefficient, kg/s
D	Diameter, m
F	Force, N
f	Frequency, Hz
g	Gravitational acceleration, m/s^2
H	Height of the wave, m
h	Depth, m
i	$\sqrt{-1}$
k_e	Energy period, s
m	Mass, kg
m_n	Spectral moment
m_0	Spectral energy function
P	Power, W
P	Pressure, Pa

[1]School of Mechanical Engineering, Vellore Institute of Technology, Vellore 632014, India. [2]TIFAC-CORE, Vellore Institute of Technology, Vellore 632014, India. [3]Department of Mechatronics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India. [4]Department of Electrical and Telecommunication, Rajamangala University of Technology, Krungthep, Bangkok, Thailand. ✉email: santanu4129@gmail.com; umesh.sahu@manipal.edu

Re Real part
p Apparent power, VA
S Restoring force coefficient, N/m
S_f Spectrum
T Period, s
W Watts
W Annually produced energy
x Acceleration, m/s^2

Greek symbols

α Angle, rad or degree
α Arbitrary constant
α Displacement in x direction, m
α Utility factor
Δ Damping ratio
δ Phase angle, rad or degree
ϵ Phase angle, rad or degree
θ Angle, rad or degree
π 3.14159
ρ Density, kg/m^3
ω Angular velocity, rad/s
γ Damping function
τ Torque, Nm

Subscripts

abs Absorbed
d Damped
e Energy
em Electromagnetic inductive force
es End stop
f Friction
L Loss
o Resonant
p Phase
p Peak wave
r Radiated
s Significant
z Zero-up crossing

Abbreviations

AC Alternating current
ANN Artificial neural networks
ARO Artificial rabbits optimization
AWS Archimedes wave swing
CS Cuckoo search
DC Direct current
MPPT Maximum power point tracking
OBWEC Oscillating-body wave energy converter
OWCWEC Oscillating water column wave energy converter
PAWEC Point absorber wave energy converter
PMSG Permanent-magnet synchronous generator
PV Photovoltaic
PQ Power quality
SBWEC Sealed-buoy wave energy converter
SWWEC Solar-wind-wave energy converter
UPQC Unified power quality conditioners
VAWT Vertical axis wind turbine
VQ Voltage quality
WEC Wave energy converter
WHO Wild horse optimizer

Amidst the escalating threat of global warming and the urgent need to address its catastrophic repercussions, there is a pressing demand for sustainable energy sources. The persistent reliance on finite and environmentally harmful fossil fuels underscores the necessity of transitioning to renewable energy alternatives. Among these, wave energy stands out as a promising yet underexploited resource with substantial potential for contributing to the global energy transition. By harnessing the kinetic energy present in the oceanic waves, wave energy conversion technologies offer a reliable and abundant source of green energy, with minimal environmental impact compared to conventional energy sources. The predictability and high energy density of oceanic waves make wave energy an attractive option for meeting the increasing energy demands of coastal regions globally. Researchers posit that oceanic waves have the capacity to generate 2 Terawatts (TW) annually on a global scale. The theoretical global wave energy potential is estimated at 8×10^6 Terawatt hours (TWh) per year, surpassing the total hydroelectric generation worldwide by approximately 100-fold. In contrast, harnessing an equivalent amount of energy through fossil fuels would result in the emission of 2 million tons of CO2[1]. Over the past few decades, there has been ongoing progress in the advancement of technologies associated with harnessing and converting wave energy. This evolution has led to the emergence of various types of WECs[2]. Researchers from diverse global regions have proposed and developed a range of prototypes, with a particular emphasis on buoy design such as a, heaving buoy WEC[3], design of the oscillating buoy WEC[4] and structural optimization on the oscillating-array-buoys[5] as they are currently undergoing testing and verification stages. A list of full-scale installed WECs across the globe are summarized in. "Laboratory Validation and Result Analysis" discusses the results obtained in the laboratory. Finally, "Conclusion" concludes the findings obtained dynamic emulation for the SWWEC.

Table 1 shows different types of WECs based by location, capture system and power take off system are shown in Fig. 1. The location of the deployed WEC determines the capture system and power take off system accordingly, Fig. 2 shows the classifications of the location.

J.C.C. Henriques et al.[6] proposed a design of oscillating-water-column WEC with an application to self-powered sensor buoys. Yung-Lien Wang performed a numerical study on the optimal size of the cylindrical buoy based on the wave characteristics[7]. Centre for renewable electric energy conversion, Uppsala University proposed and implemented the concept of WECs where the concept of buoy on sea surface connected to linear generator placed on the seabed[8]. Northwest National Marine Renewable Energy Centre reported the development of Ocean Sentinel instrumentation buoy which is actually a surface buoy as well as oceanographic meteorological automatic device for the testing of immature WECs at the site of ocean[9]. Marine energy harvesting is currently exploring various aspects, and research has classified different WECs including Pelamis, Aquabuoy, Wave Dragon, and Oscillating Water Column. Modesto Amundarain, Mikel Alberdi have reported and explained clearly about the control scheme implemented for the generation of energy through the oscillating water column[10]. Feng Wu, Xiao-Ping Zhang mentioned about the development of AWS based WEC system where the generator and grid side converter control scheme are emphasized[11]. WECs on the basis of hydrodynamic principle based on point absorber principle is introduced by Budal and Falnes[12]. Nicolas Müller and Samir Kouro mentioned about the wave dragon principle for the generation of electric energy which consists of several low voltage source converters with back-to-back configuration[13]. Offshore WECs necessitate sea cables to connect to the onshore grid. Enhancing transmission and cost efficiency, a seabed-based offshore marine substation connects all WECs. Uppsala University developed and implemented this technology[8]. Some researchers suggest integrating wind and wave farms with a shared offshore substation to enhance substation efficiency on the seabed. Cost and expenditure aspects for wave energy farm installations are explored by Fergus Sharkey and Elva Bannon in[14]. Hui Huang et.al implemented different control schemes for those converters for proper control. This control schemes can be applied to wave energy conversion system[15] as the controller scheme is very much essential for converters present in the WECs, Adel A. A. Elgammal proposed adaptive Fuzzy Logic Sliding Mode Controller for grid side converter control[16]. Inspite of different proposed simulation, M. Rahm et.al implemented and tested the marine substation which is clearly seen in[17].

Table 2 shows a list of researchers with their objectives and contributions in developing novel WECs for harnessing clean wave energy.

Performance enhancements of WEC is also a major criterion for energy harnessing from wave energy resources therefore various researchers have proposed efficient control techniques. In the present era to enhance the control of efficiency adaptive controllers , robust controller and intelligent controllers are proposed and implemented for various categories of renewable energy system controller such as PV systems, wind systems and wave energy systems.*Nagwa F. Ibrahim* et al.[18] proposed an effective PI controller for a dynamic voltage restorer to reduce the PQ problems, using ARO to achieve optimal tuning. *Mohamed Metwally Mahmoud* et al.[19] presented the application of a whale optimization algorithm based on a fractional order proportional-integral controller for unified PQ conditioner and STATCOM tools. *B. Srikanth Goud* et al.[20] aimed to enhance the PQ of the electronic equipments for the consumers by implementing a dynamic voltage restorer. *Mohamed Metwally Mahmoud*[21] implemented a WHO method to optimally design a wind turbine system based on PMSG. *Mohamed Metwally Mahmoud* et al.[22] proposed a Harris Hawks algorithm to improve the dynamic voltage resistor's control system for enhancing the VQ in low levels of voltages in smart homes. *Nagwa F. Ibrahim* et al.[23] developed two MPPT algorithms: ANN and CS, to investigate the PQ of the electricity harnessed from renewable energy resources which include DC-DC, DC-AC converters, PV, power grid, filter and control schemes. *Santanu Kumar Dash and Pravat Kumar Ray*[24] developed a new version of JAYA algorithm which has two distinct objective functions to

Name reference	Installed capacity	Category	Country	Grid-connected
Aqua buoy[31]	250 kW	PAWEC	Ireland-Canada-Scotland	Yes
Powerbuoy[32]	150 kW	OBWEC	America	No
WaveStar[33]	6 MW		Denmark	Yes
Pelamis[34]	750 kW		England	Yes
Wave Dragon[35]	12 MW	Overtopping WEC	Denmark	Yes
Penguin[36]	0.5–1 MW	Direct-drive WEC	Finland	Yes
Ocean energy buoy[37]	1.25 MW	OWCWEC	Ireland	No
GreenWave Oceanlinx[38]	450 kW/1 MW		Australia	Yes

Table 1. List of full-scale installed WECs across the globe.

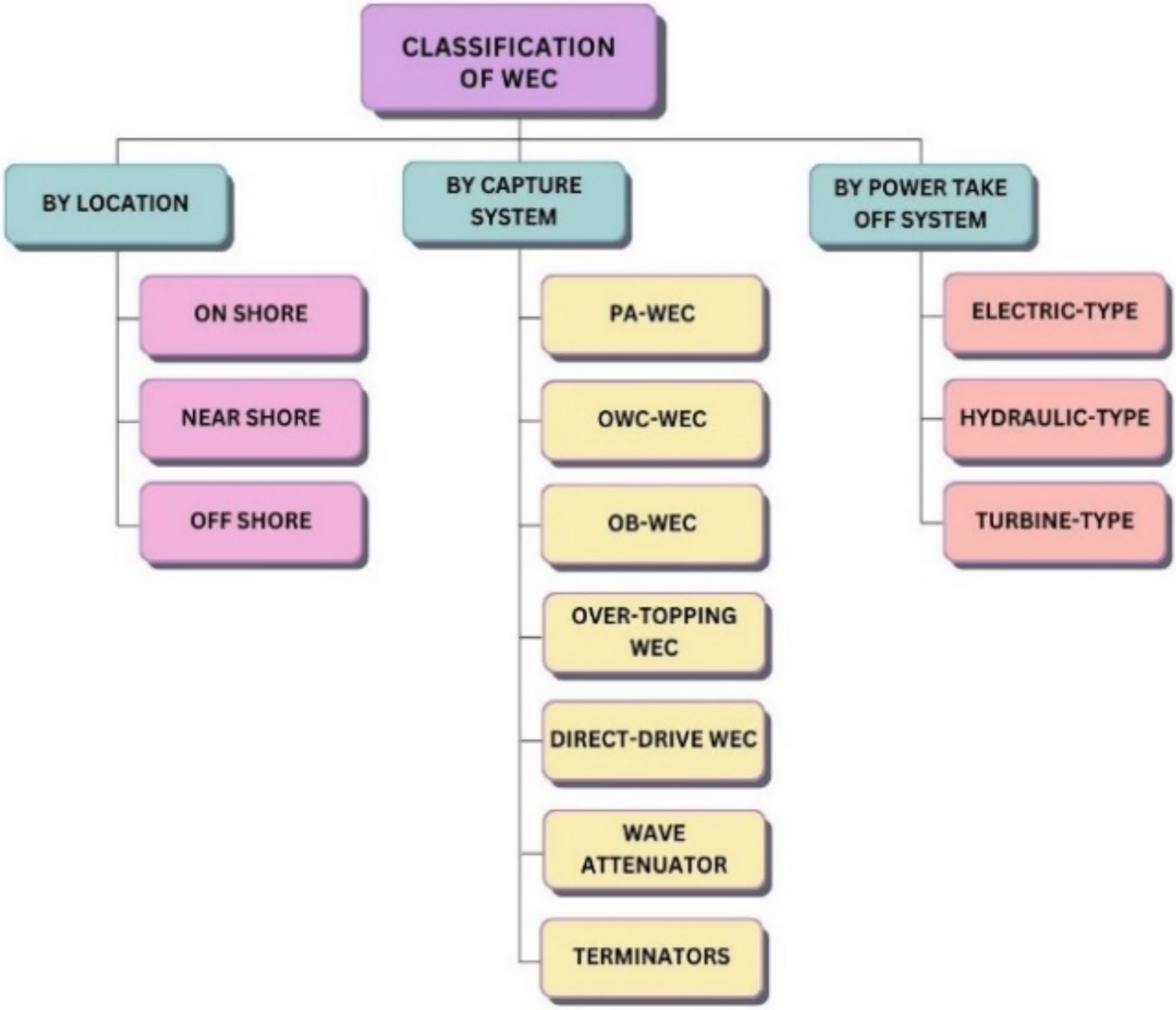

Fig. 1. Classification of the WEC based by Location, Capture System and Power Take Off System.

optimally control the PV-UPQC. From the above literatures controller like adaptive control, optimization based control, and robust control increase the efficiency of renewable energy based systems. Therefore, these control methodologies can be applied to WECs. Against this background, the aim of this research are as follows:

- Instantaneous control theory dq-method has been implemented for the control of both grid and generator side controller. This method is effectively used to control the variable voltage and frequency generated by the variance of the waves.
- A novel efficient 3D CAD design integrating three sources of renewable energy i.e. solar, wind and wave energy has been presented.
- Dynamic emulation of the SWWEC in real-time simulation environment by driving the DC generator using an electrical motor has been achieved.

In this article, "Wave Concept and Theory for floating buoy:" illustrates the theory behind the wave concept and characteristics of the waves in the ocean. "Case 1: wave energy converter of a floating buoy Archimedes Wave Swing:" explains the design and control of the conventional PAWEC. "Case 2: design of wave energy converter" proposes a new design of the point absorber WEC in which the electrical generator is kept above the surface of water instead of completely keeping it submerged in a water-tight container. "Design of the buoy of WEC" discusses the design of the buoy of WEC. The key advantages of the proposed SWWEC are listed in "Advantages over a point absorber WEC". "Laboratory validation and result analysis" discusses the results obtained in the laboratory. Finally, "Conclusion" concludes the findings obtained dynamic emulation for the SWWEC.

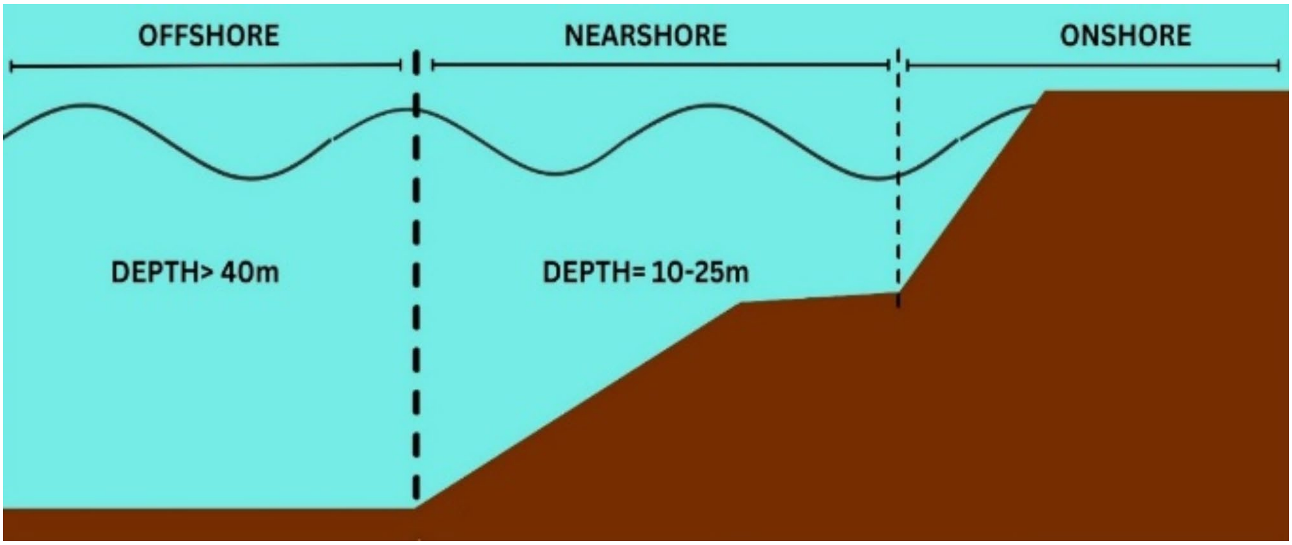

Fig. 2. Schematic representation of the locations of Onshore, Nearshore and Offshore.

Type of WEC	Ref	Objectives	Remarks
Point absorber wave energy converter (PAWEC)	39	To employ a turbine generator propelled by the Magnus effect in a point-absorber WEC	Simulation model of the proposed design is developed, and the results are presented
	40	To develop and numerically analyze a point-absorber with 2 DOF using CFD	The heaving and pitching motions can be considered interdependent, simplifying the wave energy conversion to the combined single DOF motion of heave and pitch
	41	To examine the implementation of a backward bent duct buoy (BBDB) with a point absorber (PA)	The results suggest optimizing hybrid WEC designs and indicate potential synergy between BBDB and PA for efficient use of ocean space for energy
	42	This research demonstrates the simulation of harnessing energy using WEC from ocean waves in Indonesia	The average value of electrical powers generated during the simulation and accumulated electrical powers were presented
	43	To numerically analyze a self-reacting WEC	Numerical analysis has been conducted using both frequency-domain and time-domain approaches for regular waves
Swing motion bouy	4	To check the performance of a longitudinal swing motion of the buoy	The results obtained after the numerical analysis show that the performance of the buoy with swing motion has improved when compared to heave motion
Oscillating-array-buoys	5	To optimize the energy capturing mechanism of the oscillating array-buoys	The experimental values show that there is an improvement of 38% when compared to the basic model
	44	The oscillating array of buoys is integrated with the development of a semi-submersible platform	The numerical analysis of the test rig shows a combined average of 18.115% in regular and irregular waves
Oscillating water column wave energy converter (OWCWEC)	6	To design two self-powered sensor buoys for long term monitoring based on the oscillating-water-column principle	The performance of the designed buoys was analyzed, and the results shown give positive feedback for implementing them in the future applications
	45	To design and model 2 different types of OWC-WEC	The results obtained from the hydrodynamic performance, mooring tension results and free-decay tests are presented and discussed
Sealed-buoy wave energy converter (SBWEC)	46	To capture energy from low energy flow density sea areas using a SBWEC	The estimated efficiencies of the SBWEC calculated were 54.44%

Table 2. WEC researcher insights: objectives & contributions.

Wave concept and theory for floating buoy

The utility factor is important for any schemes proposed and is the key parameter in the economics of renewable energy production. This utility factor can be defined as

$$\alpha = \frac{P_{avarage}}{P_{rated}} = \frac{W}{P_{rated}.8760} \tag{1}$$

where the rated power is denoted by $P_{rated,}$ and average power is denoted as $P_{average}$. The investment payback is determined by the annually produced energy *W*. The comparison of the utility factors for wind, solar and wave energy can be obtained through Eq. (1) which says that the wave energy has the higher utility factor. The generated energy flux by sea waves attenuates on a slower time scale in comparison to wind and solar. Due to the higher utility factor claimed by the wave energy[28,29], it is required to be considered for the design of the wave energy farms.

The wave theory presents the energy in the wave as potential energy and kinetic energy. The time averaged wave power per unit width L of the wave front is given by

$$\frac{dP}{dL} = cTH^2 \tag{2}$$

where c is approximately equal to 976 Wm^{-3} s^{-1} the height H of the wave is twice the amplitude means $H = 2A$.

Wave theory

The statistical characteristic of ocean waves can be modelled through vast number of parameters where the irregular waves are described by a spectrum S_f indicates the amount of wave energy at different wave frequencies f. The spectral characteristic and the wave parameters can be calculated using the time series representation with spectral moment $m_{n.}$ The area under the spectral energy function is denoted as $m_{0.}$ For the calculation of higher spectral can be calculated by

$$m_n = \int_0^\infty f^n S(f)df \tag{3}$$

In this equation the n can take any integer value both positive and negative. Some of the important wave parameters are as follows:

(i) Standard deviation of the sea level can be denoted as the significant wave weight Hs, corresponding to the significant wave height estimated from the spectral moments H_{m0}.

$$H_s \cong H_{m0} = 4\sqrt{m_0}$$

(ii) T_e is the energy period or mean wave period with respect to the spectral distribution of energy T_{-10}, is defined by

$$T_e = T_{-10} = \frac{m_{-1}}{m_0}$$

The zero-up crossing period T_z and the peak wave period T_p are the most important wave parameters for the wave period. T_p is the predominant wave period and T_e represents the average energy period of the wave spectrum.

For example, Atlantic oceanic values of T_e and H_s value is between 5 and 15 s and 0 and 10 m respectively. On the basis of these parameters, the omnidirectional wave power (kW/m) can be defined with the wave number based on the energy period k_e and taking the water depth h into consideration, by

$$P_{wave} = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \left[1 + \frac{2k_e h}{sinh2k_e h}\right] tanhk_e h \tag{4}$$

Wave characteristics

In the ocean, waves are typically categorized into two primary types: long-period swell waves and short-period wind waves Fig. 3. Swell waves, characterized by their extended wavelengths and gradual crests, constitute the primary source for wave energy conversion. Conversely, the wind waves or short-period waves, with their shorter wavelengths and abrupt crests, tend to induce undesirable energy rippling and should thus be minimized in design considerations.

Fundamentally, waves in ocean transmission are characterized by three critical parameters: wavelength, which denotes the distance between consecutive crests or troughs; wave amplitude, representing the height of a wave from its trough to its crest; and wave velocity, signifying the speed at which a wave propagates through the water medium. These factors collectively influence the behaviour and impact of waves on the design of buoy for the WEC.

Case 1: wave energy converter of a floating buoy Archimedes wave swing

There are several types of WECs proposed and under developmental condition for the harnessing of the wave energy, however the PAWEC is the most popular one. Figure 4 shows the schematic diagram of a conventional PAWEC system. There are different forces acting on it when it is on the sea surface. The movement of the buoy depends on the waves passing through it; the buoy is lifted, and the corresponding motion is reflected with the translator in the generator[29]. The relative motion in between the stator and magnets generates the voltage in the stator windings[25].

The piston present in the generator is driven by the buoy with a force corresponding to the lift force where the diameter is much smaller than the wavelength. The actual motion of the piston connected to the buoy is as follows:

$$m\frac{d^2x}{dt^2} = F_{buoy} + F_{spring} + F_{em} \tag{5}$$

The present equation shows that the total force is a sum of buoyant force, mechanical spring force and generator inductive force.

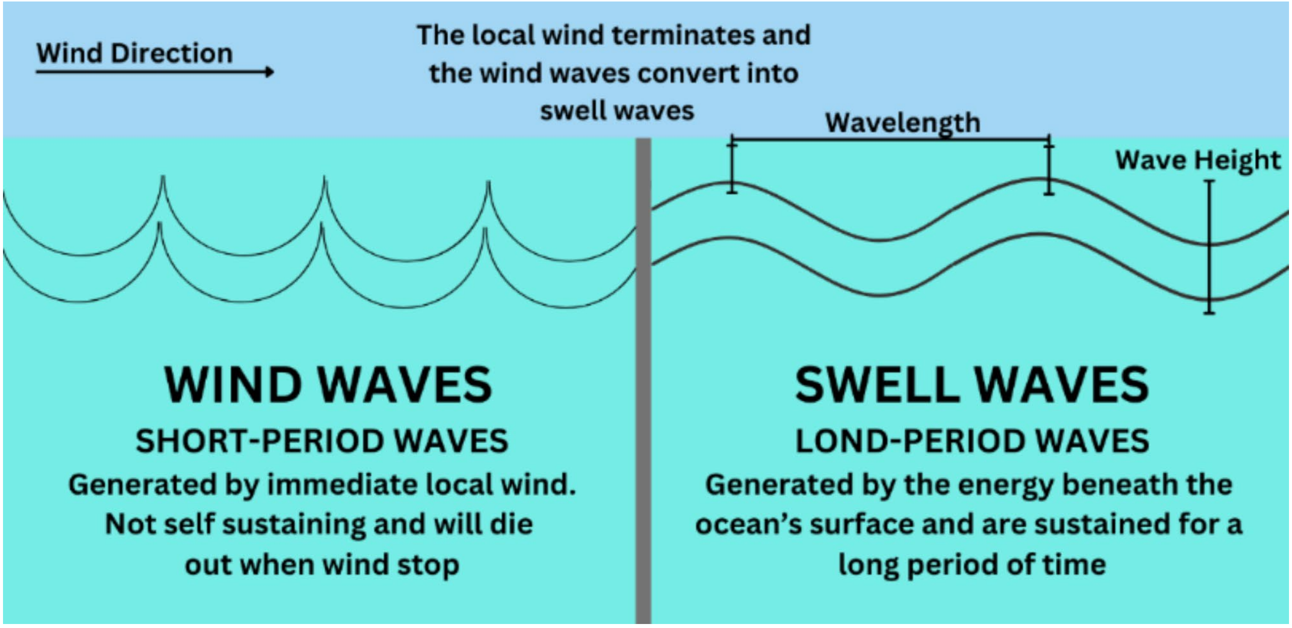

Fig. 3. Difference between Short-Period Waves and Long-Period Waves.

$$F_{spring} = -F_0 - k_{sp}x \tag{6}$$

$$F_{em} = -k_{em}\frac{dx}{dt} \tag{7}$$

For electromagnetic inductive force generation, the computation of the retarding effect on the piston associated to stator currents and load applied. The AWS tolerates damping and energizing motion of the translator.

$$mx = F_s + F_b + F_{em} + F_{es} + mg \tag{8}$$

In the denoted equation for WECs, m is the mass of the translator, x is the acceleration. F_s and F_b are the spring force and buoy force respectively. The end stop force at the top is denoted as F_{es} and F_{em} is the electromagnetic force depending on electrical damping of the generator. The relation between the electromagnetic force F_{em} and the damping function γ can be represented as follows:

$$F_{em} = \gamma A_{fac}x \tag{9}$$

where the active area of stator is represented as A_{fac} and the required operating range of active area of stator is given as $0 \leq \gamma \leq 1$.

The damping function can be obtained by the relation of the force and the velocity represented here as

$$\gamma = \frac{P_{abs}}{A_{fac}x^2} \tag{10}$$

where the P_{abs} is represented for absorbed power.

$$P_{abs} = P_{mech} + P_{load} + P_{cu} + P_{iron} \underset{-}{\sim} P_{load} + P_{cu} \tag{11}$$

P_{iron}, P_{mech}, P_{cu} are the iron losses, mechanical losses, and copper losses respectively. The copper losses are the conductor losses in armature winding and the sea cable.

Figure 5 shows the configuration of the total system of the power circuit and controller required for converting power from WEC to the utility grid. The AC/DC converter in the configuration is designed to convert the variable frequency generated by the AC power for the regulation of the DC power. The controlled and regulated DC power can charge battery storage to supply the DC loads. The DC power is required to deliver to the DC side of the 3-phase inverter to be converted to the 3-phase AC power for the AC loads and the grid. Problems arise due to the variation of the terminal DC voltage for the variation of the wave speed and the frequent change in load. To overcome this problem an effective method of control is required for the control of the DC bus voltage. Instantaneous control theory dq-method has been used in the present paper as given in Fig. 6 for the control of both grid and generator side controller. This method is effectively used to control the variable voltage and frequency generated by the variance of the waves.

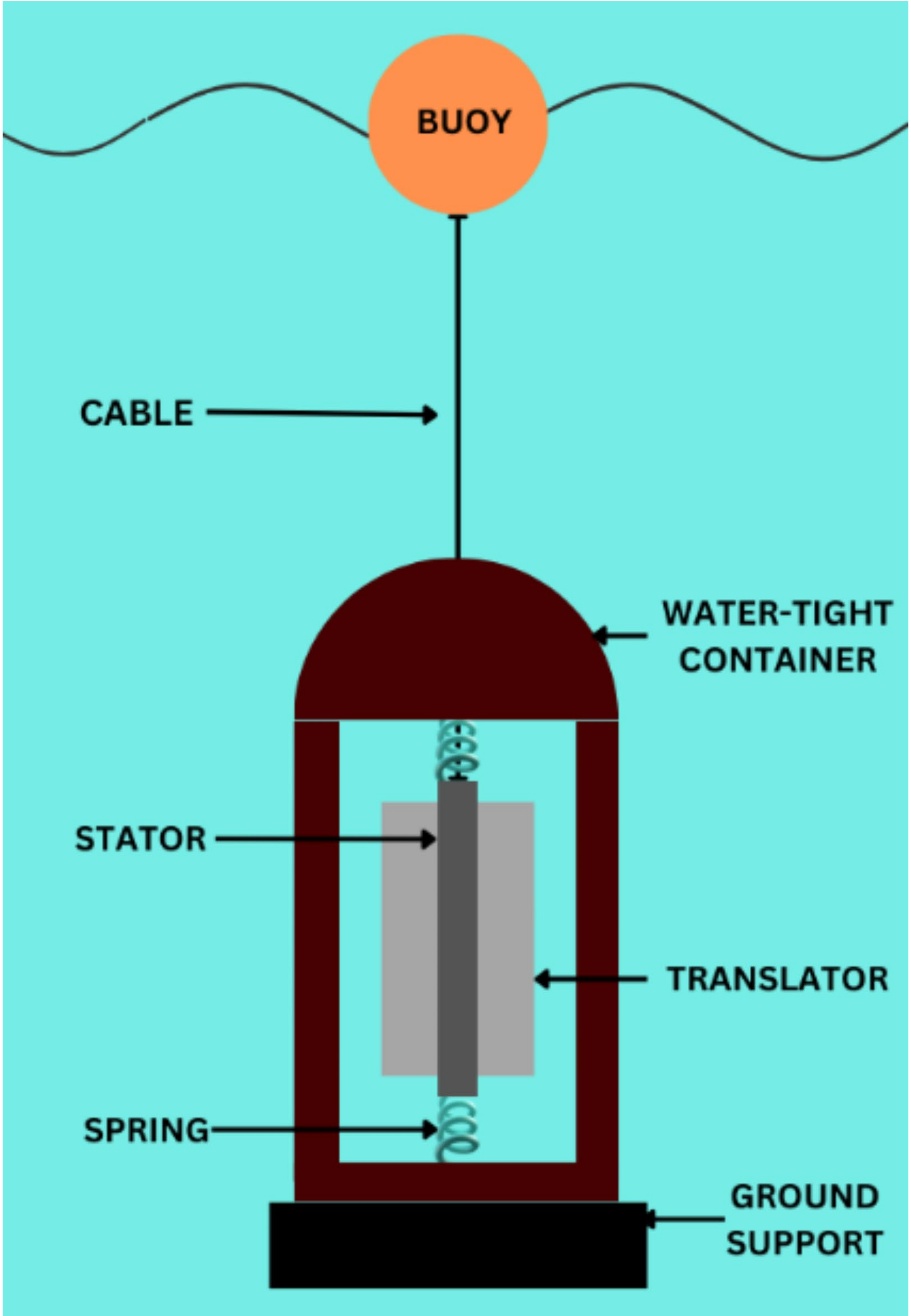

Fig. 4. Conventional Design of PAWEC system.

Case 2: design of wave energy converter

The SWWEC design proposed in this paper is a modification of the PAWEC design (Fig. 7) where instead of keeping the main body consisting of the generator and electronic components such as batteries underwater in a seal proof container, we have directly kept it above the floating buoy which completely eliminates the increased cost of manufacturing a watertight container and the installation costs inside the ocean.

Table 3 shows the front view, side view, top view, and isometric view of the proposed hybrid SWWEC. The SWWEC outlined in this paper (Fig. 8) comprises several key components: a sturdy metal frame, PV

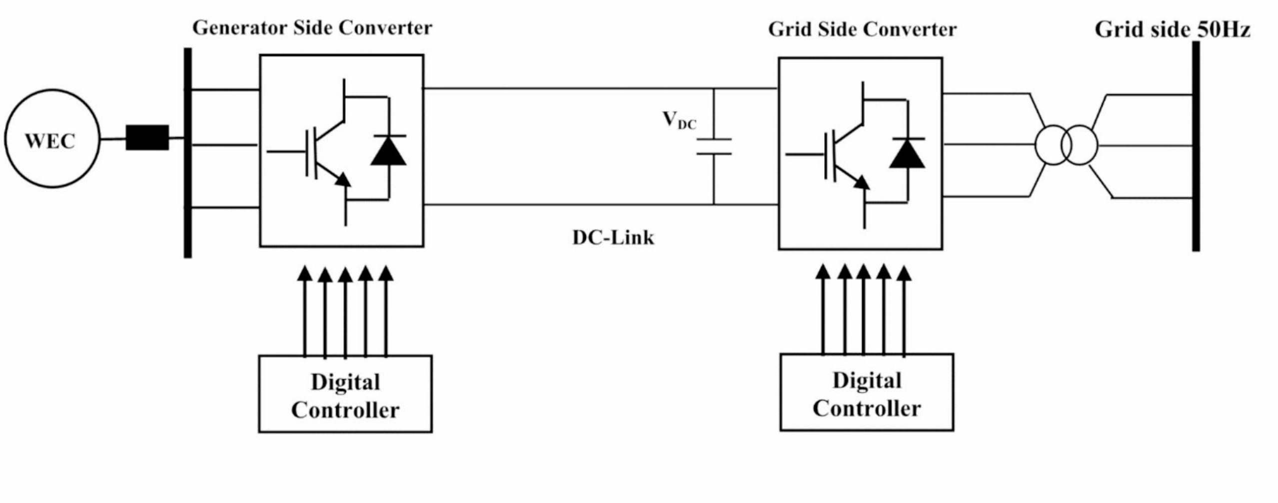

Fig. 5. Configuration of the power circuit and controller for the WEC.

panels, VAWT, cylindrical floating buoy, rack and pinion gear mechanism, pulley system, DC generator, and a controller[30]. The frame serves as the backbone of the system, offering structural support and stability to the other components. It ensures that the various parts of the SWWEC are securely held together and properly positioned for efficient energy conversion. Monocrystalline PV panels were chosen for this application due to their higher efficiency, increased longevity and better durability than the polycrystalline PV panels. The PV panels are situated on top of the SWWEC for maximum absorption of the global radiation received by the sun, it also serves as a shelter for the electronic components which reduces the heat gained directly from the sun's radiation avoiding frequent replacements of damaged electronic components. The VAWT is also situated on top of the SWWEC for maximum capture of wind energy. The design of the 3-bladed VAWT is inspired from the savonius VAWT due to its simple construction, reduced noise, minimal wear and the ability to work in low wind speed conditions. The wave energy flow diagram of the proposed SWWEC is shown in Fig. 9. The cylindrical floating buoy performs a heaving motion when a sea wave passes through. Simultaneously the rack also heaves in the upward direction causing the pinion to rotate. This rotation of the pinion also rotates the rod to which it mounted on, then the larger pulley also rotates with the rotation of the rod and transmits the rotation to the smaller pulley via a belt. The smaller pulley acts as an input shaft for the DC generator. A pulley system with a ratio of 1:2 is considered where for each rotation of the larger pulley results in two rotations of the smaller pulley which also results in the increased input rotation of the DC generator, hence increasing the power generated. The DC generator produces power, which is subsequently rectified by a full-wave rectifier. This rectified power then flows through an inverter, followed by a charge controller, and finally stored in the battery storage unit. The entire SWWEC system is moored to the seabed to prevent it from floating away from the location at which it is installed. The power captured by solar, wind and wave are stored in the battery which can be utilized for either domestic or industrial use according to the location of the SWWEC.

Forces acting on a WEC

The motion of the WEC depends on the amplitude and angular frequency of the incident wave. The forces acting on a WEC has been presented in Fig. 10. This produces a periodic disturbing force $Fcos\left(\omega t\right)$ which is controlled by a restoring force, produced by changing buoyancy and a damping force caused by the friction, energy extraction and radiation[26].

$$\underbrace{Fcos\left(\omega t\right)}_{Applied\ force} - \underbrace{D\dot{y}}_{Damping\ force} - \underbrace{Sy}_{Restoring\ force} = \underbrace{m\ddot{y}}_{mass\ \mathrm{X}\ acceleration} \tag{12}$$

Hence.

$$m\ddot{y} + D\dot{y} + Sy = Fcos\left(\omega t\right) \text{ or } Re.F\exp(i\omega t) \tag{13}$$

To simplify the problem considering the natural undamped oscillation so that $D = F = 0$.

Thus,

$$m\ddot{y} + Sy = 0 \tag{14}$$

Substituting the value of $y = A\exp(i\omega_o t)$ in Eq. (13)

$mA(i\omega_o)^2\exp(i\omega_o t) + SA\exp(i\omega_o t) = 0$ or $-m{\omega_o}^2 + S = 0$

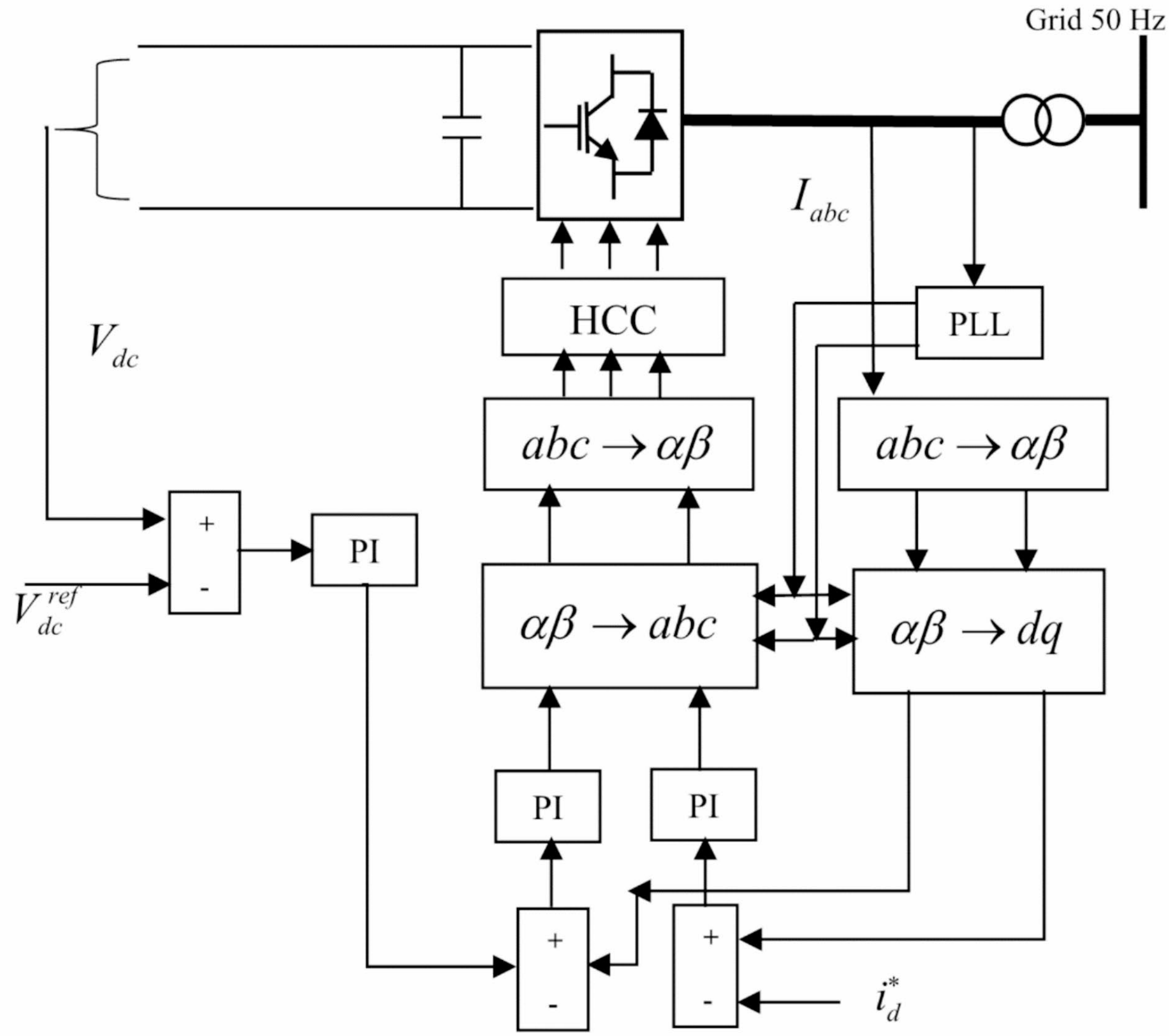

Fig. 6. Grid side controller design of PAWEC.

$$=> \omega_o = \sqrt{\frac{S}{m}} \quad (\text{where } \omega_o \text{ is the resonant angular frequency}) \tag{15}$$

Now reintroducing the damping term $D\dot{y}$ in Eq. (14)

$$m\ddot{y} + D\dot{y} + Sy = 0 \tag{16}$$

Now substituting the form $y = A\exp(\alpha t)$ and its differentials and cancelling $A\exp(\alpha t)$ throughout

$$m\alpha^2 + D\alpha + S = 0 \tag{17}$$

$$\alpha = \frac{-D \pm \sqrt{D^2 - 4mS}}{2m} \tag{18}$$

Unless

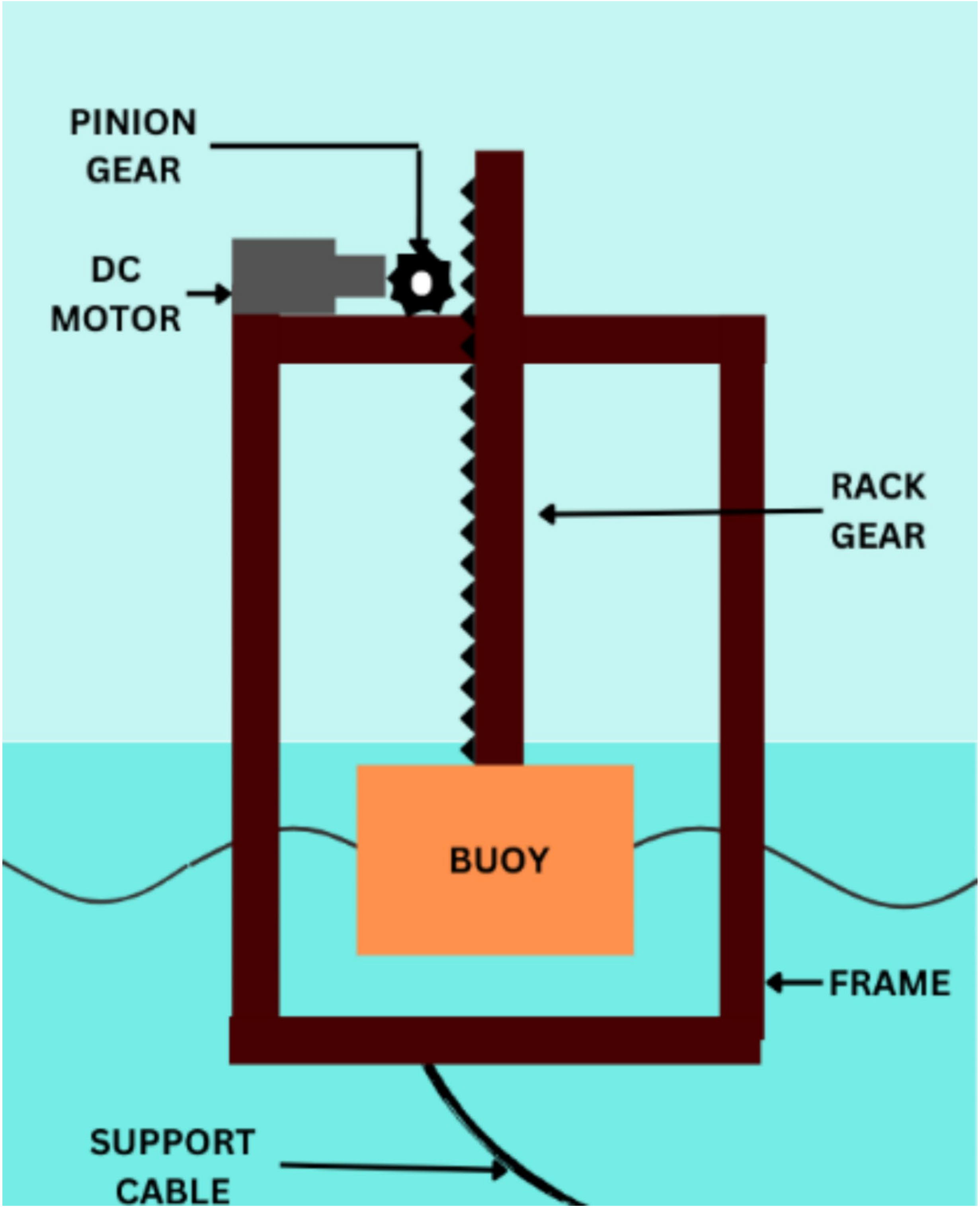

Fig. 7. Proposed Design of PAWEC.

$D^2 - 4mS < 0$, α is real and negative and the displacement decreases to zero asymptomatically with time without periodic motion, which is not relevant to wave energy devices and so the solution of interest is

$$y = \exp\left(-\frac{Dt}{2m}\right)\left[A_1 \exp\left(i\omega_d t\right) + A_2 \exp\left(-i\omega_d t\right)\right] \tag{19}$$

where,

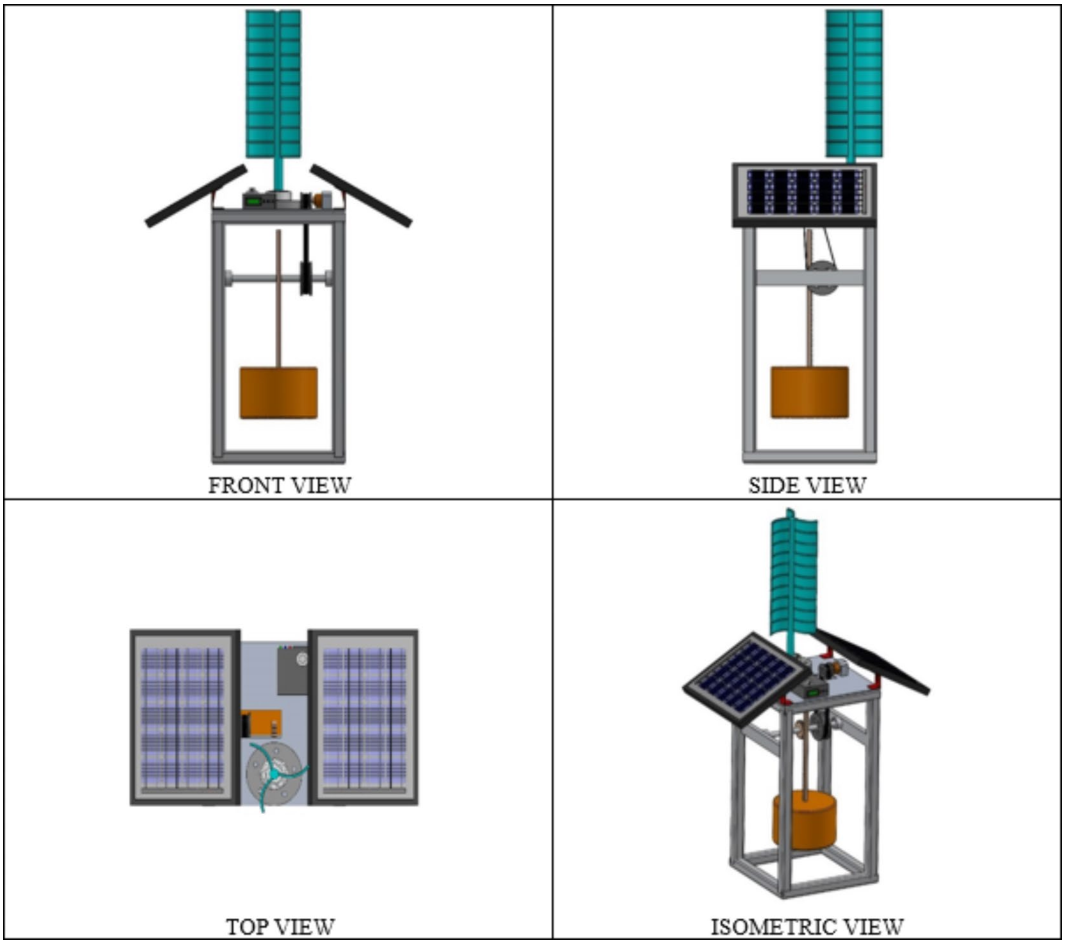

Table 3. Front view, side view, top view & isometric view of the proposed hybrid SWWEC.

$$\omega_d = \sqrt{\frac{S}{m} - \frac{D^2}{4m^2}} \tag{20}$$

Putting, $A_1 = \frac{A(cos\delta + sin\delta)}{2}$ and $A_2 = \frac{A(cos\delta - sin\delta)}{2}$ in Eq. (8) we get

$$y = \exp\left(-\frac{Dt}{2m}\right) A[\frac{(cos\delta + sin\delta)\exp(i\omega_d t)}{2} + \frac{(cos\delta - sin\delta)\exp(-i\omega_d t)}{2}]$$

$$y = \exp\left(-\frac{Dt}{2m}\right)\cos(\omega_d t - \delta) \tag{21}$$

Now to satisfy the RHS of Eq. (13) the solution for the disturbing frequency should be of the form,

$$y = \mathrm{B}\ \exp(i\omega t) \tag{22}$$

Substituting y and its derivatives in Eq. (13)

$$-m\omega^2 B + iD\omega B + SB = F \tag{23}$$

$$=> B = \frac{F}{(S - m\omega^2) + iD\omega} \tag{24}$$

Now using the properties of complex numbers, the denominator can be written as

$$\{\sqrt{(S - m\omega^2)^2 + D^2\omega^2}\}\exp(i\alpha) \tag{25}$$

where,

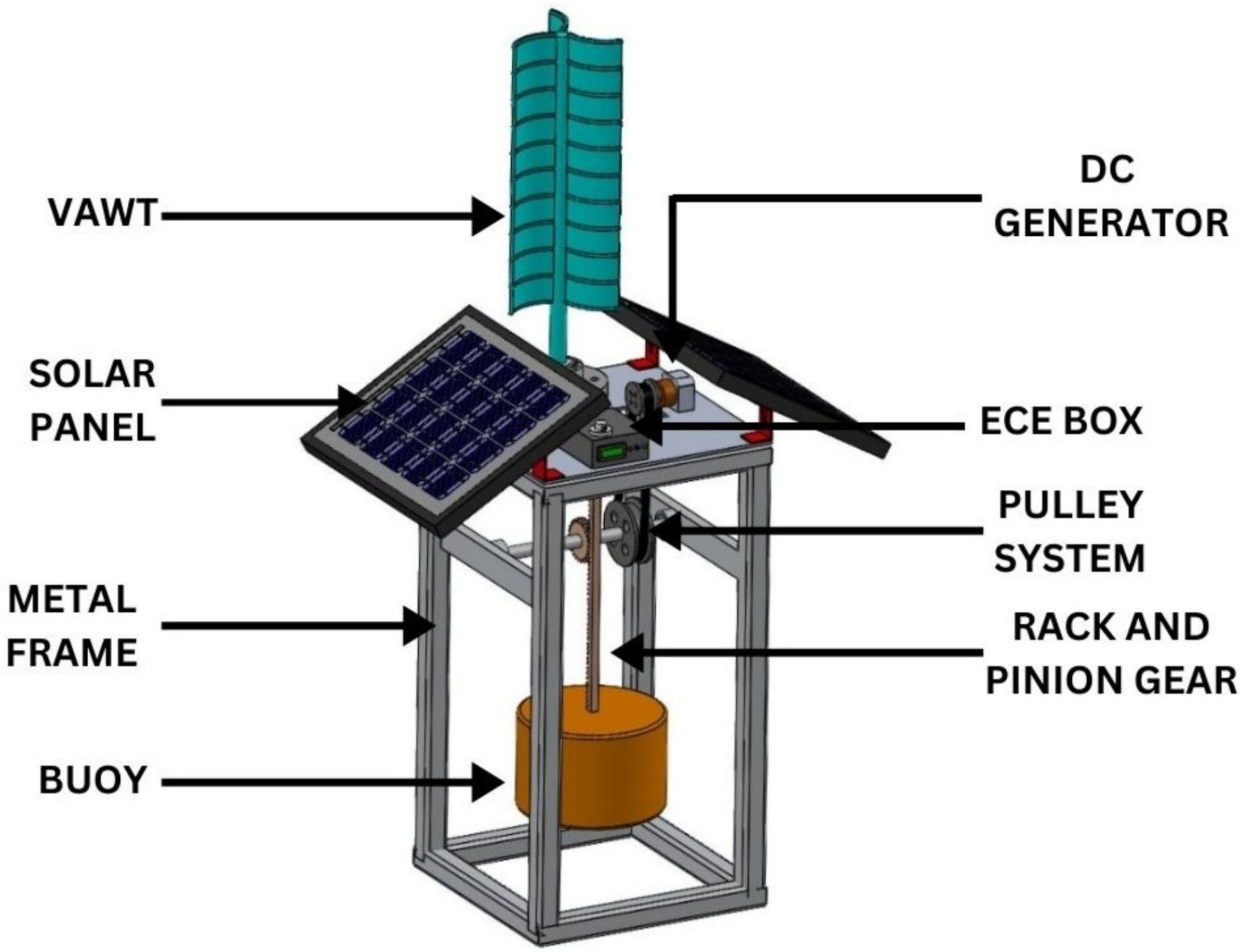

Fig. 8. Conceptual design of the proposed hybrid SWWEC.

$$\alpha = \tan^{-1}\{\frac{D\omega}{S - m\omega^2}\} \tag{26}$$

So that if F is complex $F = |F|\exp(i\theta)$ and

$$y = \frac{|F|\exp[i\,(\omega t + \epsilon)]}{\sqrt{(S - m\omega^2)^2 + D^2\omega^2}} \tag{27}$$

where $\epsilon = (\theta - \alpha)$.

Equations on the cylindrical buoy

Considering the horizontal cross-section of a cylindrical buoy,

$$A = \pi a^2$$

For a vertical displacement y, the change in buoyancy force is $\rho g(Ay)$, hence the restoring force coefficient is,

$$S = \rho g A = \rho g \pi a^2 \tag{28}$$

Now the damped natural frequency ω_d by observing in the period $T = t_3 - t_1$ is

$$\omega_d = 2\pi/t_3 - t_1 \tag{29}$$

Also, $\omega_d = \sqrt{\frac{S}{m} - \frac{D^2}{4m^2}}$ and $y = A\exp\left(-\frac{Dt}{2m}\right)\cos(\omega_d t - \delta)$

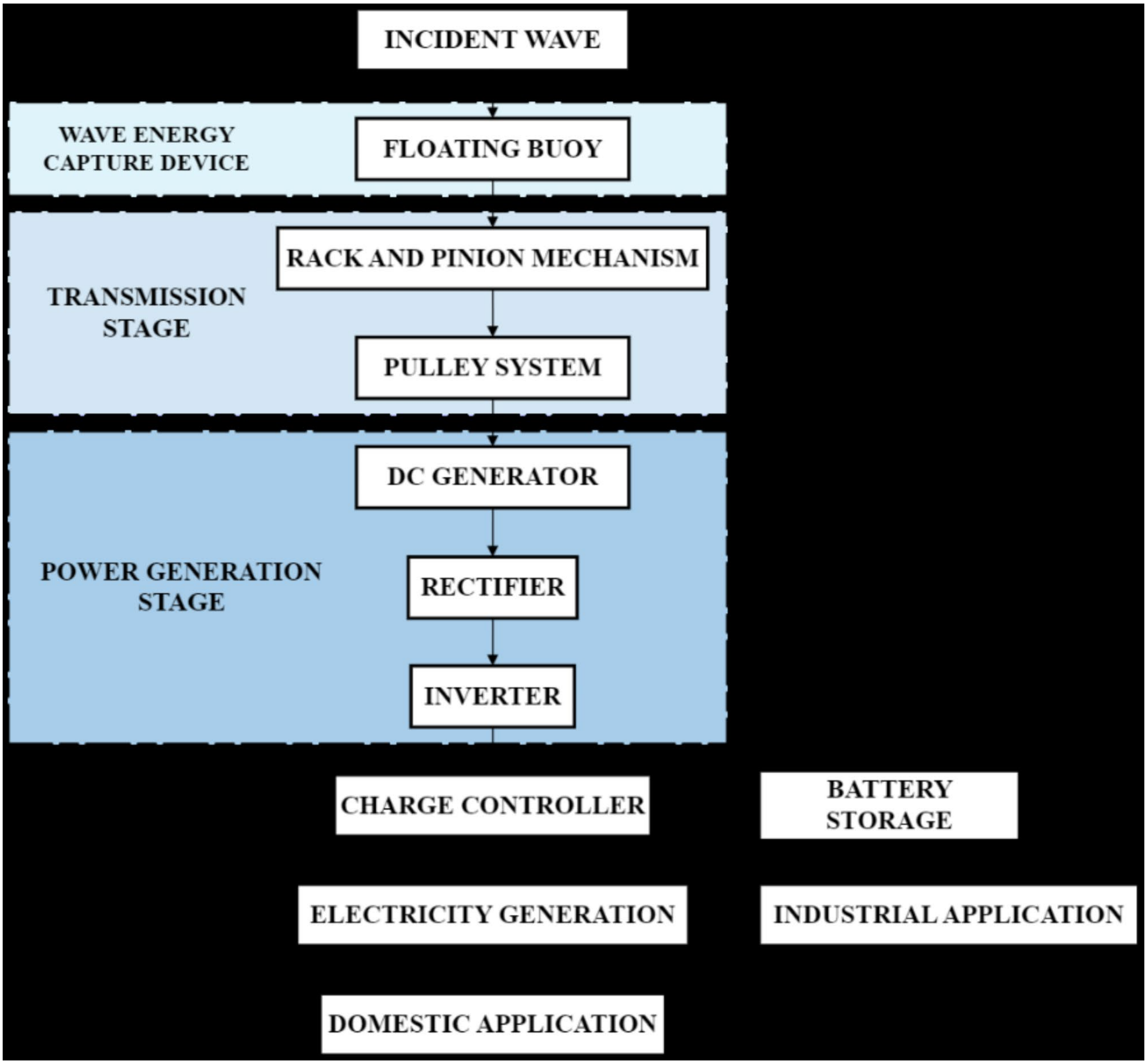

Fig. 9. Wave Energy flow diagram in the proposed hybrid SWWEC.

$$\frac{y_1}{y_3} = \frac{\exp\left(-\frac{Dt_1}{2m}\right)}{\exp\left(-\frac{Dt_3}{2m}\right)} = \exp(\frac{2\pi D}{2m\omega_d}) \tag{30}$$

For convenience, introducing a damping ratio Δ which is defined as the ratio of actual damping coefficient D to the critical damping coefficient when $\omega_d = 0$ and $D = \sqrt{2mS}$. Hence,

$$\Delta = \frac{D}{\sqrt{2mS}} = \frac{D}{2m\omega_o} \tag{31}$$

From Eqs. (30) and (31)

$$\frac{y_1}{y_3} = \exp(\frac{2\pi\Delta\omega_o}{\omega_d}) \tag{32}$$

Now, (20) can be written as

$$\omega_d = \omega_o\sqrt{1-\Delta^2} \tag{33}$$

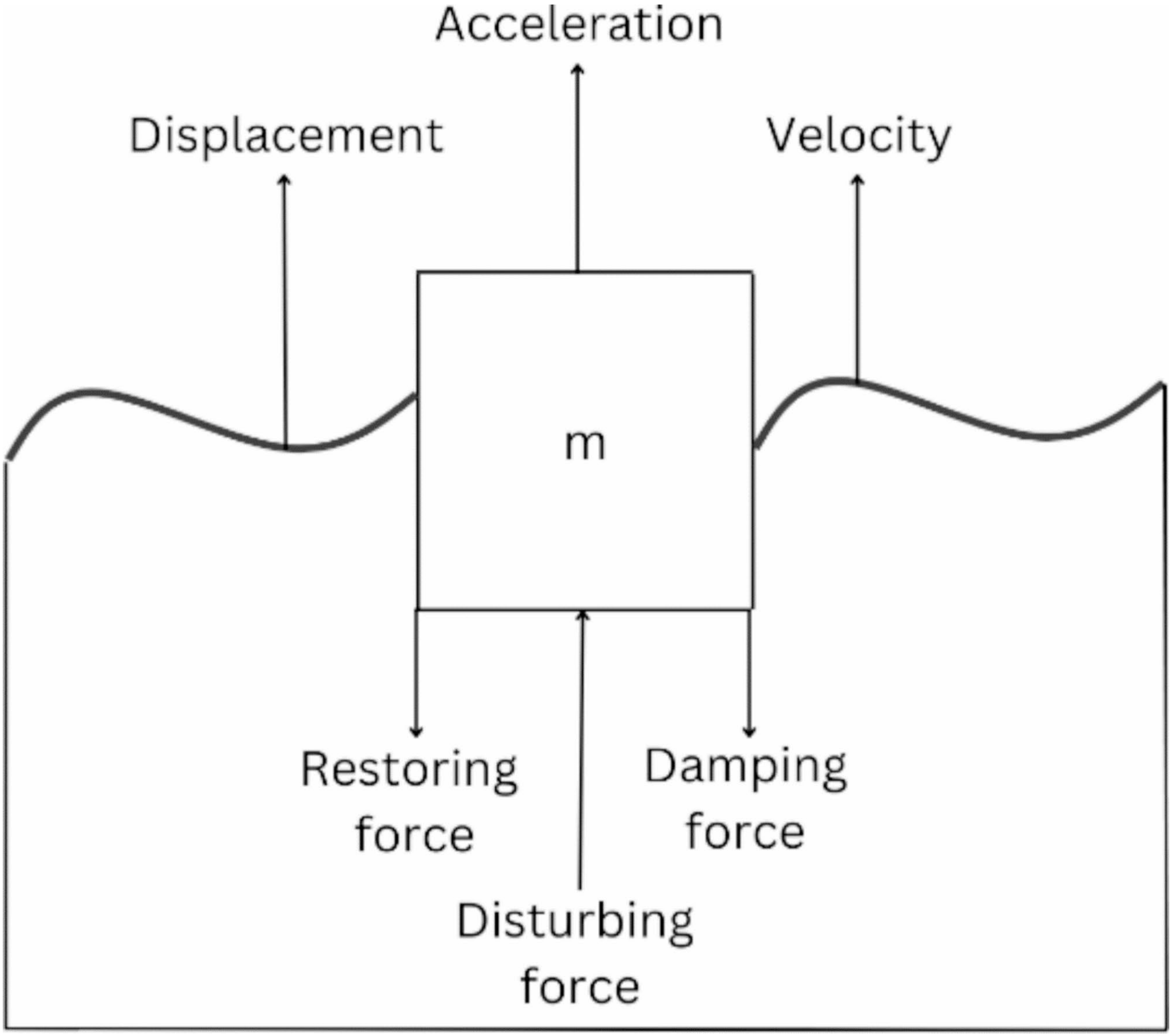

Fig. 10. Forces acting on a WEC.

And (32) becomes,

$$\frac{y_1}{y_3} = \exp(\frac{2\pi\Delta}{\sqrt{1-\Delta^2}}) \tag{34}$$

Rearranging the above equation

$$\Delta = \frac{\ln(\frac{y_1}{y_3})}{\sqrt{4\pi^2 + (\ln\frac{y_1}{y_3})^2}} \tag{35}$$

The instantaneous damping force due to energy extraction $= D_e\dot{y}$ so that the instantaneous energy extraction rate $= D_e\dot{y}^2$,

$$\text{We know that } y = Ccos(\omega t + \epsilon) \tag{36}$$

$$\text{Where } C = |F|\,/\sqrt{(S - m\omega^2)^2 + D^2\omega^2} \tag{37}$$

$$D = D_e + D_f + D_r = D_e + D_L \tag{38}$$

Differentiating (36)

$$\dot{y} = -C\omega sin(\omega t + \epsilon) \tag{39}$$

Therefore, the instantaneous energy extraction rate of power

$$= D_e\dot{y}^2 = D_eC^2\omega^2 sin^2(\omega t + \epsilon) \tag{40}$$

$$\text{Mean power } = \overline{D_e\dot{y}^2} = D_eC^2\omega^2\overline{sin^2(\omega t + \epsilon)} \tag{41}$$

Now the mean square of a sine wave over a period of ½, hence the mean power is,

$$\overline{P} = D_eC^2\omega^2/2 \text{ W} \tag{42}$$

The maximum power demand when the undamped natural frequency be matched to the forcing frequency of the waves and the $D_e = D_L + D_f + D_r$,

$$\overline{P}_{max} = |F|^2/8D_L \text{ W} \tag{43}$$

Design of the buoy of WEC

The motion of the buoy considered in this paper is a heave type of motion. The wave velocity decides the decay time as the buoy will not be able to capture the wave energy if the decay time is too long. Hence, when creating a buoy's response to big, slow waves, it's best for the buoy to move smoothly up and down. This helps stop the waves from causing too much bouncing or splashing around.

A WEC buoy's performance is influenced by three key factors discussed in wave characteristics. The buoy operates like a particle, undulating with incoming waves as long as the wavelength isn't excessively short. Typically, the size of the buoy is kept below one-tenth of the wavelength. If the wavelength is too short or matches the size of the buoy, the buoy may straddle the wave's crest and trough simultaneously, resulting in inefficient energy capture.

The amplitude of the wave is crucial as it determines the vertical potential energy of the buoy and the amount of energy captured. Wave velocity, representing the speed of wave transfer, impacts the dynamic response of the buoy. A slow buoy dynamic response in fast wave velocity conditions leads to the wave passing the buoy without significant motion. Conversely, a fast buoy dynamic response in slower wave velocity conditions reduces the captured wave energy as mentioned by Yung-Lien Wang[7].

Advantages over a point absorber WEC

The design of the hybrid SWWEC outlined in this paper offers several notable advantages over the conventional Point Absorber Wave Energy Converters (PAWECs) as shown in Table 4:

Laboratory validation and result analysis

The dynamic model of the hybrid SWWEC is emulated in a real-time simulation environment using DSpace. The DSpace model is shown in Figure. It can be interfaced with the real world through its analog and digital I/Os. The DSpace being a user-friendly program in which it can be interfaced with the real world through its analog and digital I/Os and the ability to programme like Simulink blocks is chosen instead of programming a processor for the required application.

Hardware configuration

To execute the emulated SWWEC using a motor-generator setup, it's important to have speed feedback from the motor. This feedback informs the torque command necessary for driving the motor. The motor is operated in torque-controlled mode, while the generator can be managed to generate power at the highest efficiency. A PMSG is used for this application.

Electrical torque is regulated in direct relation to the speed of the rotor is shown in Fig. 11. Rectified generated voltage is shown in the Fig. 12. Rotor speed is for the SWWEC is presented in the Fig. 13 and the corresponding Generator Torque, Rotor Speed, Generator Power are shown in Fig. 14.

Category	Conventional PAWEC	Proposed SWWEC
Proximity to shore installation	✓	✓
Watertight structure	✓	×
Reduced manufacturing and installation costs	×	✓
Integration with other renewable energy sources	×	✓
Implementation of a battery swapping station	×	✓
Preservation of ocean corals	×	✓
Information of the ocean current	✓	✓
Mid sea local charging station	×	✓
Standalone systems	×	✓

Table 4. Comparison of Conventional PAWEC and Proposed SWWEC.

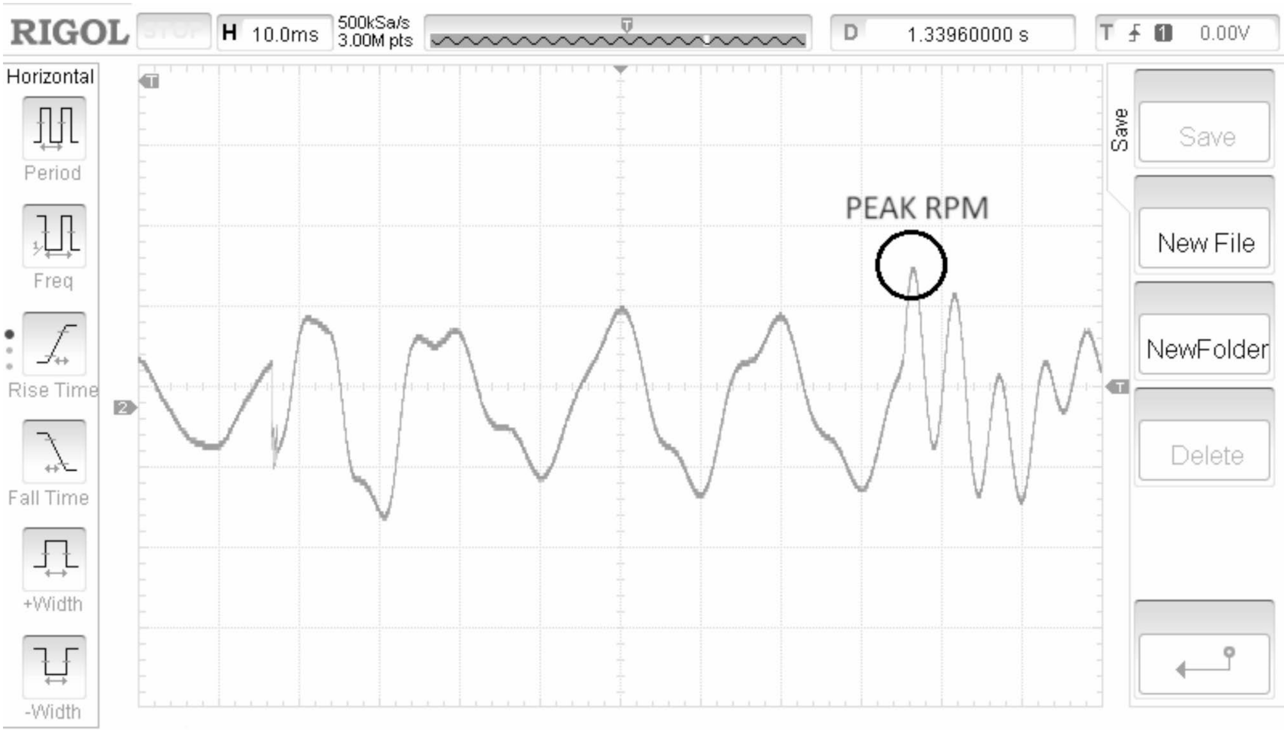

Fig. 11. Generator Torque τ (1000/Div) (Nm).

Figure 11 shows the hardware configuration. DSpace is responsible for supplying torque reference to the drive. The system is initially tested with a speed reference to demonstrate the oscillatory behaviour of the motor-generator setup. The emulating motor is speed controlled with sinusoidal speed reference and the generator output is shown in Figure. The highest frequency of 0.266 Hz of the sinusoidal component of the wave data is considered[27]. The SWWEC generated power in kW is from the laboratory prototype is shown in Fig. 15. Figure 16 shows the hardware configuration. DSpace is responsible for supplying torque reference to the drive. The system is initially tested with a speed reference to demonstrate the oscillatory behavior of the motor-generator setup. The emulating motor is speed controlled with sinusoidal speed reference and the generator output is shown in Figure.

The peak torque obtained during the experimentation was found to be 1200 Nm. The peak rectified generator voltage and generator power was found to be 38 V and 510 kW respectively at a maximum rotor speed of 290 rpm.

Conclusion

The paper discusses dynamic emulation for a WEC along with a CAD model of the SWWEC, integrating solar, wind, and wave energy sources is proposed. The advantages of the SWWEC model over conventional PAWEC are highlighted. Additionally, real-time simulation results obtained using DSpace software are presented. The peak torque, rectified generator voltage, power and rotor speed obtained after the experimentation of the WEC are found to be 1200 Nm, 38 V, 510 kW and 290 rpm respectively. The emulation involves controlling an emulating motor using speed reference, with the results obtained of this control process are presented in the paper. To facilitate torque feedback-based emulation, the rotor speed needs to be fed back to the DSpace system. This feedback loop ensures that the emulation closely mimics the real-world behaviour of the WEC. In addition, the paper presents a comprehensive overview of WECs deployed worldwide along with their installed capacity. The objectives and conclusions drawn by various researchers across the world on different types of WECs are also compiled and presented for easy reference and comparison.

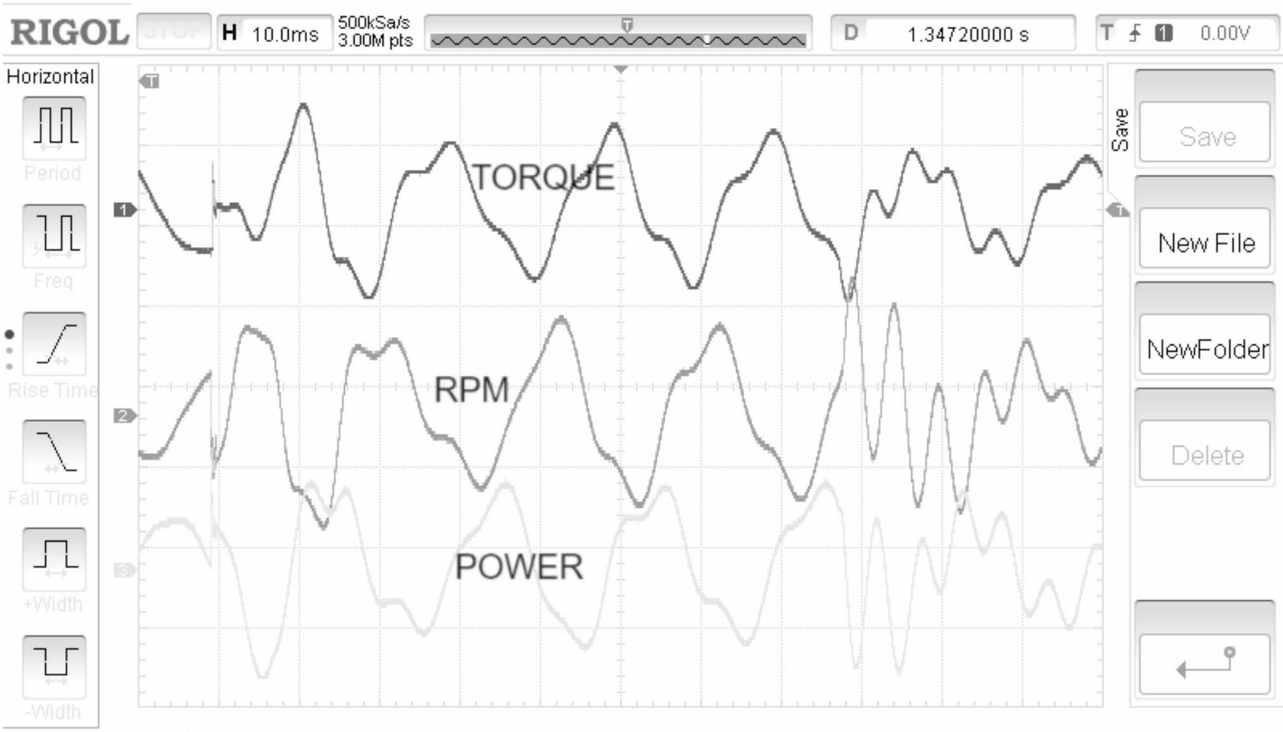

Fig. 12. Rectified generator voltage (10/Div) (V).

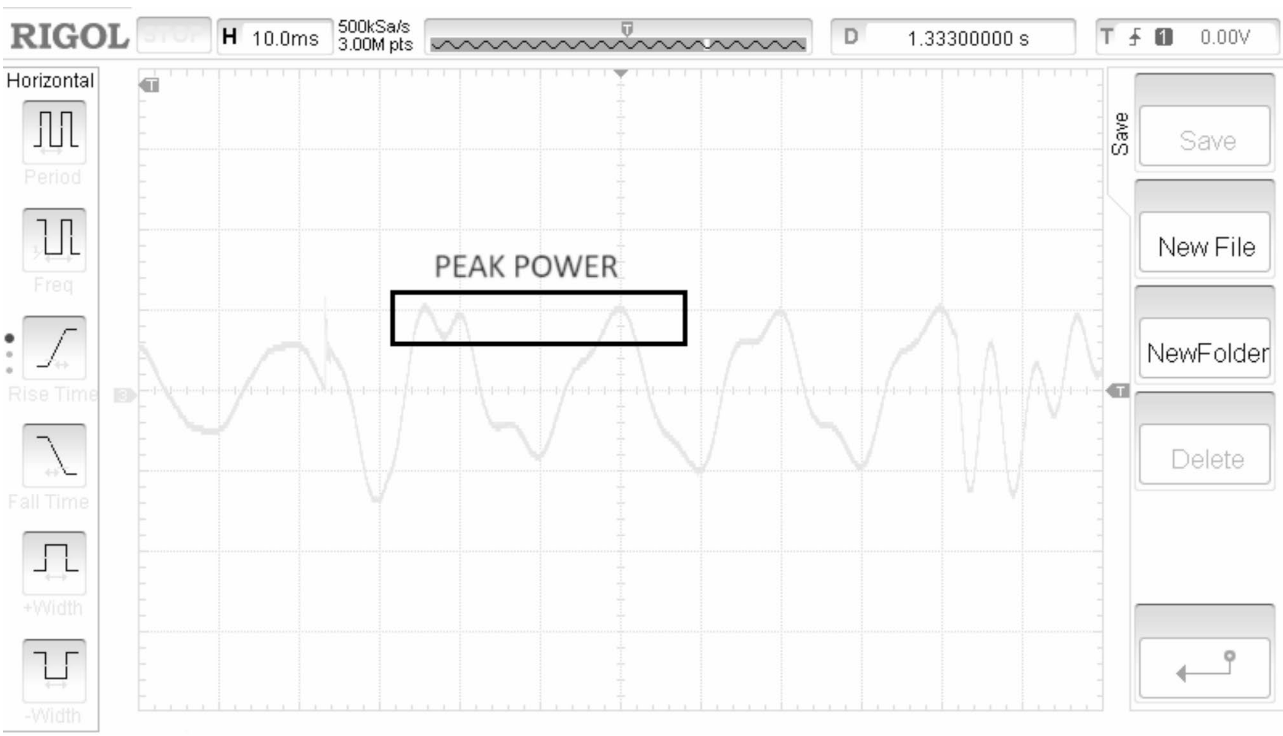

Fig. 13. Rotor Speed ω (250/Div) (rad/sec).

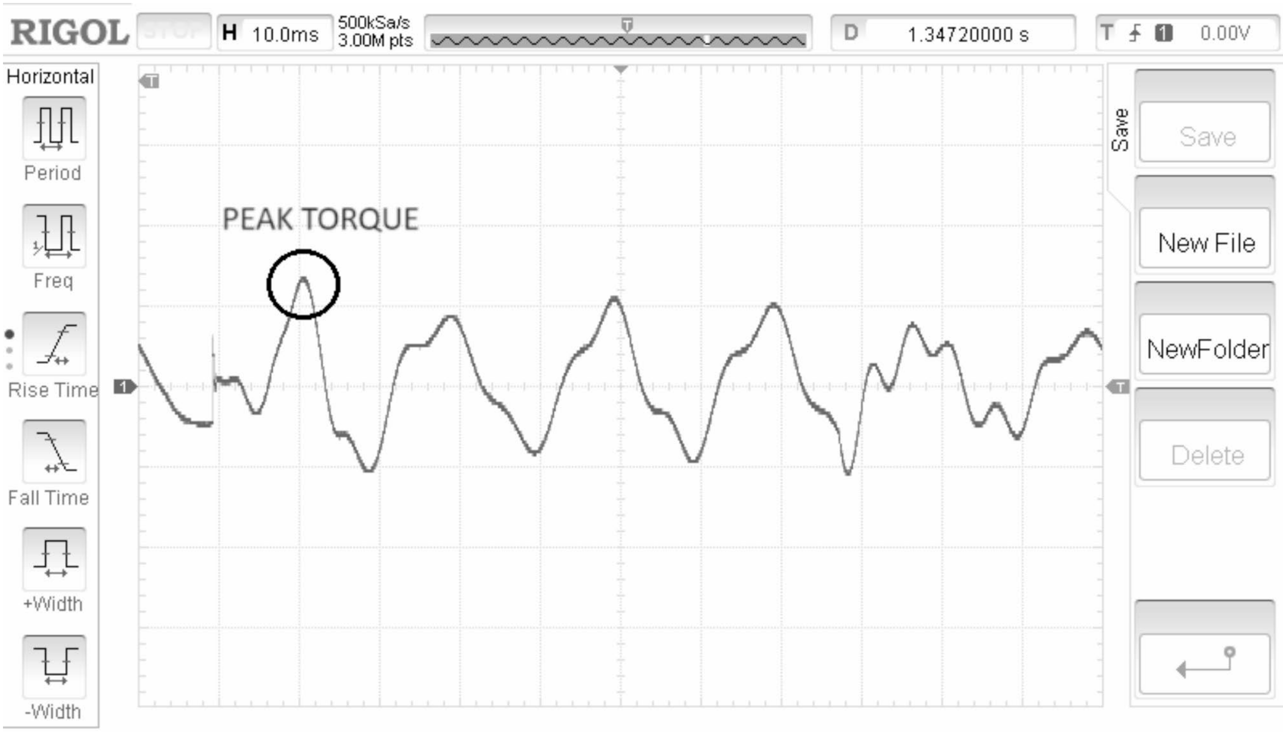

Fig. 14. Generator Torque, Rotor Speed, Generator Power.

Fig. 15. Generator Power (500/Div) (kW).

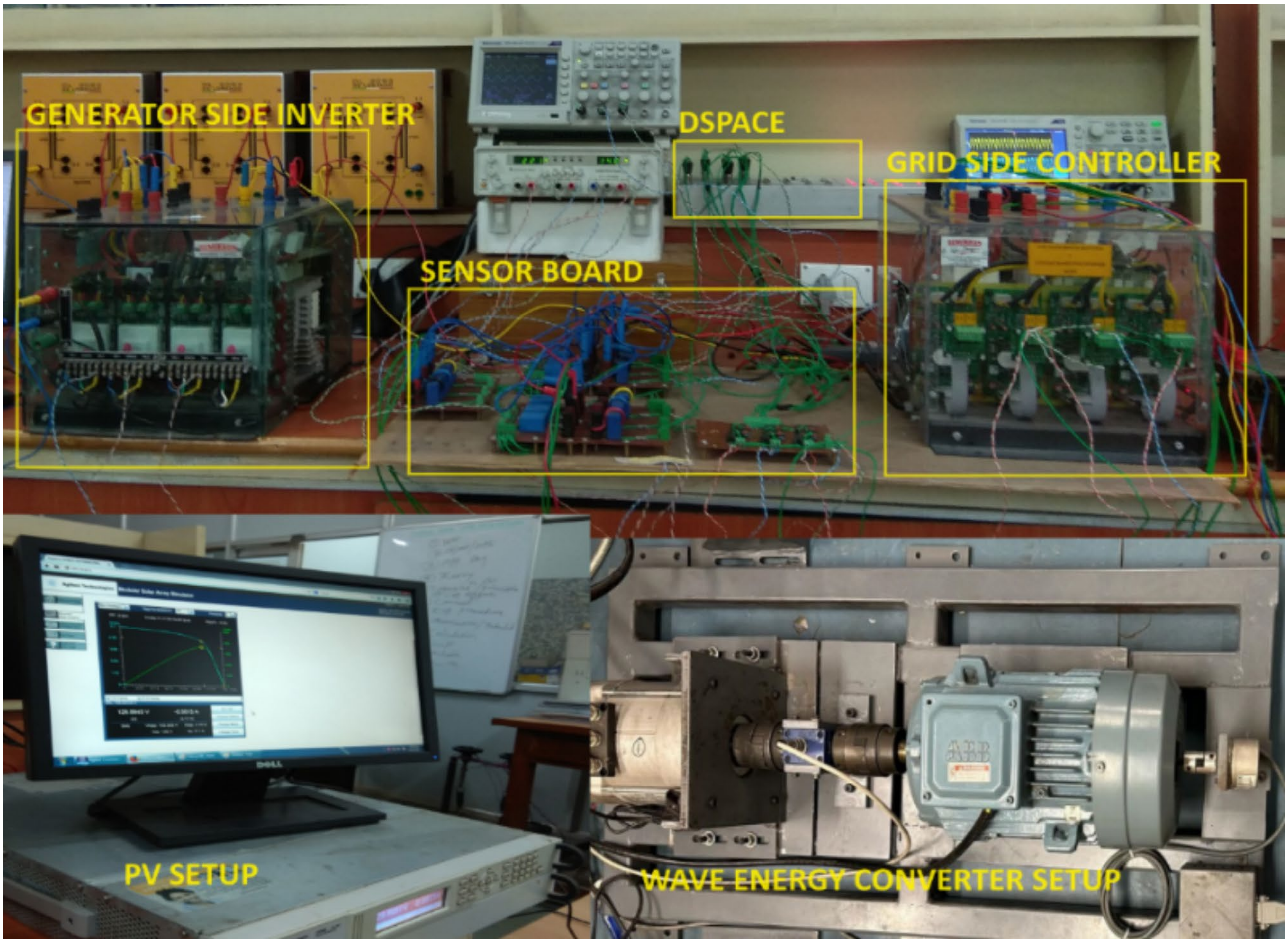

Fig. 16. DSpace model, PV Setup & WEC Setup.

Data availability

The data used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Received: 17 May 2024; Accepted: 11 September 2024
Published online: 30 September 2024

References

1. Rodrigues, L. Wave power conversion systems for electrical energy production. *Renew. Energy Power Qual. J.* https://doi.org/10.24084/repqj06.380 (2008).
2. Son, D. & Yeung, R. W. Optimizing ocean-wave energy extraction of a dual coaxial cylinder WEC using nonlinear model predictive control. *Appl. Energy* **187**, 746–757 (2017).
3. Han, Z., Cao, F. & Shi, H. Numerical simulation on the energy capture spectrum of heaving buoy wave energy converter. *Ocean Eng.* **280**, 114475. https://doi.org/10.1016/j.oceaneng.2023.114475 (2023).
4. Lai, W., Li, D. & Xie, Y. Numerical study on the improvement design of the oscillating buoy wave energy converter. *Ocean Eng.* **232**, 109080. https://doi.org/10.1016/j.oceaneng.2021.109080 (2021).
5. Sun, P. et al. Structural optimization on the oscillating-array-buoys for energy-capturing enhancement of a novel floating wave energy converter system. *Energy Convers. Manag.* **228**, 113693. https://doi.org/10.1016/j.enconman.2020.113693 (2021).
6. Henriques, J. C. C. et al. Design of oscillating-water-column wave energy converters with an application to self-powered sensor buoys. *Energy* **112**, 852–867. https://doi.org/10.1016/j.energy.2016.06.054 (2016).
7. Wang, Y.-L. Design of a cylindrical buoy for a wave energy converter. *Ocean Eng.* **108**, 350–355. https://doi.org/10.1016/j.oceaneng.2015.08.012 (2015).
8. Chatzigiannakou, M. A. *et al.* Offshore deployments of wave energy converters by Uppsala University, Sweden. *Mar. Syst. Ocean Technol.* **14**, 67–74 (2019).
9. von Jouanne, A., Brekken, T., Lettenmaier, T., Amon, E. & Phillips, R. A novel ocean sentinel instrumentation buoy for wave energy testing, Oceans-Yeosu, Yeosu. *Korea (South)* **2012**, 1–6. https://doi.org/10.1109/OCEANS-Yeosu.2012.6263366 (2012).
10. Amundarain, M., Alberdi, M., Garrido, A. J. & Garrido, I. Modeling and simulation of wave energy generation plants: Output power control. *IEEE Trans. Indus. Electron.* **58**(1), 105–117. https://doi.org/10.1109/TIE.2010.2047827 (2011).
11. Wu, F., Zhang, X.-P., Ju, P. & Sterling, M. J. H. Modeling and control of AWS-based wave energy conversion system integrated into power grid. *IEEE Trans. Power Syst.* **23**(3), 1196–1204. https://doi.org/10.1109/TPWRS.2008.922530 (2008).
12. Kjell, B. & Johannes, F. Wave power conversion by point absorbers—A Norwegian project. *Int. J. Ambient Energy* **3**(2), 59–67. https://doi.org/10.1080/01430750.1982.9675829 (1982).

13. Müller, N. et al. Medium-voltage power converter interface for multigenerator marine energy conversion systems. *IEEE Trans. Indus. Electron.* **64**(2), 1061–1070. https://doi.org/10.1109/TIE.2016.2615276 (2017).
14. Sharkey, F., Bannon, E., Conlon, M. & Gaughan, K. Maximising value of electrical networks for wave energy converter arrays. *Int. J. Mar. Energy* **1**, 55–69. https://doi.org/10.1016/j.ijome.2013.06.002 (2013).
15. Huang, H., Mao, C., Lu, J. & Wang, D. Electronic power transformer control strategy in wind energy conversion systems for low voltage ride-through capability enhancement of directly driven wind turbines with permanent magnet synchronous generators (D-PMSGs). *Energies* **7**, 7330–7347. https://doi.org/10.3390/en7117330 (2014).
16. Elgammal, A. Adaptive fuzzy sliding mode controller for grid interface ocean wave energy conversion. *J. Intell. Learn. Syst. Appl.* **06**, 53–69. https://doi.org/10.4236/jilsa.2014.62006 (2014).
17. Rahm, M., Boström, C., Svensson, O., Grabbe, M., Bülow, F. & Leijon, M. *Laboratory Experimental Verification of a Marine Substation 8th European Wave and Tidal Energy Conference, Uppsala, Sweden*. 51–58 (2009).
18. Ibrahim, N. F., Alkuhayli, A., Beroual, A., Khaled, U. & Mahmoud, M. M. Enhancing the functionality of a grid-connected photovoltaic system in a distant Egyptian region using an optimized dynamic voltage restorer: Application of artificial rabbits optimization. *Sensors.* **23**(16), 7146. https://doi.org/10.3390/s23167146 (2023).
19. Mahmoud, M. M. et al. Application of whale optimization algorithm based FOPI controllers for STATCOM and UPQC to mitigate harmonics and voltage instability in modern distribution power grids. *Axioms* **12**(5), 420. https://doi.org/10.3390/axioms12050420 (2023).
20. Srikanth Goud, B., Kiran Kumar, M., Ashok Kumar, N. & Kalyan, N. S. Dynamic voltage restorer to mitigate voltage sag/swell using black widow optimization technique with FOPID controller. *EAI Endorsed Trans. Energy Web*https://doi.org/10.4108/ew.4331 (2023).
21. Metwally Mahmoud, M. Improved current control loops in wind side converter with the support of wild horse optimizer for enhancing the dynamic performance of PMSG-based wind generation system. *Int. J. Model. Simul.* **43**(6), 952–966. https://doi.org/10.1080/02286203.2022.2139128 (2022).
22. Mahmoud, A. et al. Voltage quality enhancement of low-voltage smart distribution system using robust and optimized DVR controllers: Application of the Harris Hawks algorithm. *Int. Trans. Electric. Energy Syst.*https://doi.org/10.1155/2022/4242996 (2022).
23. Ibrahim, N. F. et al. Operation of grid-connected PV system with ANN-based MPPT and an optimized LCL filter using GRG algorithm for enhanced power quality. *IEEE Access* **11**, 106859–106876. https://doi.org/10.1109/ACCESS.2023.3317980 (2023).
24. Dash, S. K. & Ray, P. K. Power quality improvement utilizing PV fed unified power quality conditioner based on UV-PI and PR-R controller. *CPSS Trans. Power Electron. Appl.* **3**(3), 243–253. https://doi.org/10.24295/CPSSTPEA.2018.00024 (2018).
25. Boström, C. & Leijon, M. Operation analysis of a wave energy converter under different load conditions. *IET Renew. Power Gener.* **5**(3), 245–250 (2011).
26. Hebenstreit, G.T. *Wave Energy: A Design Challenge: by Ronald Shaw*. (Ellis Horwood Limited, (distributed by Wiley, Chichester), 1982) *Coastal Eng.* **11**(2), 186–187 (1987).
27. *Mapping and Assessment of the United States Ocean Wave Energy Resource*. Vol. 1024637 (EPRI, 2011)..
28. Berenjkoob, M. N., Ghiasi, M. & Soares, C. G. Influence of the shape of a buoy on the efficiency of its dual-motion wave energy conversion. *Energy* **214**, 118998. https://doi.org/10.1016/j.energy.2020.118998 (2021).
29. Chandrasekaran, S. & Sricharan, V. V. S. Numerical analysis of a new multi-body floating wave energy converter with a linear power take-off system. *Renew. Energy* **159**, 250–271. https://doi.org/10.1016/j.renene.2020.06.007 (2020).
30. Müller-Pollmann, N. & Kouro, S., Malinowski, M. & Rivera, S. & Wu, B. Cascaded H-bridge multilevel converter interface for wave dragon energy conversion system. In *IECON Proceedings* (*Industrial Electronics Conference*). 6201–6206. https://doi.org/10.1109/IECON.2013.6700155 (2013).
31. Weinstein, A. et al. AquaBuOY-the offshore wave energy converter numerical modeling and optimization. In *Oceans 2003. Celebrating the Past ... Teaming Toward the Future* (*IEEE Cat. No.03CH37492*), *San Diego, CA, USA*. Vol. 4. 1988–1995 https://doi.org/10.1109/OCEANS.2003.178203 (2003).
32. Aggidis, G.A. & Taylor, C.J. Overview of wave energy converter devices and the development of a new multi-axis laboratory prototype. *IFAC-PapersOnLine* **50**(1), 15651–15656 (2017).
33. O'Connor, M., Lewis, T. & Dalton, G. Techno-economic performance of the Pelamis P1 and Wavestar at different ratings and various locations in Europe. *Renew. Energy* **50**, 889–900. https://doi.org/10.1016/j.renene.2012.08.009 (2013).
34. Retzler, C. Measurements of the slow drift dynamics of a model Pelamis wave energy converter. *Renew. Energy* **31**(2), 257–269 (2006).
35. Tedd, J. Measurements of overtopping flow time series on the wave dragon, wave energy converter. *Renew. Energy* **34**(3), 711–717. https://doi.org/10.1016/j.renene.2008.04.036 (2009).
36. Zhang, Z., Chen, X., Haitao, W., Liu, W. & Cui, L. Numerical study of a novel hybrid system with the Wavestar wave energy converter array and a SPIC semi-submersible floating platform. *J. Clean. Prod.* **407**, 137178. https://doi.org/10.1016/j.jclepro.2023.137178 (2023).
37. Falcão, A. F. O. & Henriques, J. C. C. Oscillating-water-column wave energy converters and air turbines: A review. *Renew. Energy.* **85**, 1391–1424 (2016).
38. López, I., Andreu, J. & Ceballos, S. Review of wave energy technologies and the necessary power-equipment. *Renew. Sustain. Energy Rev.* **27**, 413–434 (2013).
39. Yamashita, K. -I., Tsuchikawa, T. & Takekoshi, S. Development of a point absorber wave energy converter with magnus effect-based turbine generator. In *2022 25th International Conference on Electrical Machines and Systems* (*ICEMS*), *Chiang Mai, Thailand*. 1–6. https://doi.org/10.1109/ICEMS56177.2022.9982922 (2022).
40. Guo, W., Zhou, Yh., Zhang, Wc. et al. Hydrodynamic analysis and power conversion for point absorber WEC with two degrees of freedom using CFD. *China Ocean Eng.* **32**, 718–729 (2018). https://doi.org/10.1007/s13344-018-0073-2
41. Jalani, M. A., Saad, M. R., Samion, M. K. H., Imai, Y. & Nagata, S. Numerical study on a hybrid WEC of the backward bent duct buoy and point absorber. *Ocean Eng.* **267**, 113306 (2023).
42. Aji, N., Ekawati, E. & Haq, I. N. The simulation of wave energy conversion by floating point absorber buoy in Indonesian sea waves. In *2021 International Conference on Instrumentation, Control, and Automation* (*ICA*), *Bandung, Indonesia*. 112–117 https://doi.org/10.1109/ICA52848.2021.9625671 (2021).
43. Olaya, S., Bourgeot, J. -M. & Benbouzid, M. Modelling and preliminary studies for a self-reacting point absorber WEC. In *2014 First International Conference on Green Energy ICGE 2014, Sfax, Tunisia*. 14–19. https://doi.org/10.1109/ICGE.2014.6835390 (2014).
44. Sun, P., Hongzhou He, H., Chen, J. Z. & Li, H. Sensitivity analysis of geometric characteristics on the cavity-buoy for energy capture efficiency enhancement of a semi-submersible floating-array-buoy wave energy converter system. *Ocean Eng.* **294**, 116735. https://doi.org/10.1016/j.oceaneng.2024.116735 (2024).
45. Portillo, J. C. C. et al. Wave energy converter physical model design and testing: The case of floating oscillating-water-columns. *Appl. Energy* **278**, 115638. https://doi.org/10.1016/j.apenergy.2020.115638 (2020).
46. Derong, D., Fei, C., Hui, Z., Xuefeng, Y. & Fang, Z. Study on capture power of the sealed-buoy wave energy converter in low energy flow density area. *Renew. Energy* **152**, 1024–1034. https://doi.org/10.1016/j.renene.2020.01.136 (2020).

Author contributions

A.M.J. designed the SWWEC, prepared the figures, performed the experimental calculations. The first draft of the manuscript was written by A.M.J., supervised by S.K.D and extended by U.K.S. and S.C.. All authors participated in discussions, interpretation of data and finalization of the manuscript. S.K.D., U.K.S. and S.C. coordinated the project. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to S.K.D. or U.K.S.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.