2020

Progress in Piezoelectric Material Based Oceanic Wave Energy Conversion Technology

Mahbubur Kiran
Omar Farrok
Md Abdullah-Al-Mamun
Md Rabiul Islam

University of Wollongong, mrislam@uow.edu.au

Wei Xu
weix@uow.edu.au

Follow this and additional works at: https://ro.uow.edu.au/eispapers1

Part of the Engineering Commons, and the Science and Technology Studies Commons

Recommended Citation
Kiran, Mahbubur; Farrok, Omar; Abdullah-Al-Mamun, Md; Islam, Md Rabiul; and Xu, Wei, "Progress in Piezoelectric Material Based Oceanic Wave Energy Conversion Technology" (2020). Faculty of Engineering and Information Sciences - Papers: Part B. 4318.

https://ro.uow.edu.au/eispapers1/4318

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
Progress in Piezoelectric Material Based Oceanic Wave Energy Conversion Technology

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.

Keywords
progress, material, oceanic, wave, piezoelectric, technology, conversion, energy

Disciplines
Engineering | Science and Technology Studies

Publication Details
M. Kiran, O. Farrok, M. Abdullah-Al-Mamun, M. Islam & W. Xu, "Progress in Piezoelectric Material Based Oceanic Wave Energy Conversion Technology," IEEE Access, vol. 8, pp. 146428-146449, 2020.

This journal article is available at Research Online: https://ro.uow.edu.au/eispapers1/4318
Abstract—The perpetual oscillations of ocean waves produce potential energy, which can be converted to electrical energy with the help of direct drive linear generators. The fluctuating generated power poses a major challenge when it is supplied to the power grid. In this paper, a supercapacitor provides the short-term energy storage to buffer and smooth out the power fluctuations. A new coupled model of a wave energy converter and a linear generator is proposed for its response characterization under varying system conditions. The developed model and an advanced control strategy is used to exhibit a smooth and stable operation of the wave-to-wire system. The generator side converter is controlled to extract the maximum power from the waves and to minimize the generator losses by controlling its $d$-axis and $q$-axis currents. The grid side converter is controlled to keep the dc-link voltage constant and to generate the required voltage waveforms at the point of common coupling. The performance of the proposed control strategy for the wave-to-wire system is investigated under different applied diffraction forces. The simulation results show that with the use of proposed control scheme and the supercapacitor, the wave-to-wire system can operate in a smooth and stable operation under normal and fault conditions.

Index Terms—Wave energy conversion, linear generator, maximum power tracking, supercapacitor, wave-to-wire.

I. INTRODUCTION

THE ocean covers almost 70% of the world, and it has a gigantic potential to be used as a renewable energy resource. The ocean energy has the potential to meet the world energy demand [1]. The continuous availability of the wave energy on the ocean surface can play a vital role in the production of clean and eco-friendly energy [2]. In the recent decades, the wave energy has gained much attention of the researchers because of its enormous potential. According to a recent study, the global wave power has been also increased due to the oceanic warming [3]. Different types of wave energy converters (WECs) are used to convert the wave energy into the rotatory or translatory motion, such as the Archimedes wave swing (AWS), the oscillating water column (OWC), the wave-activated bodies (WAB), the bulge-wave, the wave-heaving bodies, the over-topping devices (OTD), the wave-surge and the rotating-mass devices. The operating principles of these WECs are illustrated in Fig. 1. The WECs transform the wave energy into the mechanical energy, which is then converted to the electrical energy by deploying a rotary or linear electric generator (LEG).

A direct drive LEG can generate electricity without the need of any intermediate stage of mechanical conversions. This makes the LEG a most suitable option for the wave energy applications [4]. The wave power generating systems can be integrated with the utility networks by using advanced conversion technologies. Although, the technology developed for the wind energy sector can serve as a blueprint for the wave sector, but it cannot be directly applied to the wave energy technology, as these are two different forms of energies, the wind and the wave energy resources, which are radically different. The continuous unsettled nature of the waves produces a fluctuating power output from the WECs, and if the LEG is deployed, the electric output voltage frequency and amplitude will be variable [5]. The performance of the power take-off (PTO) unit of the WEC, which converts the kinetic and potential energy of the oscillating gravity waves into electrical energy, depends upon the control topology used. A passive control for the PTO is easy to implement but it cannot absorb the maximum power from the incoming wave excitation force [6]. The reactive control topologies are able to absorb most of the wave power, but the physical constraints of WECs pose a limitation in such control strategies [7]. A power electronic interface is usually required to connect the variable magnitude, variable frequency output of the LEG to the fixed voltage, fixed frequency grid power. Full-scale back-to-back power electronic converters are required for parallel operation with the utility grid, as the power electronic control is relatively easy to implement when compared to that of the mechanical counterpart [8].

The issue of the high peak to average power ratio of WECs can be resolved with the latching control of the WEC. In this active control scheme, the amplitude and the phase of the WEC are controlled by physically locking and unlocking it for an optimized duration of time [9].

Most of the LEGs are of synchronous type, based on the permanent magnet LEG (PMLEG), which is a relatively mature and is a widely used technology for wave energy applications [10]. The power conditioning can be achieved

![Fig. 1. A schematic demonstration of the working principle of (a) AWS (b) OWC (c) WAB (d) Bulge wave (e) Heaving body (f) OTD (g) Wave surge, and (h) Rotating mass.](image)

The paper 2019-IACC-0911, was presented at 2019 IEEE Industry Applications Society Annual Meeting, Baltimore, MD, USA, Sep 29th - Oct 3rd, 2019. (Corresponding author: Safdar Rasool.) The authors are with the

SECTE, University of Wollongong, Wollongong, NSW 2522, Australia (e-mail:sr785@uowmail.edu.au; mrislam@uow.edu.au; kashem@uow.edu.au; soetanto@uow.edu.au ).
via: (a) the energy storage, such as the hydraulic accumulator, the supercapacitor, the battery, or the reservoir [11]; (b) the inertial storage through variable speed control and the system inertia [12]; and (c) the inherent smoothing ability with spacing among devices in a farm [13]. One way of tracking the maximum power is the selection of the optimum loading. The power produced should ideally match the load to absorb the maximum power [14]. But in practical scenarios, this is hard to realize if only one specified load is used.

The wave energy has more short term variations as compared with the wind energy, as it goes to zero on average twice per cycle of the wave [15]. The power peaks from the WEC occur for very short duration; one way to level the power is by using the energy storage system, to store this peak energy for use at the off-peak time, the other way is to reduce the installed capacity, but this will lower its annual energy production. The control strategies affect the voltage fluctuations, the active and reactive power at the point of common coupling (PCC) under different grid impedances [16]. An ill-configured connection of the WEC with the grid can significantly distort the injected current waveform. Therefore, an optimal design must be investigated prior to the connection of the LEGs with utility networks.

In most practical scenarios, the output from a single PMLEG is only a few hundreds of kW, to have a single connection of the LEGs with utility networks. The control strategies affect the voltage fluctuations, the active and reactive power at the point of common coupling (PCC) under different grid impedances [16]. An ill-configured connection of the WEC with the grid can significantly distort the injected current waveform. Therefore, an optimal design must be investigated prior to the connection of the LEGs with utility networks.

The primary condition for the extraction of the maximum power from the incoming oceanic wave is the ability to ensure that the WEC resonates with the wave, where the natural frequency of the WEC coincides with the wave [7]. But with the change in the frequency for every incoming wave, the mechanical system cannot be modified once it has been built [19]. Therefore, a power electronic control is essential to achieve the resonance by controlling the damping of the PMLEG. The second condition for the extraction of the maximum power from the waves is to ensure that the damping coefficients for the PMLEG match those of the waves [20]. Full-scale back-to-back power electronic converters can be used to achieve these two conditions, using a scheme shown in Fig. 2. The earlier work of the authors [22] has been extended in this paper that presents a coupled modelling of wave-to-wire system and an advanced control of a wave energy conversion system. The mechanical model of the AWS is coupled with the dq-frame of reference model of a PMLEG. The electrical output of the PMLEG is synchronized with the grid with the help of two back-to-back power electronic converters as shown in Fig. 2. The converter on the PMLEG side is controlled by adjusting the reference currents, in such a way that the vertical displacement of the PMLEG is in resonance with exciting waves’ amplitude to track the maximum power. The dc-link voltage may vary in an unacceptable magnitude without a proper control scheme. Therefore, the grid side converter is controlled to stabilize the dc-link voltage and to inject a controlled active power to the grid. A supercapacitor (SC) is integrated with the dc-link through a dc-dc buck-boost converter for power conditioning to fix the dc-link voltage. In this way, dc-link voltage is being controlled by both controllers while ensuring its stable operation. In this way, the power produced from the oceanic wave can be smoothly injected into the onshore grid. This paper also presents the performance of the wave-to-wire system under various fault conditions, showing that the use of SC along with its controller ensures the smooth operation of the WEC, even when the system experiences fault conditions. The development and the operational verification; under uncertain conditions, of the coupled model of an AWS and a PMLEG are the main contributions of the paper.

II. THE COUPLED MODEL OF AWS-WEC AND PMLEG
A. The model of the AWS-WEC
The AWS-WEC is a completely water-submersible system of a WEC, which makes the system more robust against Tsunami waves. The AWS is made of an air-filled chamber, covered with an airtight moveable lid with respect to the fixed bottom placed at the seabed. When the crest of a wave passes over the top of the AWS, the heavy weight of the water mass pushes the lid down and the inside air is compressed. On the other hand, when a trough of the wave comes, the weight of the water on the top of the AWS is reduced and the air inside is compressed. When the crest of a wave passes over the top of the AWS, the heavy weight of the water mass pushes the lid down and the inside air is compressed. On the other hand, when a trough of the wave comes, the weight of the water on the top of the AWS is reduced and the air inside is compressed. On the other hand, when a trough of the wave comes, the weight of the water on the top of the AWS is reduced and the air inside is compressed.

\[ F_{\text{wave}} = (M + \mu)z' + \beta_gz' + \beta_wz + k_zz \]  

where, \( M \) represents the mass of the floater including the translator, \( \mu \) is the added mass of the water on the floater top, and \( z' \) represents the vertical displacement of the floater. The damping coefficients of the PMLEG and the AWS-WEC are \( \beta_g \) and \( \beta_w \) respectively, whereas \( k_z \) is the spring constant of
the whole mechanical system. The velocity and the acceleration of the floater are represented with \( \dot{z} = \frac{dz}{dt} \) and \( \ddot{z} = \frac{d\dot{z}}{dt} \). The total mass of the dynamic system is \( M_{\text{tot}} = M + \mu \). A dynamic model of the AWS is developed which will calculate the ‘\( \dot{z} \)’ depending upon the applied ‘\( F_{\text{wave}} \)’ and the damping force ‘\( F_d \)’ exerted by the PMLEG on the floater of the AWS.

The block diagram of the model of the AWS is shown in Fig. 3. From the linear vertical displacement ‘\( z \)’, the angular displacement of the translator ‘\( \omega \)’ can also be obtained with the model by employing the pole pitch ‘\( \omega \)’ of the translator of the PMLEG.

**B. The model of the synchronous PMLEG**

A basic model of the synchronous PMLEG can be expressed in the \( dq \) frame of reference. If \( v_{abc} = [v_a, v_b, v_c]^T \), shows the 3-phase vector, then the \( dq \) vector \([v_d, v_q]^T\) can be obtained from the Park transformation as follows,

\[
[v_d, v_q]^T = D_v v_{abc}
\]

(2)

where, \( D = \frac{2}{\pi} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \end{bmatrix} \)

and \( \theta = (2\pi/3)z - \pi/2 \), which shows the angular position of the rotating \( dq \) frame of reference.

This \( dq \) frame of reference for the PMLEG is different from that of the rotating machines, where the rotor motion has the same direction at all times, whereas in the case of the PMLEG, the translator moves in two directions. This requires two sets of equations for the model, one for the positive velocity and another for the negative velocity \([8, 20]\).

i. When \( \dot{z} \) is positive:

\[
\begin{align*}
V_{ds} &= -R_s i_{ds} + \omega L_s i_{qs} - L_s \frac{di_{ds}}{dt} \\
V_{qs} &= -R_s i_{qs} - \omega L_s i_{ds} - L_s \frac{di_{qs}}{dt} + \omega \Psi_{PM}
\end{align*}
\]

(3)

ii. When \( \dot{z} \) is negative:

\[
\begin{align*}
V_{ds} &= -R_s i_{ds} - \omega L_s i_{qs} + L_s \frac{di_{ds}}{dt} \\
V_{qs} &= -R_s i_{qs} + \omega L_s i_{ds} + L_s \frac{di_{qs}}{dt} + \omega \Psi_{PM}
\end{align*}
\]

(4)

where, \( \omega = 2\pi f \), \( \Psi_{PM} \) is the flux linkage of the PM of the translators, \( R_s \) and \( L_s \) are the internal synchronous resistance and inductance of the stator of the PMLEG.

Equations (3) and (4) can be represented in a more compact form by using the logic of \( \frac{\omega}{|\omega|} \) for the change of sign for both the directions of the velocity, as given in (5).

\[
\begin{align*}
L_s \frac{\omega}{|\omega|} \frac{di_{ds}}{dt} &= -R_s i_{ds} + X_s i_{qs} - V_{ds} \\
L_s \frac{\omega}{|\omega|} \frac{di_{qs}}{dt} &= -R_s i_{qs} - X_s i_{ds} - V_{qs} + \omega \Psi_{PM}
\end{align*}
\]

(5)

where \( X_s = |\omega| L_s \).

The state-space matrix representation of the model of the PMLEG has been derived in (6),

\[
\begin{bmatrix}
\frac{di_{ds}}{dt} \\
\frac{di_{qs}}{dt}
\end{bmatrix}
= \begin{bmatrix}
\frac{\omega}{L_s} & \frac{\omega}{L_s} & 0 \\
\frac{\omega}{L_s} & -\frac{\omega}{L_s} & 0 \\
0 & 0 & \frac{\omega}{L_s} \\
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\
i_{qs} \\
\omega \Psi_{PM}
\end{bmatrix}
\]

(6)

If the PMLEG is assumed to be symmetric, then the variables of the zero-sequence component can be eliminated, and the \( dq \)-frame of reference takes the simple form of the \( dq \)-frame of reference. The active power of the generator is given in (7).

\[
P_g = 1.5 \omega i_{qs} \Psi_{PM}
\]

(7)

\[
F_d = \beta \frac{g^2}{z} = 1.5 \frac{\omega}{z} i_{qs} \Psi_{PM}
\]

(8)

The block diagram of the model of the PMLEG based on (6) is shown in Fig. 3. The angular displacement of the translator ‘\( \omega \)’, which is the output of the AWS block, works as an input to the model of PMLEG and excites it. The voltage is built up and it appears as an output of the model in \( dq \)-frame of reference. The load current is fed-back to the model, which helps in exhibition of the losses in the winding of the PMLEG. Similarly, ‘\( F_d \)’ is calculated based on the loading of the PMLEG, and it is sent back to the AWS block, where it affects the dynamics of the AWS. In this way, both models are mutually coupled and the electrical and the mechanical dynamics have direct effect on each other as shown in Fig. 3. The coupling of the PMLEG and the ASW-WEC is important to realize the dynamics of a practical WEC.
C. The maximum power tracking control scheme

The PMLEG side converter is controlled in such a way that it captures maximum power from the incoming ocean waves by controlling the \( d \)- and the \( q \)-axis currents, \( i_{ds} \) and \( i_{qs} \), of the PMLEG. The \( d \)-axis, \( q \)-axis currents and the wave elevation are the control variables for the PMLEG model. The wave energy conversion system can be divided into two subsystems for developing the control scheme for the irregular waves [19]. The derivation of the reference value of the \( q \)-axis current, \( i_{qs,ref} \), for the irregular waves has been discussed in detail in [22]. This reference value is derived from the condition where the damping force of the PMLEG and the damping force of the water are equal. This implies that the converter limits the PMLEG current in such a way that it keeps the ‘\( z \)’ in phase with the incoming wave. In this way, the damping force \( F_d \) is controlled by the converter, which depends upon the \( q \)-axis current of the PMLEG.

\[
i_{qs,ref} = \frac{R_{eq} \lambda}{3\pi\psi_{PM}} + \frac{M_{ev} \lambda \ddot{\phi} - \lambda k_{qz}}{3\pi\psi_{PM}} \tag{9}\]

The losses of generator are minimized if \( I_{ds,ref} \) is set equal to 0.

III. THE ADVANCED CONTROL STRATEGY OF THE WAVE-TO-WIRE SYSTEM

The proposed control strategy of the wave-to-wire system is shown in detail in Fig. 4.

A. The control of the PMLEG-side VSC

The VSC on the PMLEG side is a pulse width modulation (PWM) rectifier which allows a bidirectional current control by employing a voltage-oriented control (VOC) strategy. This enables the control of ‘\( F_d \)’ of the PMLEG to capture the maximum power from the waves as explained in Section II.C. In VOC, with the Park transformation, the measured three-phase currents are converted into the \( d \)- and the \( q \)-axis components of currents in synchronous frame of reference which are subsequently controlled by the PI controllers. The electrical angular displacement, \( \theta \) is calculated from the position of \( z \), which can be measured using a position sensor in the AWS. The measured values for \( i_{ds} \) and \( i_{qs} \) of the PMLEG are compared with the zero and the reference signal from (9) respectively, and error signals are generated. A new reference voltage signal is created by feeding error signals to the respective PI controllers. Thereafter, the reference signal is compared with a triangular carrier waveform based on the PWM algorithm. The switching pulses generated by the PWM are used to turn the IGBTs of the VSC ON/OFF. In this way, the current of the PMLEG is accordingly forced to follow the reference current, by the switching operations of \( Sa1, Sa2, Sb1, Sb2, Sc1, \) and \( Sc2 \).

In VOC, a fast dynamic response and an appreciable steady-state response can be achieved at the cost of fine tuning requirement for the PI controllers [23]. However, the fast dynamic response is limited due to the limitation of the current loop bandwidth. The optimized gain values for the PI controllers in the PMLEG side converter derived from the water-cycle based algorithm in [24] were used as an initial guess and the thereafter further tuning was achieved by the system identification with the help of control system tuning application of MATLAB. This further tuning was required, as a slight change in the parameters of the system greatly affects the system performance and the gain values have to be adjusted accordingly.

![Fig. 4. The complete control scheme of the wave-to-wire system including supercapacitor.](image-url)
B. The control of the grid side VSC

The grid side VSC control is designed to keep the dc-link voltage at a fixed voltage level. The synchronization of the inverter voltages with the grid voltages is achieved with the help of a phase-locked-loop (PLL) to inject the current into the distribution grid. Further, the voltage feedforward and cross-coupling terms are used to improve the performance of the PI controllers [25]. The active current is used to control the active power injected into the grid. The reference value of the $d$-axis current for the active current loop is calculated from the voltage loop of the dc-link voltage controller. The voltage at the PCC is also adjusted by a PI controller, whose output acts as a reference for the reactive controller. In conventional control, this reactive controller has a zero reference when the reactive power control is not required. The complete control scheme for the wave-to-wire system is shown in Fig. 4. The reference signal for the power can be defined as in (10).

$$P_{g,ref} = 1.5 \omega I_{qs,ref} \Psi_{PM}$$  \hspace{1cm} (10)

C. The control of DC-DC converter for supercapacitor

A supercapacitor (SC), which is an electrochemical double-layer capacitor, is used for the power conditioning of the WEC. The SC is used to provide power for a short duration only, and is not intended for long-term backup storage. It is connected to the dc-link through a buck-boost converter [26]. The converter allows the power flow in both directions, and in this way the SC is charged and discharged depending upon the operating conditions. The converter is operated in the boost mode when the dc-link voltage tends to decrease due to the decreasing feed-in current from the PMLEG in a wave cycle. In the boost mode of the converter, the current is supplied to the dc-link and the SC starts discharging. On the other hand, the buck mode of the converter is initiated when the dc-link voltage tends to increase from the reference dc voltage, and consequently, the converter starts charging the SC for the next cycle. The control structure for the bidirectional buck-boost converter, has two cascaded control loops as shown in Fig. 4. The outer loop of the control structure maintains the dc-link voltage to the fix reference by generating a reference value for the SC current according to the dynamically updated value of measured dc-link voltage. The reference value of the SC current is used in the inner current loop to decide whether the SC has to be charged or discharged. Typically, a commercial SC has a long life, up to 1,000,000 duty cycles or a 10 year life along with a high power density [27]. Some of the Maxwell Technologies SCs are rated 48 V, 83 F per cell. Therefore, a series parallel combination of the cells is used to make the SC voltage to the desired rating. In this study, a more exact model of the SC is used rather than a simplified model [28]. Fig. 4 shows that the SC has multiple series-parallel combination of cells to make the SC storage bank. The more details on the exact model of the SC are available in [22].

IV. SYSTEM PARAMETERS AND THE SIMULATION

The coupled model of the wave-to-wire system is implemented in the MATLAB/Simulink environment in accordance with the schematics shown in Fig. 2. A diffraction force, $F_{\text{wave}}$, can be derived from the wave parameters, such as the significant wave height and the peak period of the incoming wave, and is employed here to represent different sea states. When $F_{\text{wave}}$ is applied to the AWS, it starts heaving in accordance with its dynamics. The dynamics of the AWS are observed under four different states of $F_{\text{wave}}$: (a) during 0 - 30s; peak = 0.8MN, period = 8.5s (b) during 30 - 60s; peak = 0.9MN, period = 6.5s (c) during 60 - 90s; peak = 1.0MN, period = 4.5s (d) during 90 - 120s; peak = 1.1MN, period = 2.5s as shown in Fig. 5 (a). When the PMLEG is operating at no load condition, its damping force $F_d$ will also be zero, therefore the vertical displacement of the AWS-WEC will be higher than the displacement at loading conditions. The no load dynamics of the AWS-WEC, in terms of the heaving velocity ‘$\dot{z}$’ and the vertical displacement ‘$z$’ with respect to the varying applied ‘$F_{\text{wave}}$’ are shown in Fig. 5 (b). The rest of the design parameters for the PMLEG and the AWS-WEC are adopted from [8] and [21] and are shown in Table I.

With the heave motion of the translator coupled with the top lid of the AWS, an emf is induced on the stator windings. The waveform of the no-load voltage at the output of the PMLEG in abc-frame of reference is shown in Fig. 5 (c). The back-to-back power electronic converters are essentially the voltage source converters (VSCs), which are used to interface the intermittent power of the WEC with the grid.

| Table I. PMLEG AND WEC PARAMETERS |
|-----------------------------------|
| **AWS-WEC** | **PMLEG** |
| Total mass ($M_o$) | 6x10^3 kg |
| Water damping ($J_w$) | 1.004x10^9 Ns |
| Peak Power ($P_p$) | 235 kW |
| Spring constant ($k_s$) | 0.56x10^6 N/m |
| PM flux linkage ($\Psi_{PM}$) | 23 Wb |

$F_d$ is applied to the AWS, it starts heaving in accordance with its dynamics. The dynamics of the AWS are observed under four different states of $F_{\text{wave}}$: (a) during 0 - 30s; peak = 0.8MN, period = 8.5s (b) during 30 - 60s; peak = 0.9MN, period = 6.5s (c) during 60 - 90s; peak = 1.0MN, period = 4.5s (d) during 90 - 120s; peak = 1.1MN, period = 2.5s as shown in Fig. 5 (a). When the PMLEG is operating at no load condition, its damping force $F_d$ will also be zero, therefore the vertical displacement of the AWS-WEC will be higher than the displacement at loading conditions. The no load dynamics of the AWS-WEC, in terms of the heaving velocity ‘$\dot{z}$’ and the vertical displacement ‘$z$’ with respect to the varying applied ‘$F_{\text{wave}}$’ are shown in Fig. 5 (b). The rest of the design parameters for the PMLEG and the AWS-WEC are adopted from [8] and [21] and are shown in Table I.

With the heave motion of the translator coupled with the top lid of the AWS, an emf is induced on the stator windings. The waveform of the no-load voltage at the output of the PMLEG in abc-frame of reference is shown in Fig. 5 (c). The back-to-back power electronic converters are essentially the voltage source converters (VSCs), which are used to interface the intermittent power of the WEC with the grid.

![Image](image1.png)

**Fig. 5.** (a) The diffraction force acting on the AWS-WEC (b) No-load dynamics of the AWS-WEC (c) No-load three-phase voltage of the PMLEG.
The output from the inverter is fed to a step-up transformer through an RL filter. The reactive power support is provided through a static VAr compensator between the filter and the transformer. The output from the transformer is fed to the distribution network. The lumped load is used to model any onshore critical load, which could be supplied even in the case of loss of grid power. The significant parameters of the system are presented in Table II, which are used in the simulated model.

### RESULTS AND DISCUSSIONS

The proposed coupled AWS-PMLEG based wave-to-wire system implemented in Simulink is tested under various operating conditions. The no load dynamics of the AWS and the no load voltage of the PMLEG were presented in Fig. 5, which were obtained based on the developed coupled model of the AWS and the PMLEG without applying the proposed control strategy. Now, the performance of the wave-to-wire system will be evaluated in detail when the proposed control system is enabled. In the first case, the designed system is tested without using the SC, and in the second case the performance is evaluated in the presence of the SC.

#### A. Case I: Dynamics of the proposed wave-to-wire system under the fault conditions and without the SC

The model is simulated for 120s, and the $F_{\text{wave}}$ applied to the AWS is changed after an interval of every 30s as it was shown in Fig. 5. In this way, the system is operated under four different wave conditions and each condition remains for a duration of 30s. In each segment of the differently applied force, the last cycle of the wave is selected for an intended three-phase to ground fault for a presumably longer period (0.5s) than the usual practical scenarios. This longer period helps in observing the dynamics of the wave-to-wire system in more details. In the first segment of 30s simulation, the fault is triggered for the first time, when $F_{\text{wave}}$ and $\dot{z}$ are crossing the zero at the instant of 25.50s. Similarly, the reaming fault events are presented in Table III. The time of the fault initiation is chosen at four different magnitudes of $F_{\text{wave}}$ to investigate its effect on the system dynamics. In Fig. 6(a), the dynamic displacement $z$ and the velocity $\dot{z}$ are shown and it is observed that in comparison with the no-load dynamics shown in Fig. 5(b), the amplitudes of $z$ and $\dot{z}$ have been

### TABLE II. SIGNIFICANT PARAMETERS OF EMPLOYED SYSTEM

| PMLEG side VSC | Grid side VSC |
|----------------|--------------|
| Choke: $R=0.001 \Omega$, $L=0.018 \text{H}$, Converter Control: Feedforward $R=0.34 \Omega$, Cross-coupling $L=0.03 \text{H}$, PI Gains: $k_p=1.2$, $k_i=0.1 \text{s}^{-1}$, $k_{pI}=2.5$, $k_{iI}=0.5 \text{s}^{-1}$; PWM Sampling natural frequency: 1620Hz. |
| Feedforward $R=0.0039 \Omega$, Cross-coupling $L=0.21 \text{H}$, Grid side filter: $R=0.0029 \Omega$, $L=7.8 \times 10^{-5} \text{H}$; Static compensator: $P_c=0.4 \text{kW}$, $Q_c=20 \text{kVAR}$; PI Gains: $k_p=0.3$, $k_i=20 \text{s}^{-1}$, $k_{pI}=0.3$, $k_{iI}=20 \text{s}^{-1}$, $k_{pQ}=0.045$, $k_{iQ}=300 \text{s}^{-1}$, $k_{pIQ}=5$, $k_{iIQ}=0.5 \text{s}^{-1}$; PWM carrier frequency: 1980 Hz. |

#### Bidirectional dc-dc converter

- dc-link: $V_{dc}=1200 \text{V}$, dc-link capacitance: 0.004 F; SC rated capacitance: 8 F; dc-dc converter: resistance: 0.001 $\Omega$, inductance: $2 \times 10^{-7} \text{H}$; PI Gains: $k_p=15$, $k_i=0.2 \text{s}^{-1}$, $k_p=2$, $k_i=0.2 \text{s}^{-1}$. |

#### Grid characteristics

- Rated phase-to-phase voltage of grid, $V_{pp}=120 \text{kV}$, Nominal grid frequency $f=60 \text{Hz}$, Short-circuit level power $=2500 \text{MVA}$, Source $X/R$ ratio: 7; Grid-side transformer: 120/25 $\text{kV}$, Converter side transformer: 0.625/25 $\text{kV}$, PCC voltage: 25 $\text{kV}$. |

#### Sampling

- Simulation time: 120 s, system sample time: $1 \times 10^{-4} \text{s}$, control sample time: $1 \times 10^{-4} \text{s}$, Solver: ode4 (Runge-Kutta). |

The model is simulated for 120s, and the $F_{\text{wave}}$ applied to the AWS is changed after an interval of every 30s as it was shown in Fig. 5. In this way, the system is operated under four different wave conditions and each condition remains for a duration of 30s. In each segment of the differently applied force, the last cycle of the wave is selected for an intended three-phase to ground fault for a presumably longer period (0.5s) than the usual practical scenarios. This longer period helps in observing the dynamics of the wave-to-wire system in more details. In the first segment of 30s simulation, the fault is triggered for the first time, when $F_{\text{wave}}$ and $\dot{z}$ are crossing the zero at the instant of 25.50s. Similarly, the reaming fault
reduced due to the damping force ‘$F_d$’ of the generator. Figs. 6(b) and (c) show that ‘$F_d$’ is in phase with the measured value of ‘$i_{qs}$’ as expressed in (8). When a large current is drawn from the PMLEG, the damping of the generator will cause a reduction in the dynamics of the AWS according to the Lenz’s law, and this reduces the movement of the AWS, which can reduce the current output of the PMLEG. But thanks to the externally applied force $F_{wave}$, which keeps the system in equilibrium and the PMLEG keeps supplying the current until $F_{wave}$ is applied. This equilibrium is disturbed when a fault occurs at the distribution grid. During the fault, the grid side VSC is unable to inject the PMLEG current to the grid. Therefore, ideally the current of the PMLEG should be reduced to zero, to keep the dc-link voltage stable, otherwise the PMLEG must be isolated from the power electronic converters. However, if the PMLEG stays connected during the fault, ‘$i_{qs}$’ will be lower than the value of its pre-fault condition, and ‘$F_d$’ will be lower as well and $I_{qs,ref}$ may be slightly higher due to the increased ‘$z$’ at the lower damping. Fig. 6(c) shows that the measured current tracks the reference current. During the first event of the fault when the fault occurs at the zero-crossing of $F_{wave}$, there is no significant difference between the measured and the reference value. But during the faults which occur at the peak value of $F_{wave}$, the measured and the reference value does not match, and in this case the maximum power will not be captured from the waves. This shows that the timing of the fault during the wave period will also determine the severity of the disturbance created.

In Fig. 6(d), the current in the abc-frame of reference is plotted for a short time scale to highlight the dynamics during the second fault event only. Fig. 6(e) shows the dc-link voltage, and during the fault event, the dc-link voltage rises, and its peak depends upon the magnitude of $F_{wave}$ at the instant of fault. This voltage rise is unusual, and this may rupture the capacitor, which has a rated voltage of 1200V only. It is pertinent to mention here that the reference current is not being forced to zero to evaluate the system dynamics, when it is operating under the continuous tracking of maximum power. The PCC grid voltage and current being injected to the grid is shown in Figs. 6(f) and (g), and they show that the current of the PMLEG, which was at a lower variable frequency, now has been fixed to the grid frequency. The grid current during the third fault event is shown in Fig. 6(h), to show the dynamics of the disturbance. During the fault events, due to the distorted currents, no power is being fed to the grid and the power generated by the WEC raises the dc-link voltage. This is shown in Fig. 6(i) where the grid power goes to the zero during the fault while the PMLEG is still supplying power to keep the system in resonance with the waves to track the maximum power. The grid frequency variations at the instant of fault are shown in Fig. 6(j).

| Time (s) | 0-30 | 30-60 | 60-90 | 90-120 |
|---------|------|-------|-------|--------|
| Fault time (s) | 25.50- | 53.62- | 60±0.1Hz | 84.38- | 117.82- |
| Wave force | Zero-crossing | Positive-peak | Negative-peak | Middle-value |
the ocean waves by controlling the damping force of the generator and it also minimizes the generator losses. The grid side VSC is employed for a smooth injection of the active power to the grid while stabilizing the PCC and the dc-link voltage. A bidirectional dc-dc converter is used to interface a power conditioning supercapacitor (SC) with the dc-link. The converter works in the buck and the boost mode to charge and discharge the SC respectively, to inject a constant power to the grid. The dynamic performance of the complete system is investigated under different wave conditions and different fault events. The dc-link voltage may rise above the safe operating voltage in the absence of SC, while with the use of SC and the proposed control strategy, the wave-to-wire system is able to perform satisfactorily. This will eliminate the need of a commonly used dc-link copper circuit which dissipates the power to reduce the dc-link voltage in case of faults. In this way, the proposed SC configuration will not only help in providing a stable power to the grid, but it will also be fault tolerant. The simulation results show that the proposed control strategy works effectively and the employed controllers can adjust the wave-to-wire system output according to the desired command signals.

References

1. J. Prendergast, M. Li, and W. Sheng, “A Study on the Effects of Wave Spectra on Wave Energy Conversions,” IEEE J. Ocean. Eng., vol. 45, no. 1, pp. 271–283, Jan. 2020.
2. S. Rasool, M. R. Islam, K. M. Muttaiq, and D. Sutanto, “The Grid Connection of Linear Machine-Based Wave Power Generators,” in Advanced Linear Machines and Drive Systems, Singapore: Springer Singapore, 2019, pp. 303–341.
3. B. G. Reguerro, I. J. Losada, and F. J. Méndez, “A recent increase in global wave power as a consequence of oceanic warming,” Nat. Commun., vol. 10, no. 1, p. 205, Dec. 2019.
4. S. Rasool, M. R. Islam, K. M. Muttaiq, and D. Sutanto, “Advanced Modelling and Performance Analysis of Permanent Magnet Linear Generators,” in Advanced Linear Machines and Drive Systems, Singapore: Springer Singapore, 2019, pp. 37–71.
5. O. Farrok, M. R. Islam, M. R. Islam Sheikh, Y. Guo, J. Zhu, and G. Lei, “Oceanic Wave Energy Conversion by a Novel Permanent Magnet Linear Generator Capable of Preventing Demagnetization,” IEEE Trans. Ind. Appl., vol. 54, no. 6, pp. 6005–6014, Nov. 2018.
6. E. Anderlini, D. I. M. Foresti, E. Bannour, and M. Abusara, “Control of a Realistic Wave Energy Converter Model Using Least-Squares Policy Iteration,” IEEE Trans. Sustain. Energy, vol. 8, no. 4, pp. 1618–1628, Oct. 2017.
7. J. Falnes, Ocean Waves and Oscillating Systems. Cambridge: Cambridge University Press, 2002.
8. F. Wu, X. P. Zhang, P. Ju, and M. J. H. Sterling, “Modeling and control of AWS-based wave energy conversion system integrated into power grid,” IEEE Trans. Power Syst., vol. 23, no. 3, pp. 1196–1204, 2008.
9. S. Park, B.-G. Gu, J. R. Kim, I. H. Cho, I. Jeong, and J. Lee, “Active Phase Control for Maximum Power Point Tracking of a Linear Wave Generator,” IEEE Trans. Power Electron., vol. 32, no. 10, pp. 7651–7662, Oct. 2017.
10. O. Farrok, M. R. Islam, K. M. Muttaiq, D. Sutanto, and J. Zhu, “Design and Optimization of a Novel Dual-Port Linear Generator for Oceanic Wave Energy Conversion,” IEEE Trans. Ind. Electron., vol. 66, no. 1, pp. 1–1, 2019.
11. J. N. Forestieri and M. Farasat, “Integrative Sizing/Real-Time Energy Management of a Hybrid Supercapacitor/Undersea Energy Storage System for Grid Integration of Wave Energy Conversion Systems,” IEEE J. Emerg. Sel. Top. Power Electron., pp. 1–1, 2019.
12. X. Zhao, Z. Yan, and X.-P. Zhang, “A Wind-Wave Farm System With Self-Energy Storage and Smoothed Power Output,” IEEE Access, vol. 4, pp. 8634–8642, 2016.
13. D. L. O’Sullivan, G. Dalton, and A. W. Lewis, “Regulatory, technical and financial challenges in the grid connection of wave energy

VI. CONCLUSION

This paper proposes a coupled model of AWS-PMLEG for a complete wave-to-wire system connected to a power grid. A PMLEG side VSC is used to track the maximum power from
devices,” *Renew. Power Gener. IET*, vol. 4, no. 6, pp. 555–567, 2010.

[14] C. Boström and M. Leijon, “Operation analysis of a wave energy converter under different load conditions,” *IET Renew. Power Gener.*, vol. 5, no. 3, p. 245, 2011.

[15] S. K. Maddagari, V. B. Borghate, S. Sabyasachi, and R. R. Karasani, “A Linear-Generator-Based Wave Power Plant Model Using Reliable Multilevel Inverter,” *IEEE Trans. Ind. Appl.*, vol. 55, no. 3, pp. 2964–2972, May 2019.

[16] E. Tedeschi and M. Santos-Mugica, “Modeling and control of a wave energy farm including energy storage for power quality enhancement: The bimep case study,” *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1489–1497, 2014.

[17] O. Farrok, M. R. Islam, Y. Guo, J. Zhu, and W. Xu, “A Novel Design Procedure for Designing Linear Generators,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 2, pp. 1846–1854, Feb. 2018.

[18] I. Villalba, M. Blanco, J. I. Pérez-Díaz, D. Fernández, F. Díaz, and M. Lafoz, “Wave farms grid code compliance in isolated small power systems,” *IET Renew. Power Gener.*, vol. 13, no. 1, pp. 171–179, Jan. 2019.

[19] F. Wu *et al.*, “Modeling, Control Strategy, and Power Conditioning for Direct-Drive Wave Energy Conversion to Operate With Power Grid,” *Proc. IEEE*, vol. 101, no. 4, pp. 925–941, Apr. 2013.

[20] Feng Wu, Xiao Ping Zhang, Ping Ju, and M. J. H. Sterling, “Optimal Control for AWS-Based Wave Energy Conversion System,” *IEEE Trans. Power Syst.*, vol. 24, no. 4, pp. 1747–1755, Nov. 2009.

[21] H. Polinder, M. E. C. Damen, and F. Gardner, “Linear PM Generator System for Wave Energy Conversion in the AWS,” *IEEE Trans. Energy Convers.*, vol. 19, no. 3, pp. 583–589, Sep. 2004.

[22] S. Rasool, M. R. Islam, K. M. Mustaqi, and D. Sutanto, “An Advanced Control Strategy for a Smooth Integration of Linear Generator Based Wave Energy Conversion System with Distribution Power Grids,” in *2019 IEEE Industry Applications Society Annual Meeting*, 2019, pp. 1–6.

[23] Y. Zhang, J. Jiao, J. Liu, and J. Guo, “Direct Power Control of PWM Rectifier With Feedforward Compensation of DC-Bus Voltage Ripple Under Unbalanced Grid Conditions,” *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 2890–2901, May 2019.

[24] H. M. Hasanien, “Transient Stability Augmentation of a Wave Energy Conversion System Using a Water Cycle Algorithm-based Multi-objective Optimal Control Strategy,” *IEEE Trans. Ind. Informatics*, pp. 1–1, 2018.

[25] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of Control and Grid Synchronization for Distributed Power Generation Systems,” *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[26] L. Wang, Q.-S. Vo, and A. V. Prokhorov, “Dynamic Stability Analysis of a Hybrid Wave and Photovoltaic Power Generation System Integrated Into a Distribution Power Grid,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 404–413, Jan. 2017.

[27] “MAXWELL TECHNOLOGIES.” [Online]. Available: https://www.maxwell.com/. [Accessed: 02-Dec-2019].

[28] A. S. Weddell, G. V. Merrett, T. J. Kazmierski, and B. M. Al-Hashimi, “Accurate Supercapacitor Modeling for Energy Harvesting Wireless Sensor Nodes,” *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 58, no. 12, pp. 911–915, Dec. 2011.