Coupled Modelling and Advanced Control for Smooth Operation of a Grid Connected Linear Electric Generator based Wave-to-Wire System

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Abstract
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Keywords
grid, connected, linear, electric, generator, wave-to-wire, coupled, system, modelling, advanced, control, smooth, operation

Disciplines
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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 oscillating gravity waves produces a fluctuating power output from the WECs, radically different. The continuous unsettled nature of the wave energy technology, as these are two different forms of 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...
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 the chamber expands and the lid moves upwards [21]. In this way, the lid moves up and down with each incoming wave. The translator of the PMLEG is fixed with the heaving lid of the AWS, and the stator of the PMLEG is fixed in the stationary chamber. The translator produces an emf at the windings of the stator. The force exerted on the translator with respect to the stator produces an emf at the windings of the stator. The force exerted on the translator including the translator, μ 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 β_g and β_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 \( \ddot{z} = \frac{d^2z}{dt^2} \). 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 ‘\( z \)’ 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 ‘\( \lambda \)’ 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 \( dq_0 \) frame of reference. If \( v_{abc} = [v_a \ v_b \ v_c]^T \), shows the 3-phase vector, then the \( dq_0 \) vector \( [v_d \ v_q \ v_0]^T \) can be obtained from the Park transformation as follows,

\[
[v_d \ v_q \ v_0]^T = \mathbf{D} \cdot v_{abc}
\]

where, \( \mathbf{D} = \frac{2}{\sqrt{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \)

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

This \( dq_0 \)-frame 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:

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

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

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

where, \( \omega = \frac{2\pi}{\lambda} \), \( \Psi_{PM} \) 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 \( \frac{\partial}{\partial \omega} \) for the change of sign for both the directions of the velocity, as given in (5).

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

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

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

\[
P_a = 1.5 \ \omega \ i_q \ \Psi_{PM}
\]

\[
F_d = \beta \dot{z}^2 = 1.5 \ \omega \ i_q \ \Psi_{PM} \ \dot{z}^2
\]

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 AWS-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.

\[
i_{qs,ref} = \frac{P_{w_0}}{3\pi S_{PM}} + \frac{M_{DG}}{3\pi S_{PM}} \cdot \lambda \cdot \alpha \cdot \lambda \cdot \alpha \cdot \lambda \cdot \alpha
\]  

(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.
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 fixed 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, \( F_{wave} \), 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 \( F_{wave} \) 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 \( F_{wave} \): (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 \( 'z' \) and the vertical displacement \( 'z' \) with respect to the varying applied \( F_{wave} \) 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 enmf 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>
<thead>
<tr>
<th>TABLE I. PMLEG and WEC PARAMETERS</th>
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<tbody>
<tr>
<td><strong>AWS-WEC</strong></td>
</tr>
<tr>
<td>------------------------------------</td>
</tr>
<tr>
<td>Total mass ((M_{o}))</td>
</tr>
<tr>
<td>Water damping ((\beta_{w}))</td>
</tr>
<tr>
<td>Peak Power ((P_{p}))</td>
</tr>
<tr>
<td>Spring constant ((k_{s}))</td>
</tr>
<tr>
<td>Stator resistance ((R_{s}))</td>
</tr>
<tr>
<td>Stator inductance ((L_{s}))</td>
</tr>
<tr>
<td>Pole pitch ((\lambda))</td>
</tr>
<tr>
<td>PM flux linkage (\psi_{PM})</td>
</tr>
</tbody>
</table>

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.
TABLE II. SIGNIFICANT PARAMETERS OF EMPLOYED SYSTEM

<table>
<thead>
<tr>
<th>PMLEG side VSC</th>
<th>Grid side VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choke: $R_e=0.001$ Ω, $L_e=0.018$ H; Converter Control: Feedforward $R=0.3$ G, Cross-coupling $L=0.03$ H, PI Gains: $k_p=1.2, k_i=0.1$ s⁻¹, $k_{pQ}=2.5, k_{iQ}=0.5$ s⁻¹; PWM Sampling natural frequency: 1620 Hz.</td>
<td>Feedforward $R=0.0039$ Ω, Cross-coupling $L=0.21$ H, Grid side filter: $R_f=0.0029$ Ω, $L_f=7.8x10^{-4}$ H; Static compensator: $P_r=0.4$ kVAR, $Q_r=20$ kVAR; PI Gains: $k_{pR}=0.3, k_{iR}=20$ s⁻¹, $k_{pQ}=0.3, k_{iQ}=20$ s⁻¹, $k_{pS}=0.045, k_{iS}=300$ s⁻¹, $k_{pc}=5, k_{vc}=0.5$ s⁻¹, PWM carrier frequency: 1980 Hz.</td>
</tr>
<tr>
<td><strong>Bidirectional dc-dc converter</strong></td>
<td><strong>dc-link</strong>: $V_{dc,sw}=1200$ V, dc-link capacitance= 0.004 F; SC rated capacitance=8 F; dc-dc converter: resistance= 0.001 Ω, inductance= 2x10⁻¹² H; PI Gains: $k_p, i_1=15, k_p, i_2=0.2$ s⁻¹, $k_i, z=2, k_i, z=0.2$ s⁻¹.</td>
</tr>
<tr>
<td><strong>Grid characteristics</strong></td>
<td><strong>Rated phase-to-phase voltage of grid, $V_{sw}=120$ kV, Nominal grid frequency $f=60$ Hz, Short-circuit power $P_{sw}=2500$ MVA, Source X/R ratio=7; Grid-side transformer: 120/25 kV, Converter side transformer: 0.625/25 kV; PCC voltage= 25 kV.</strong></td>
</tr>
</tbody>
</table>

**Sampling**

Simulation time: 120 s, system sample time: 1x10⁻⁸ s, control sample time: 1x10⁻⁸ s, Solver: ode4 (Runge-Kutta).

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 PCC, where a lumped load is attached before the distribution feeders of the utility 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.

V. 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 $F_{wave}$ 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 $F_{wave}$ and $\dot{z}$ are crossing the zero at the instant of 25.50s. Similarly, the remaining fault events are presented in Table III. The time of the fault initiation is chosen at four different magnitudes of $F_{wave}$ 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...
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).

### Table III. The Fault Events

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>0-30</th>
<th>30-60</th>
<th>60-90</th>
<th>90-120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault time (s)</td>
<td>25.50</td>
<td>53.62</td>
<td>84.38</td>
<td>117.82</td>
</tr>
<tr>
<td>Wave force</td>
<td>Zero crossing</td>
<td>Positive peak</td>
<td>Negative peak</td>
<td>Middle peak</td>
</tr>
<tr>
<td>Value</td>
<td>26.00</td>
<td>54.12</td>
<td>84.88</td>
<td>118.32</td>
</tr>
</tbody>
</table>

B. Case II: Dynamics of the proposed wave-to-wire system under the fault conditions and with the SC

In the second case, the SC is integrated with the dc-link through a bidirectional dc-dc converter. The dynamic characteristics of the implemented system are presented in Fig. 7. The damping ‘\(F_d\)’ and the current ‘\(I_{qs}\)’, are in phase with each other; there is no observable disturbance at any of the fault events and the measured current strictly follows the command signal, as shown in Figs. 7(a) and (b). In Fig. 7(c), there is no reduction in the three-phase current dynamics as compared to that from Case-I results. Figs. 7(d) and (e) show the dc-link voltage, and with the use of the SC and the dc-dc converter, the dc-link voltage does not rise to the extreme limits, which can damage the dc-link capacitor. Further, the voltage ripples in the dc-link voltage, which were present in Case-I have been eliminated. This results in a smooth dc-link voltage which is ideal for the grid. The control system of the dc-dc converter acts in such a way to damp out the sudden voltage rise which occurs during the faults. Figs. 7(f) and (g) show the current being injected into grid, in comparison with the Case-I, the amplitude of the current is also stable along with the frequency. The current gradually reaches to its full value, because in the beginning the SC takes most of the current as it is charging. Fig. 7(g) also shows that during the fault, the current waveform is not distorted to the extent shown in the previous case. It is distorted at the start of the fault, and as the controller stabilizes the dc-link voltage, the current also becomes smoother. When the fault is cleared after 0.5s, then it produces a transient in the current due to the re-synchronization with the grid. Fig. 7(h) shows the WEC generated power and the power injected into the grid, in contrast with those from the results from Case-I, a smooth power is continuously being fed to the grid except at the fault events, where no active power can be injected to the grid. Fig. 7(i), shows that the frequency variations at the PCC are now 60±0.1Hz which were 60±0.2Hz in Case-I. The PWM rectified current of the PMLEG, which is controlled for maximum power tracking of the WEC is shown in Figs. 7(j) and (k). They also show the charging/discharging current of the SC. It can be observed that when the rectified current is being injected into the dc-link, the dc-dc converter acts in the buck mode and it starts charging the SC, the negative current shows the charging of the SC. Similarly, when the PMLEG rectified current starts decreasing, the control system initiates the boost mode and the SC start injecting current to the dc-link, this is shown by the positive current. In this way, the SC keeps charging and discharging to supply a smooth power to the grid. During the fault events, when no power can be injected into the grid, the control system charges the SC with the excess power. In this way, it prevents the dc-link capacitor from rising beyond its limits. The SC charging current dynamics during the fault is shown in Fig. 7(k), where the suddenly increased current takes some time to adjust to the new increased value. In this way, the proposed control structure for a coupled model of AWS-PMLEG based wave-to-wire system effectively attains its control objectives. The advantage of using the SC is twofold, firstly, it supplies a...
The PMLEG side VSC is used to track the maximum power from 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.

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 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


