Optimal Energy Management System Control of
Permanent Magnet Direct Drive Linear Generator for
Grid-Connected FC-Battery-Wave Energy Conversion

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Abstract — The Wave Energy Conversion System (WECS) control strategy is presented in this study to make sure the system operates at its best under fluctuating wave resource situations. The suggested system consists of a MOPSO based MPC approach, a point absorber WEC oscillating in heave, back-to-back power converter for grid connections, and a linear permanent magnet generator. Despite the benefits of model predictive control, problems including switching frequency variations, steady-state errors, high processing costs, and constrained prediction horizons continue to exist. The article presents a method that incorporates the switching control action into the cost function while maintaining the finite nature of a model predictive control to handle the switching frequency issue. In order to minimise switching frequency variations while also addressing other control goals, such as regulating the direct current linked voltage and controlling the flow of active and reactive power, the switching control weight factors are optimised. In order to increase power quality, a fuel cell-based short-term energy storage system is also included to direct current link between the back-to-back converters.

Key words — Fuel Cell, Linear Permanent Magnet Generator, Model Predictive Control, Multi-Objective Particle Swarm Optimization, Wave Energy Conversion.

I. INTRODUCTION

There are significant problems in the modern world due to the excessive usage of conventional fossil fuel power plants. These sources produce a lot of greenhouse gases, which is a major factor in anthropogenic environment change. They are crucial for overcoming the risks associated with fossil fuel facilities as countries transition to sources of RE to fulfill their energy needs and battle the consequences of climate change. Due to this increased interest in wave energy over the past two decades to address difficulties with energy demand, a variety of wave energy devices have been created [1]. Wave energy will be essential in the evolution of a world where all energy sources are renewable. The theoretical potential wave energy of the earth is estimated to be 16000 Tera-watt hour/year. [2], [3]. This might significantly help fulfill the planet’s expanding energy requirement. The periodic compatibility of wave resources with other RE sources, which include solar and wind, can lead to beneficial synergies between these energy sources [4]–[6]. The supply systems will be able to receive renewable energy at cheaper costs because of these synergies than the current system, which mainly depend on solar and wind energy. The wave energy resource presents a substantial difficulty for grid integration because it is intermittent, somewhat highly variable, and unpredictable, just like other RES. Integration of wave energy into the grid is fraught with issues like variable power output, controlling power converters, and needing enough storage. Wave energy is made more difficult by the deployment of reactive WEC controls, which needs bidirectional energy transmission between a grid and a device. The aforementioned problems need to be fixed so as to increase the penetration of wave’s energy into power networks. The review of literature in this article is emphasis on comprehensive wave-to-grid modeling. It also describes control as opposed to a wave-to-wire (W2W) system. The generator-side converter, PTO mechanism, and WEC are components of a W2W system. In contrast, a wave to grid system additionally contains grid, grid-side converter, storage converter, and DC bus dynamics, in addition to generator-side converter, PTO mechanism, and WEC. Grid integration studies for wave energy typically suffer from shortcomings such underdeveloped proportional integral (PI) power converter regulation, oversimplified power converter models, and oversimplified hydrodynamic models [7]. For grid integration, the accompanying power converters must be properly controlled. PI control is largely used in wave energy grid integration studies [8]–[19]. For power converters, linear Proportional Integral controllers might not necessarily be the most effective control strategy. The reason for this is that power converter models are nonlinear [20]. Therefore, it could be challenging to tune Proportional Integral controllers to provide stability across the whole operating envelope. However, there are other circumstances where PI controllers are optimized by utilizing different algorithms, such as multi objective salp swarm algorithm in [21], and water cycle algorithm in [22]. The validity of these investigations is however constrained by the oversimplification of wave energy conversion models. On the side of device, reactive hydrodynamic controller and modeling are provided in several works in the W2W literature [23]–[27]. However, limited reports give enough data for the grid-side and direct current bus. There are various W2W models for various PTO and WEC systems. A high quality W2W prototype for a point absorber WEC is described in [28]. A wave-to-wire model of an OWC is provided in [29]. A thorough analysis of various wave-to-wire models is provided in [30]. In [31], For a direct drive wave to wire structure, a piece-wise velocity control mechanism based on passivity is created while, in [32], [33], To get the most power out of waves, the scientists included the impacts of field weakening and copper losses in a MPC formulation. Power converter models and grid-side control,
However, receive scant consideration. In [34], the writers modeled both reactive and passive hydrodynamic controllers for a wave-to-wire system, in spite of the fact that the grid linked case study simply utilized the passive hydrodynamic controllers. In terms of grid integration, our work offers a technique for reactive hydrodynamic controller application for wave to grid operation of grid linked wave energy conversion. Furthermore, the significance of storage of energy for the integration of wave energy into the grid cannot be overstated. Energy storage devices make it possible to store additional power and increase the dependability of the unpredictable and sporadic wave source. Reactive control implementation using negative power from energy storage is also possible. [35] Outlines energy storage techniques for maritime applications. Due to their quick response times, high-speed kinetic buffers [36] and systems centered on ultra-capacitors [37] are becoming more and more attractive for use in wave energy applications. Applications utilizing wave energy also use a hybrid energy storing structure, which advantages from the usage of various storage systems [38], [39]. Wave energy grid integration entails a number of power train stages from the device to the grid, including a power conditioning stage, a power conversion stage, and a power take-off stage. The dynamics of each stage and their unique controllers have a major impact on coupled functioning of the entire W2G structure. The control goals of different stages might not, however, be in line with one another, which could be problematic for grid integration and economic performance. The predictive controller regulates switching frequency to reduce design complexity and ensure effective performance by controlling the grid currents on the q and d axes. This limits the amount of reactive and active power entering the grid.

II. THE PROPOSED GRID-CONNECTED FC-BATTERY-WEC SYSTEM

Fig. 1 depicts the proposed W2G system, which consists of three subsystems:

1. A device-side subsystem (an AC/DC converter, a LPMG, and a WEC).
2. A storing subsystem made up of a DC/DC buck-boost converter and an ultra-capacitor.
3. A grid model and a DC/AC inverter are both components of a grid-side subsystem.

A generator-side converter, sometimes known as a Gen-SC, is used to connect LPMG and the WEC to direct current bus. Furthermore, a bidirectional buck-boost converter links the UC to the direct current bus. A grid-side converter, sometimes referred to as a DC/AC inverter, connects the direct current connection to the grid. Hydrodynamic control, which is in charge of wringing the most power out of the waves, is the main emphasis of Gen-SC control. For the storage system, the DC/DC converter control purpose is to provide hydrodynamic control while also improving power quality via direct current bus voltage management. Finally, the Grid-SC injects the most active power possible into the grid. For a grid-connected WEC, Grid-SC and Gen-SC join to create a fully rated back-to-back energy conversion arrangement. The following needs and advantages drive the use of fully rated power converters. First off, a fully rated power converter setup is needed for LPMG full-speed range management. Second, an active full-rated converter is also necessary to meet the reactive hydrodynamic control's demand for bi-directional power flow. The FPC arrangement also offers a DC- link that naturally separates the control of the Grid-SC and Gen-SC systems. The DC bus is used to disconnect various power train subsystems. Every stage includes unique specifications, which are converted into control objectives and serve as the foundation for the overall W2G control philosophy. LPMG Two examples of criteria on the device side are the minimizing of copper (Cu) loss and the highest extraction of power from waves, based on WEC motion limits. On the other hand, grid codes regulate the demands of the grid. This places restrictions on the type of power that may be transmitted into the system (total harmonic distortion levels, voltage, frequency, etc.). It becomes problematic when the control objective on each side of direct current bus is out of phase. For instance, the DC bus experiences higher peak power as a result of exaggerated device motion when waves are extracted to their greatest capacity, which might lead to poor power quality at direct current bus. This runs counter to what grid-side control requires. With a UC storage and DC link, fully-rated back-to-back converters are employed to reduce controller interaction. On either side of direct current link, UC storage and back-to-back converter control offer a decoupled control method. As a supervisory control mechanism, an energy management system (EMS) is added to the direct current bus. It guarantees the low-level storage controller's correct operation, which is necessary for decoupling actions on both ends of the direct current bus. Because storage helps with hydrodynamic control and direct current bus voltage management, it is possible to isolate the controllers on both ends. Storage sizing is critical in this aspect since it has two functions to complete. To achieve DC bus voltage control, the first step is to absorb power peaks at the direct current bus. For the WEC-controlled functioning, an FC-Battery-based storage system must be installed.

The fundamental principle of exaggerated machine motion in resonance with wave source is the basis for how the wave energy conversion hydrodynamic control works. Under controlled WEC circumstances, the excessive device movement causes the WEC output power variability to rise. The extremely irregular wave energy conversion output power cannot be sent straight into grid because to grid laws' conditions for power quality. Because of this, employing FC-Battery storage enhances the value of grid linked wave power, and lowers the wave energy conversions electrical output power's variation. In some cases, this needs electricity from the grid to operate properly, which can't be provided by just Grid-SC control and calls for a separate storage system controller. The direct current bus voltage regulation's requirement for negative (reactive) power is therefore met by the FC storing structure. In this manner, the FC storage system necessitates the usage of decoupled controller on each side of direct current bus. A rotating permanent magnet generator and the LPMG's dynamic model resemble each other greatly. The translator's motion, which reciprocates as opposed to a rotary generator's rotating rotor, is the only distinction. The dynamic model of the linear permanent magnet generator in the d-q frame, assuming the LPMG is
symmetric:

\[
\begin{align*}
\frac{d\lambda_d}{dt} &= -v_{ds} - i_{ds}R_s + \lambda_q\omega_p \\
\frac{d\lambda_q}{dt} &= -v_{qs} - i_{qs}R_s + \lambda_d\omega_p
\end{align*}
\]

with,

\[
\begin{align*}
\lambda_d &= L_d i_d - \Psi_{PM} \\
\lambda_q &= L_q i_q
\end{align*}
\]

where PM is the permanent magnet flux linkage, Rs is the stator resistance, and Ld,q, ids,qs and vds,qs are the d- and q-axis stator inductances, currents, and, voltages respectively. As illustrated below, pole pitch, flux linkage, and the stator currents all affect the Power take-off force generated by the linear permanent magnet generator:

\[
f_{po} = 1.5 \times (\pi / \tau) \times \left( \lambda_d i_q - \lambda_q i_d \right)
\]

where \( \tau \) represents the LPMG’s pole pitch. \( f_{po}(t) \) can be determined by applying the flux relations as:

\[
f_{po} = 1.5 \times (\pi / \tau) \times \left( (L_d - L_q) i_d i_q - \Psi_{PM} i_q \right)
\]

An LPMG’s developed force is divided into two halves. The first component is the saliency-induced reluctance force, and the second word denotes magnetic force generated by a PM. For the sake of simplicity, a surface mount linear permanent magnet generator machine is taken into consideration. As a result, the inductances of the d- and q-axis are equal, or \( L_d = L_q = L_s \). Using \( L_d = L_q = L_s \) allows for the model to be written as:

\[
\frac{di_{ds}}{dt} = -\frac{R_s}{L_s} i_{ds} + \omega_s i_{qs} - \frac{1}{L_s} v_{ds}
\]

\[
\frac{di_{qs}}{dt} = -\frac{R_s}{L_s} i_{qs} - \omega_s i_{ds} - \frac{1}{L_s} v_{qs} - \frac{\omega_s}{L_s} \Psi_{PM}
\]

with

\[
f_{po} = -1.5 \times (\pi / \tau) \times \left( \Psi_{PM} i_q \right)
\]

The stator d- and q-axis voltages are now stated in terms of corresponding converter control actions as follows because they serve as the inputs to the Gen-SC and can be separately controlled: \( i_{wec} = u_{ds} + u_{qs} \), and \( v_{ds} = v_{dcu} + v_{qs} = v_{dcu} + v_{dqs} \).

Using the following formulae, the generator-rectifier combination’s unified model is created, where \( u_{qs} \) and \( u_{ds} \) are Park transformations of three phase duty ratio system:

\[
\frac{di_{ds}}{dt} = -\frac{R_s}{L_s} i_{ds} + \omega_s i_{qs} - \frac{1}{L_s} v_{dc} u_{ds}
\]

\[
\frac{di_{qs}}{dt} = -\frac{R_s}{L_s} i_{qs} - \omega_s i_{ds} - \frac{1}{L_s} v_{dc} u_{qs} - \frac{\omega_s}{L_s} \Psi_{PM}
\]

III. SIMULATION RESULTS AND DISCUSSION

The effectiveness of control plans shown in Fig. 1 have been evaluated by simulations on a 4 MW WEC consisting of 2 MW LPMGS using Matlab/Simulink software. The following succinctly expresses the proposed control approach’s control objectives:

1) Reducing generator Cu-losses by setting the linear permanent magnet generator stator iqs current of q-axis to zero.
2) Tracking iqs to its reference for the grid’s maximum active power injection.
3) Controlling the iqs to zero to achieve unity power factor.

By monitoring UC current iuc to its reference, voltage on the direct current bus adjustment provides assistance for reactive hydrodynamic control.

Fig. 2-8 display the suggested system’s response. The voltage response of the dc-link is seen in Fig.5. According to the simulation result, the suggested solution results in less overshoot and roughly constant direct current bus voltage. Therefore, in spite of the large deviations in wind speed, the dc-link voltage deviation is quite minimal. Fig 3 provides an expanded view of the three phase current and voltage, where the unity power factor can be seen. Fig. 2 illustrates the quality of the injected power, with Fig. 3 (a) Displaying the grid currents in three-phase. The Phase A grid current and voltage are shown to be in phase with one another in Fig. 3 (b), ensuring unity power factor. Fig. 4 Displays frequency excursions in grid power. The frequency is still inside the contingency band of 60 ± 0.5 Hz, as shown in (c). In addition, Fig. 6 displays the current harmonics and grid voltage for Phase A. The maximum permitted Total harmonic distortion level for grid current, and voltage is 5% as per IEEE Standard 519-1992. The harmonics for voltage (0.13%) and current (0.92%) are clearly considerably below the standards established by Standard 519-1992, as seen in Fig. 6. As a result, the suggested W2G system complies with the grid and offers high-quality power.

IV. CONCLUSION

For wave energy conversion in direct drive heaving point absorber, this research proposes a comprehensive W2G control technique, high functioning control of grid sides and both devices, and comprising balanced. The linked operation of the complete W2G structure is significantly influenced by the dynamics of respective stages and their individual controller. The control goals of different stages might not, however, be in line with one another, which could be problematic for grid integration and economic performance. The PMSG, predictive control technique, and finite control...
Fig. 1. The Proposed Grid-Connected FC-Battery-WEC System.

Fig. 2. (a) Injected Active Power (b) Load power (c) Injected Reactive Power.
set model was accurately modelled and discretized in the $dq$ reference frame for the proposed grid-tied wave energy conversion system. The quantity of reactive and active power entering the grid is limited by controlling the currents of grid on the $d$ and $q$ axes, which is optimised by the predictive controller's regulation of switching frequency, lowering design complexity, and ensuring effective performance. The MOPSO-MPC could reliably estimate the grid currents' future values and minimise the difference between the expected and reference currents by developing a quadratic cost function. The converter switches were immediately applied with the appropriate switching states based on the least cost values. The suggested W2G control strategy makes sure that power quality criteria including THD levels, frequency variations, and power fluctuations stay well within the bounds established by IEEE standards and common grid codes. The other wave energy conversion devices, particularly those on power train's grid side, can simply be subjected to the proposed methodology. On the device side, however, various wind energy conversions react contrarily under regulated circumstances. The suggested plan also serves as a springboard for research into the integration of wave energy with other forms of RE, for example solar and wind, by integrating them at direct current bus, including for micro grid functions. Future study will focus on how long-term storing, such as storing in battery, can be used in these applications to increase the value of the delivered wave energy.

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