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

Professor Adel Elgammal, Assistant Professor Curtis Boodoo
University of Trinidad and Tobago (UTT)

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.

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

I. INTRODUCTION

The wave energy sector is gaining momentum as a vital component of renewable energy solutions. This technology harnesses the power of ocean waves to generate electricity, offering a sustainable and consistent energy source. As the demand for clean energy increases, wave energy presents a promising opportunity to diversify and strengthen the global renewable energy portfolio [1]-[4]. Wave Energy Converters are designed to harness the energy from ocean waves and convert it into usable electrical power. Various designs have been proposed and tested, including point absorbers, oscillating water columns, and attenuators. Point absorbers, particularly direct drive heaving point absorbers, have shown significant promise due to their ability to efficiently convert wave motion into electricity [5]-[8].

The development of a comprehensive wave-to-grid (W2G) control system is crucial for the efficient and reliable conversion of wave energy into electrical power. This system ensures that the energy captured from ocean waves is maximized, stored effectively, and seamlessly integrated into the electrical grid, thereby enhancing the overall stability and performance of renewable energy solutions [9]-[12]. Hydrodynamic modelling involves simulating the interaction between the WEC and ocean waves to optimize energy capture. Control strategies are developed to enhance this interaction, ensuring maximum power extraction and safe operation [13]-[16]. Linear Time-invariant Controllers (LiTe-Con) have been effective in this domain. These controllers optimize the resonance between the WEC and the incoming waves, maximizing energy capture while incorporating mechanisms to handle operational constraints [17],[18]. Once the mechanical energy is converted into electrical energy by the WEC, it must be efficiently converted and stabilized for grid integration. The fluctuating nature of wave energy poses challenges for power conversion and grid stability [19]-[22]. Nonlinear Lyapunov Control methods have been proposed for managing power converters. These methods provide stability and high performance, ensuring efficient power conversion and compliance with grid requirements [23]-[25]. Integrating the control of the WEC's hydrodynamic behavior with the power conversion process is complex but essential for optimizing overall system performance. Effective W2G control systems require seamless coordination between these two subsystems. Recent research has focused on developing integrated models that combine hydrodynamic and electrical components. These models facilitate the design of unified control strategies that optimize energy capture and ensure reliable power delivery to the grid [26]-[31]. The development of a complete W2G control system involves significant challenges but holds great potential for advancing wave

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energy technology. Progress in hydrodynamic modelling, control strategies, power conversion, and integrated system design is driving the field forward. Future research will likely focus on enhancing the efficiency, reliability, and scalability of W2G systems, facilitating the broader adoption of wave energy as a sustainable power source [32]-[34].

A complete wave-to-grid (W2G) control approach for a direct drive heaving point absorber Wave Energy Converter (WEC) includes balanced, high-performance control of both the device and grid sides. This approach ensures efficient energy capture from ocean waves, optimal storage and conversion, and reliable delivery of electrical power to the grid [35].

This paper presents the integration of Particle Swarm Optimization in wave-to-grid systems which offers a promising approach to enhance the performance and reliability of renewable wave energy solutions. By optimizing control strategy across the WEC, energy storage, power converters, and grid integration, PSO can help maximize energy capture, improve efficiency, and ensure stable power delivery. Additionally, the paper is addressing the challenge associated with computational complexity and parameter tuning to fully leverage the potential of PSO in W2G systems.

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

The proposed wave-to-grid (W2G) system is designed to efficiently convert wave energy into electrical power and deliver it reliably to the electrical grid as shown in Fig. 1. The system consists of three interconnected subsystems: the converter-side subsystem, the storage subsystem, and the grid-side subsystem. Each subsystem plays a crucial role in the overall functionality and efficiency of the W2G system [35]. Converter-Side Subsystem captures the kinetic and potential energy from ocean waves. In this system, the WEC is a heaving point absorber that moves vertically with the wave motion, directly driving the generator. Linear Permanent Magnet Generator (LPMG): The LPMG converts the mechanical energy from the WEC into electrical energy. It operates by moving a magnet through a coil as the WEC heaves, generating an alternating current (AC).

AC/DC Converter: This component converts the alternating current generated by the LPMG into direct current (DC). The conversion is necessary to facilitate efficient storage and further processing of the electrical energy. The converter-side subsystem is responsible for capturing wave energy and converting it into a form that can be efficiently stored and used. The AC/DC converter ensures that the variable and potentially fluctuating AC output from the LPMG is converted into a steady DC output.

DC/DC Buck-Boost Converter: This converter adjusts the voltage level of the DC output from the AC/DC converter to match the requirements of the storage device. It can either step up or step down the voltage, ensuring optimal charging of the storage device. Ultra-Capacitor: The ultra-capacitor stores electrical energy with high power density and rapid charge/discharge capabilities. It acts as a buffer, smoothing out fluctuations in energy generation and providing immediate power when needed. The storage subsystem ensures that energy captured from the waves can be stored efficiently and made available when needed. The DC/DC buck-boost converter regulates the voltage, while the ultra-capacitor provides rapid energy storage and discharge, helping to manage the intermittent nature of wave energy and maintain a stable power supply.

Grid-Side Subsystem: The grid-side subsystem is responsible for converting the stored DC power into AC power that meets the grid's specifications. The DC/AC inverter plays a critical role in this process, ensuring that the power delivered is stable and synchronized with the grid. The grid model aids in developing and validating control strategies that optimize grid integration.

DC/AC Inverter: This inverter converts the direct current from the storage subsystem back into alternating current, suitable for the grid. The inverter ensures that the output AC matches the grid's voltage, frequency, and phase requirements. Grid Model: This component represents the electrical grid to which the W2G system is connected. It is used to design and test control strategies that ensure the system's output is compatible with grid standards and can be seamlessly integrated. The proposed W2G system integrates these three subsystems to form a cohesive unit capable of converting wave energy into grid-compatible electricity. The device-side subsystem captures and converts wave energy into DC power, the storage subsystem manages the energy storage and voltage regulation, and the grid-side subsystem converts and delivers the power to the grid. Effective control strategies are employed at each stage to maximize energy capture, ensure efficient storage, and maintain stable power delivery, addressing the inherent variability of wave energy. This integrated approach enhances the efficiency, reliability, and scalability of wave energy systems, contributing to the broader adoption of wave energy as a renewable power source.

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 LPMSG using Matlab/ Simulink software. The following

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succinctly expresses the proposed control approach's control objectives:

- Reducing generator Cu-losses by setting the linear permanent magnet generator stator iqs current of q-axis to zero.
- Tracking iqg to its reference for the grid's maximum active power injection.
- Controlling the iqg 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

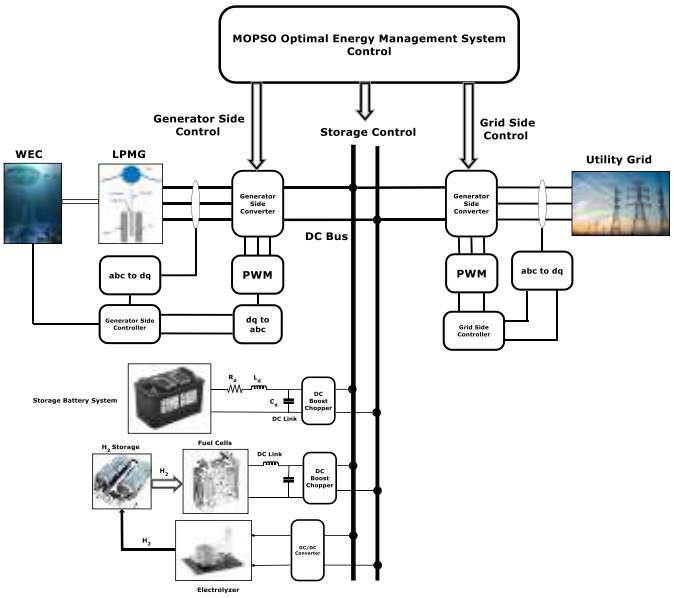

Fig. 1: The Proposed Grid-Connected FC-Battery-WEC System.

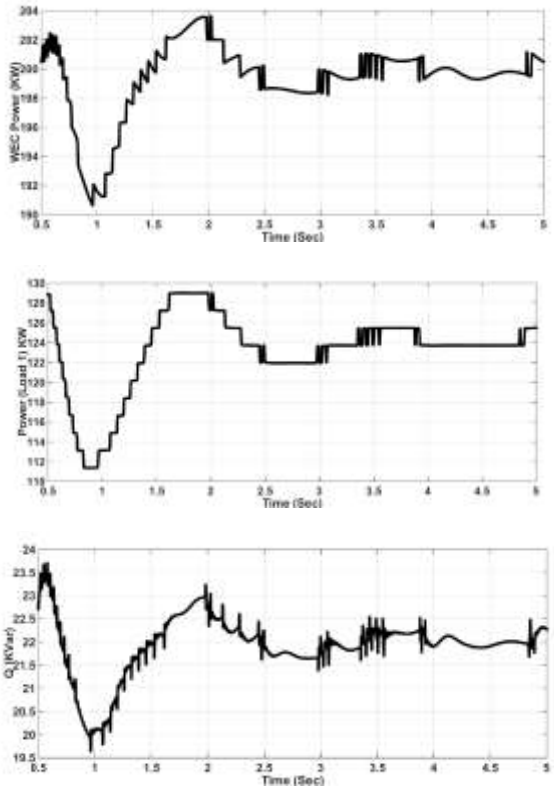

Fig. 2: (a) Injected Active Power (b) Load power (c) Injected Reactive Power.

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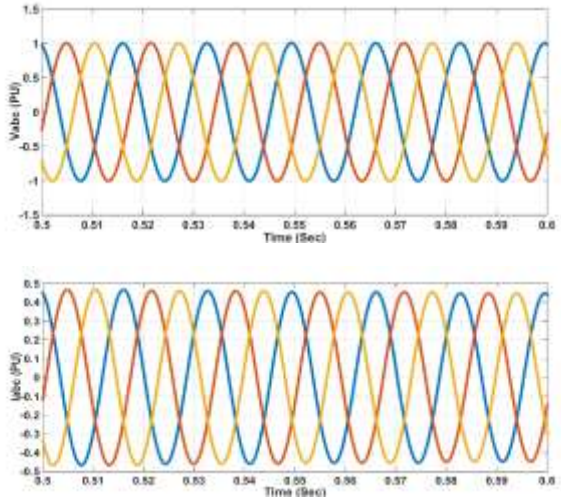

Fig. 3: (a) Grid Voltage (b) Grid Current.

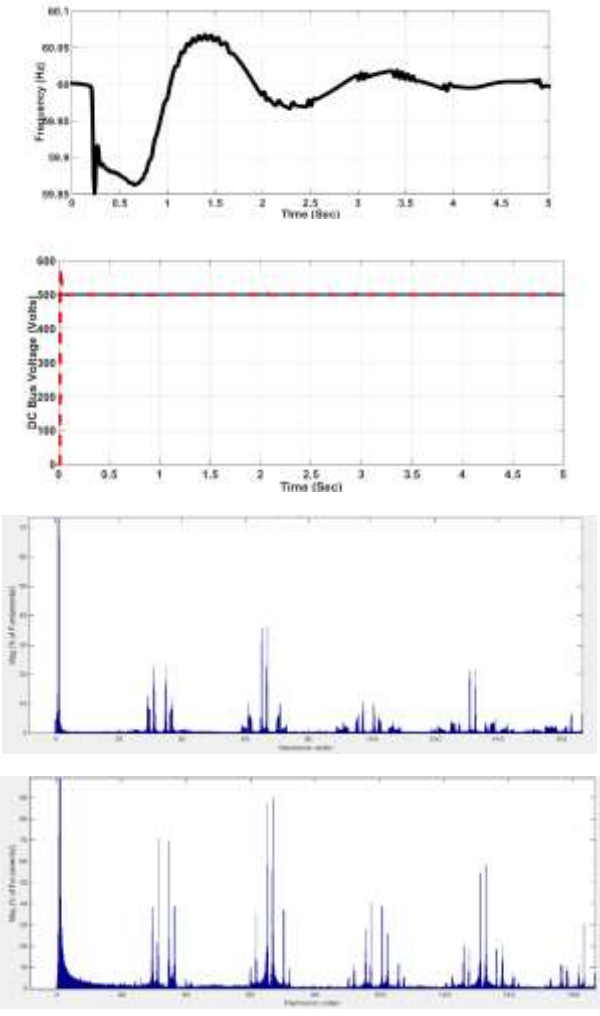

Fig. 6: Harmonic spectrum (a) Magnitude of grid voltage harmonics (b) Magnitude of grid current harmonics.

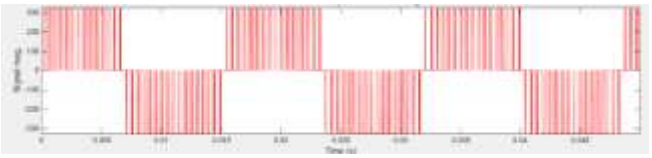

Fig. 7: Inverter Voltage.

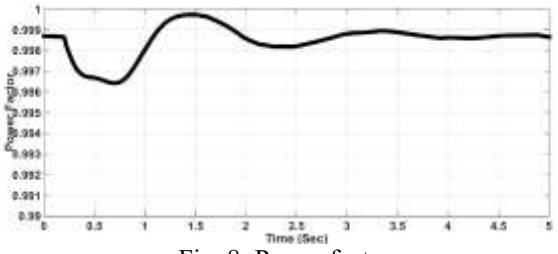

Fig. 8: Power factor

set model was accurately modelled and discretized in the $d\,q$ 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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AUTHOR PROFILE

Professor Adel Elgammal is currently a Professor at the University of Trinidad and Tobago UTT, Utilities and Sustainable Engineering. He received his B.Sc. Degree in Electrical Power Engineering from Helwan University-EGYPT in 1996. He completed his M.Eng. Degree in Electric Drives and Machines Engineering in 2002 and Ph.D. Degree in Jan-2007 from the Faculty of Engineering (Helwan University-EGYPT).

In May 2008, Prof. Elgammal joined the University of Trinidad and Tobago (UTT) as an Assistant Professor and then he was promoted to Associate Professor in May 2010 at Utilities and Sustainable Engineering, UTT. In 2010, Prof. Elgammal has been elevated to senior member of Institute of Electrical and Electronics Engineers (IEEE). Dr. Elgammal has been professionally registered as Chartered Engineer (CEng) IET. Prof. Elgammal was promoted to Professor in February 2023 at Utilities and Sustainable Engineering, UTT. Dr. Elgammal authored and co-authored over 47 Scholarly Technical Journals, and over 77 Refereed Conference Publications and three Engineering Book Chapters. His main research emphasis the application of Intelligent Systems (Particle Swarm Optimization PSO, fuzzy logic, neutral networks, and Genetic algorithms) to Power Systems, renewable / Green Energy systems, demand-side sustainable management, and Electric Drives, Efficient control and utilization of renewable energy and green technology, Hybrid renewable systems (PV, wind, diesel, small hydro, hydrogen, etc.), E-Vehicle (Battery, PV, Hydrogen FC powered).

Curtis Boodoo currently holds the position of Assistant Professor in the Utilities Engineering Unit at the University of Trinidad and Tobago (UTT). He has been a faculty member at UTT since 2004 and Program Coordinator for the Electrical / Electronics Engineering Diploma program at the John Donaldson campus since 2008. Dr. Boodoo has contributed towards the development of the Sustainable Energy Implementation Plan 2021/2030 for Trinidad and Tobago, The National Energy Policy and the National Integrated Solid Waste Management Strategy. He has also represented UTT at the Renewable Energy and Energy Efficiency subcommittee of the Economic Development Board of Trinidad and Tobago. Dr. Boodoo currently holds the position of Expert in the Systems Evaluations Group (SEG4) – Low Voltage Direct Current Applications, International Electrotechnical Commission (IEC) and was a member of the Specifications Committee for Electrical Appliances at the Trinidad and Tobago Bureau of Standards (TTBS).

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