



Cape Peninsula
University of Technology

**ENERGY MANAGEMENT FOR GRID-CONNECTED HYBRID OFFSHORE WIND-
TIDAL STORAGE POWER SYSTEMS**

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by

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ABSTRACT

The increasing demand for renewable and sustainable energy solutions has intensified interest in hybrid offshore energy systems, particularly those combining wind and tidal power. This research focused on advanced energy management for grid-connected hybrid offshore wind-tidal storage power systems, specifically focusing on South Africa's coastal regions. Leveraging South Africa's abundant marine resources and addressing its growing energy needs, this study presents a comprehensive framework for efficient energy conversion and seamless grid integration of renewable sources, aiming to optimize power output and enhance grid stability.

The primary aim was to develop and validate an advanced energy management system for such hybrid offshore systems, targeting improved renewable energy integration and enhanced grid reliability. South Africa faces the critical challenge of meeting increasing electricity demand while transitioning to sustainable and dependable renewable energy sources. The intermittent nature of offshore wind and tidal energy, combined with constraints of the existing grid infrastructure, underscores the necessity for optimized hybrid systems that ensure consistent power delivery and comply with regulatory standards.

The study developed a hybrid system integrating offshore wind, tidal stream power, battery energy storage, and a diesel generator backup. A Fuzzy Logic Controller (FLC) was designed and implemented to dynamically manage power distribution based on real-time renewable inputs and battery state of charge, maximizing resource utilization and ensuring system reliability. Simulation results demonstrated over 70% utilization of wind power alongside a stable energy supply with total harmonic distortion maintained below 5%.

Furthermore, a voltage-oriented control strategy employing a three-level H-bridge voltage source converter, supported by predictive control methods, was implemented to enhance grid interaction, reduce harmonic distortion, and improve transient response. This configuration effectively managed the variable outputs of high-capacity wind and tidal generators, resulting in improved power quality and system stability under fluctuating conditions.

Economic feasibility was evaluated through software-based hybrid optimization models, revealing that combining tidal and wind power achieves a competitive levelized cost of energy. This approach highlights the potential of hybrid systems to accelerate South Africa's transition toward a sustainable energy future. By addressing both technical challenges and regulatory requirements, this research offers a robust model for hybrid offshore energy systems and contributes valuable insights for integrating renewable energy in coastal regions worldwide.

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DEDICATION

This dissertation is dedicated to my beloved Mutunda family, with special affection for my wife, Ngcwelekazi Gwegwe-Kangaji, my daughter, Favor Kangaji Mutunda, Lonke Gwegwe and my dear brother, Willy Mbavu Mutunda, and Pastor Sylvia Kiboko. I also dedicate this work to my mother Aimerance Mujinga Kabwiza, and to all my siblings, whose unwavering support, love, and encouragement have been immeasurable and beyond words. Your contributions, both seen and unseen, have been a source of strength and inspiration throughout my academic journey. May Almighty God continue to bless and guide you all.

PREFACE

This dissertation offers a thorough exploration of hybrid offshore wind-tidal energy systems, with an emphasis on their integration, optimisation, and potential for providing sustainable energy solutions, particularly in the context of South Africa. The research further addresses both the technical and economic dimensions of these systems, offering valuable insights into their development, integration, and real-world applications.

The structure of this dissertation is organised into a series of chapters, most of which are published articles written in accordance with specific academic writing styles suited to the individual topics. This approach enables a detailed and focused examination of each area, incorporating existing literature, experimental findings, and theoretical analysis. The following provides an outline of the chapter structure:

- Chapter 1: Introduction. This provides an overview of the research topic, presenting the background, identifying the research problem, and outlining the aims, objectives, and significance of the study. It also highlights the key contributions and presents the overall framework that guides the research.
- Chapter 2: Literature Review. The chapter offers a thorough and critical analysis of offshore hybrid wind-tidal energy systems, with emphasis on the integration of energy storage technologies into the grid, exploring both theoretical foundations and practical applications. The chapter also explores various energy storage technologies, system configurations, and advanced energy management strategies, identifying key gaps in existing literature.
- Chapter 3: Advances in offshore wind and tidal stream technologies. This chapter discusses recent technological advancements in offshore renewable energy, including energy conversion, power transmission, and efficiency improvements. It also covers emerging trends that influence the development of hybrid systems.
- Chapter 4: The topic of this chapter is enhancing grid-connected tidal power systems through pulse width modulation (PWM) inverters and voltage-oriented control. It explores the pivotal role of advanced power electronic systems, specifically PWM inverters and voltage-oriented control (VOC) strategies, in optimising the performance, efficiency, and stability of tidal energy integration into the electrical grid. This chapter delves into the intricacies of power conversion and control mechanisms, highlighting the challenges and solutions associated with harmonising the fluctuating nature of tidal power generation with grid requirements.
- Chapter 5: Mitigating harmonic distortion in tidal power systems using LCL filter methods to mitigate harmonics, voltage fluctuations, and system instability, with a specific focus on the impact these issues have on the South African utility grid.

- Chapter 6: Modelling and control of hybrid offshore wind-tidal systems with LCL filters for grid-connected voltage source inverters. This delves into the modelling and optimisation of LCL filters to improve power quality in hybrid systems. The chapter also compares various control strategies for voltage source inverters in the integration of wind and tidal energy.
- Chapter 7: Power Quality Improvement of Offshore Tidal–Wind Systems Using Voltage-Oriented Control This chapter develops a Voltage-Oriented Control strategy for a hybrid offshore tidal–wind system integrated into the South African grid. Using a shared floating platform and dq-frame PMSG modelling, it ensures efficient energy conversion and grid compliance. An LCL-filtered inverter reduces harmonics, with simulations confirming enhanced power quality, system stability, and suitability for remote coastal deployment.
- Chapter 8: Optimising hybrid wind-tidal energy storage systems for off-grid coastal communities. This focuses on the technical and operational optimisation of hybrid systems for off-grid applications, ensuring energy reliability in remote coastal areas through careful system design and energy dispatch strategies.
- Chapter 9: The chapter presents a cost optimisation model for grid-connected offshore wind-tidal systems using a hybrid optimisation model for electrical renewable (HOMER) – A case study in Buffels Bay, South Africa. This evaluates the economic feasibility of hybrid offshore systems through a cost-benefit analysis and investment feasibility study, using HOMER software to optimise system performance for grid-connected applications in South Africa.
- Chapter 10: Fuzzy logic-based energy management strategy for offshore wind-tidal storage systems. This presents a fuzzy logic-based energy management system (EMS) for optimising power distribution in hybrid offshore energy systems. The chapter further showcases simulation results and performance comparisons to demonstrate the real-world applicability of the system.
- Chapter 11: Conclusions and recommendations, which summarise the key findings and contributions of the research. The chapter also highlights the advances made in hybrid offshore wind-tidal systems, energy management, power electronics, and cost optimisation. The chapter further offers recommendations for future research and further advancements in the field.

Chapters 3 to 10 are based on published articles that contribute to the growing body of knowledge in hybrid offshore wind-tidal energy systems. These articles reflect the evolution of hybrid offshore wind-tidal energy systems research and its application to real-world energy challenges. The structure of this dissertation, combining article-based chapters, allows for a focused and in-depth exploration of specific areas, ultimately contributing to the understanding of how these hybrid systems can help meet global energy demands.

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Abbreviations

A	Chamber area (m ²)
AA	Area of chamber A (m ²)
AB	Area of chamber B (m ²)
AO	Opening area of the valve (m ²)
C	Chord length / Tide coefficient
C_p	Power coefficient
DER	Distributed energy resource
DG	Distributed generation
DPC	Direct power control
E	Energy (N/m ²)
E_d, E_q	dq-coordinates of line or grid voltage (amplitude invariant transformation)
E_g	Grid phase-to-ground voltage amplitude
EES	Energy storage system
ESP	Energy services provider
EW	Liquid compressibility modulus (kPa).
F	Flux
F_m	Permanent magnet flux
F_g	Gravitational force (N)
HWT	Horizontal axis devices
I	Channel inductance (Kg.m ² . s ⁻² . A ⁻²)
IC	Initial condition
IM	Induction machine
IMC	Internal model control
J	Rotor inertia
L (M)	Inductance (mutual inductance)
MCEDs	Marine current energy devices
MG	Microgrid.
M	Pitching moment
PA	Pressure (Pa)
PB	Pressure in chamber A (Pa)
Pi	Pressure in chamber B (Pa)
PI	Proportional-integral controller
PID	Proportional-integral-derivative controller
PLL	Phase locked loop
P(Q)	Active (reactive) power
PWM	Pulse width modulation
QA	Flow rate in chamber A (m ³ /s)
QB	Flow rate in chamber B (m ³ /s)
QL	Contact pressure due to the initial compression of the O-ring (Pa)
r	Fluid density
R	Resistance
RE	Renewable energy source
S	Total leakage coefficient

s, (r)	Rotor index (superscripts) for the stator
TSS	Total sum of squares
SVM	Space vector modulation
TCCS	Tidal current conversion system
TCS	Transformer-cable system
TEC	Vertical axis device
TES	Tidal energy system
T.I.	Turbulence intensity
T_{em}	Electromagnetic torque (mechanical torque)
T_m	Electromagnetic torque
U	Line voltage
U_s	Converter voltage
V	Air velocity
U_{pcc}	Voltage at the point of common connection
V (I)	Voltage (current)
V^*	Converter voltage reference from current controller
V_{LL}	Line-to-line voltage
V_{res}	Local tidal velocity
$V_{LN(peak)}$	Amplitude of line-to-neutral voltage
VFOC	Virtual flux oriented control
VF-DPC	Virtual flux direct power control
VOC	Voltage oriented control
VT	Wind turbine
W	Mechanical speed
W_r	Rotor current frequency
w (W_s)	Rotor electrical speed (electrical synchronous speed)
XP	Piston position (m)
β	Pitch angle
θ	Yaw angle
λ	Tip-speed ratio
μ	Friction coefficient
ρ	Density
Ω	Angular velocity
α	Angle of attack

1.1 Background

The growing global energy crisis, exacerbated by climate change and rising fuel costs, highlights the urgent need for reliable, sustainable, and affordable power. While nearly 789 million people remain without electricity, even more struggle with unreliable energy access. Fossil fuel consumption continues to drive rapid climate change (Gao et al., 2014; Samrat et al., 2016; Mohammed et al., 2019), and transitioning to renewable energy is critical in mitigating environmental impact. Wind, tidal, and solar energy are examples of renewable energy that provide a practical way to cut carbon emissions and achieve sustainable development (Papari et al., 2019).

A key challenge with renewable energy sources is their intermittent nature, leading to fluctuations in electricity supply. To address this challenge, hybrid energy systems that combine multiple renewable sources, such as wind and tidal energy, are being increasingly explored (Hou et al., 2020). Hybrid systems, enhanced by advanced energy storage solutions, play a crucial role in balancing supply and demand. They ensure a reliable and consistent energy supply, even during periods of low generation, by efficiently storing excess energy and releasing it when needed most. This capability helps stabilise the grid, providing both flexibility and resilience for the energy system (Sun et al., 2020; Khan et al., 2022).

Energy storage systems (ESSs) are essential for improving grid stability by capturing excess power during peak production and discharging it when demand is highest. These systems enhance power quality and regulate frequency and offer reliable backup options, such as diesel generators, to ensure continuous energy supply (Mohammed et al., 2019; Zhou et al., 2020; Sudhakar et al., 2020). By integrating ESSs, grids become more flexible, resilient, and capable of meeting fluctuating energy needs (Ruoso et al., 2019).

The growing role of distributed energy resources (DERs) and renewable energy sources (RESs) has reshaped power generation, offering sustainable energy solutions for both on-grid and off-grid communities. The integration of ESSs with renewable energy is essential to managing fluctuating supply and meeting the evolving demands of modern grids (Waghmare et al., 2023).

This PhD research focused on energy management for a grid-connected hybrid offshore wind-tidal storage system. By optimising the integration of wind and tidal energy with energy storage technologies, this research project aimed to enhance the reliability, efficiency, and sustainability of power systems.

This study explored innovative strategies that would enable the management of energy flow, reduce reliance on fossil fuels, and provide insights into the future development of renewable energy systems for coastal and remote areas.

1.2. Overview of South African energy

South Africa's electricity generation infrastructure has evolved significantly since the initial demonstration of electric lighting in the 19th century. Historically, the energy sector has predominantly relied on coal-fired power plants, forming the cornerstone of the nation's electricity supply. Eskom, South Africa's principal electricity utility, has been instrumental in this development, starting with the construction of hydroelectric power stations and expanding its capacity to meet the rising demands of a rapidly growing urban population (Pollet et al., 2015). However, South Africa's heavy reliance on coal has contributed to various challenges, including significant environmental concerns due to high greenhouse gas emissions, increased air and water pollution. With an installed capacity exceeding 46 GW, and despite a mounting debt of over \$2 billion, Eskom strives to provide uninterrupted and affordable energy to South Africa's population of over 56 million (Akinbami et al., 2021).

Approximately 85% of South Africa's electricity generation relies on coal, rendering it one of the world's most coal-dependent nations. This fossil fuel powers electricity production and plays a pivotal role in other sectors, accounting for 43% of industrial demand, 32% of commercial and agricultural demand, and 28% of residential demand. Coal also contributes to synthetic fuel and petrochemical production, with South Africa ranking seventh globally in coal consumption. Eskom, responsible for 95% of the country's electricity supply, is pivotal in managing these coal-fired power plants, most of which are approaching obsolescence, with many facilities over 40 years old, including the notable Lethabo, Matimba, and Matla power plants (Akinbami et al., 2021).

Furthermore, insufficient electricity supply is a key factor contributing to load shedding. Eskom, South Africa's state-owned utility, has faced challenges in keeping up with the nation's growing energy needs, primarily due to underinvestment in new generation capacity. Many of the ageing power plants frequently undergo maintenance outages, and no significant new power stations have been commissioned in the last ten years. As a result, the available electricity often falls short, particularly during times of high demand. This situation has prompted South Africa to seek solutions that reduce coal dependency, improve energy security, and enhance system reliability. This shift involves adopting renewable energy sources and integrating energy storage systems to bolster grid resilience and reduce the energy sector's carbon footprint (Pollet et al., 2015).

Additionally, more than 28% of the produced coal is exported. As illustrated in Figure 1.1, the energy Sankey diagram vividly portrays these energy patterns, reflecting the flow from source to conversion and eventual utilisation (Pollet et al., 2015).

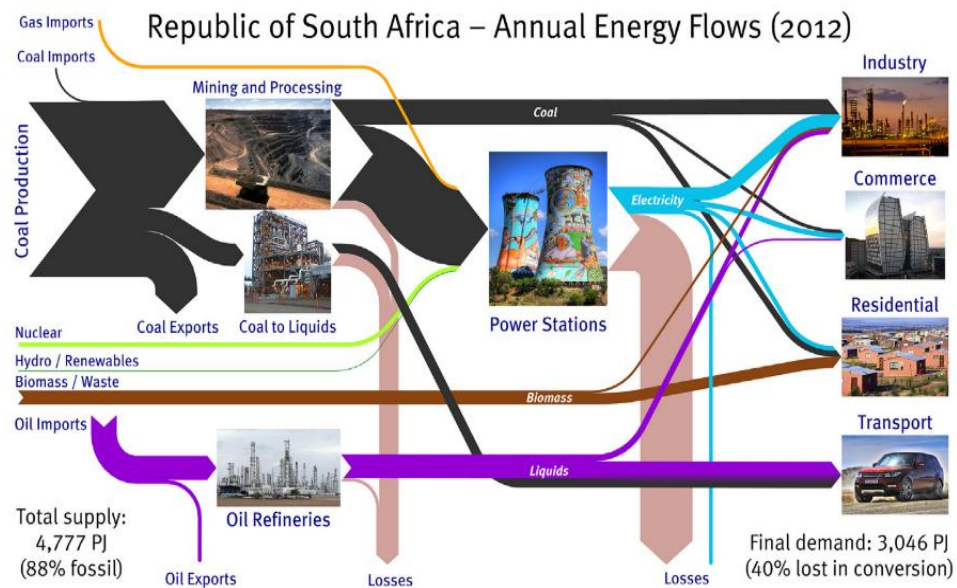


Figure 1. 1: Sankey diagram of the Republic of South Africa's energy Pollet et al. (2015).

Currently, South Africa is at a critical juncture in its energy transition. The country's electricity grid is characterised by aging coal plants and frequent outages and faces significant pressure from increasing maintenance costs and the urgent need to address sustainability concerns. As depicted in Figure 1.2, approximately 85% of South Africa's electricity is generated from coal, while nuclear, gas, hydro, solar photovoltaic (PV), and wind power constitute the remainder. This makes the country one of the world's largest coal-dependent energy producers, a statistic that underscores the country's vulnerability in terms of energy security and environmental sustainability (Bah & Azam, 2017),

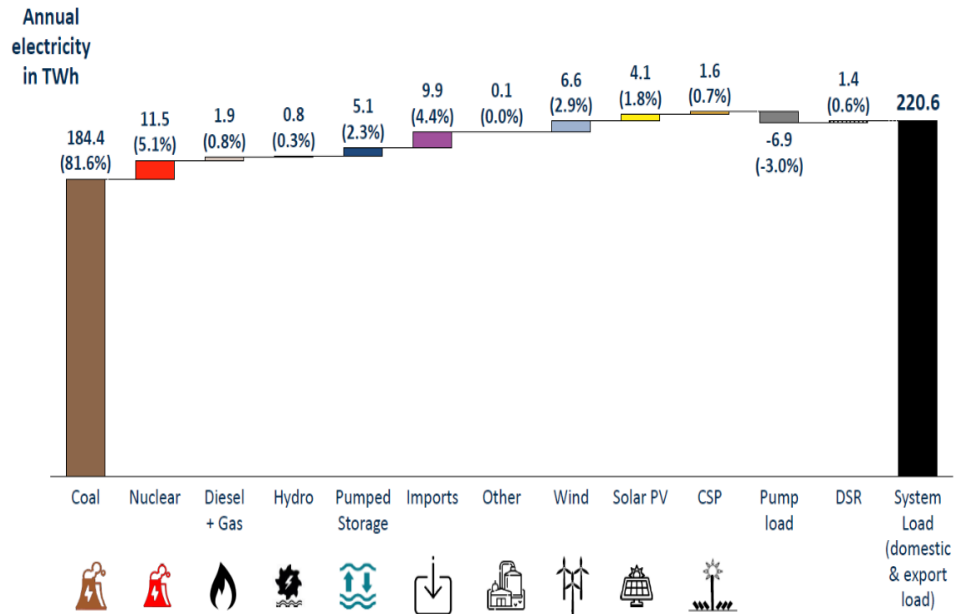


Figure 1. 2: Annual electricity production in South Africa in 2020 Grobler et al. (2022).

In view of these challenges, there is a growing push to integrate renewable energy sources with South Africa's national grid. However, the current infrastructure struggles to handle the fluctuating and unpredictable nature of renewable sources such as wind and solar power. Moreover, the surge in energy demand, illustrated in Figure 1.2, reflects an evident mismatch between oil supply and demand that originated in 2000 and is anticipated to be substantially exacerbated by 2040 (Elangovan et al., 2017).

This situation necessitates a comprehensive grid modernisation, particularly through the development of robust energy storage systems capable of stabilising supply and ensuring reliability (Elangovan et al., 2017). Offshore renewable energy, especially from wind and tidal sources, offers a compelling opportunity for South Africa to diversify its energy portfolio and significantly reduce its carbon footprint (Hwang et al., 2009; Blavette et al., 2011).

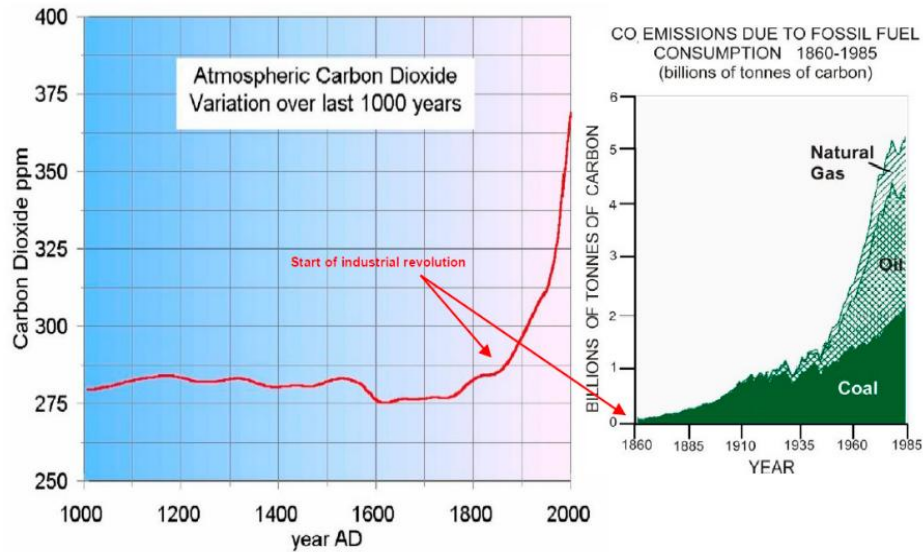


Figure 1. 3: Impact of fossil fuel CO₂ emissions over the last 1000 years Nasab et al. (2020).

Offshore wind and tidal energy offer promising opportunities to diversify South Africa's energy mix and reduce its carbon footprint. Also, offshore wind, with its higher capacity factors and greater predictability compared to onshore wind or solar power, is particularly viable (Grogan et al., 2013; Li et al., 2016). On the other hand, tidal energy complements wind with its predictable and consistent power generation (Ni et al., 2017). Therefore, by combining these two renewable sources (wind and tidal) into a hybrid system, South Africa can enhance energy security, reduce dependence on coal, and meet the growing demand for a sustainable and reliable power supply (Aneke & Wang, 2016).

This research explored energy management for grid-connected hybrid offshore wind-tidal storage systems, with a focus on optimising power generation, enhancing grid stability, and supporting South Africa's transition to a low-carbon energy future. By integrating advanced energy storage technologies with renewable sources, this study aimed to unlock the full potential of sustainable energy solutions.

1.3. Research Problem

South Africa faces ongoing energy challenges due to rising demand, ageing infrastructure, and frequent load shedding to prevent national blackouts. The existing grid is limited in integrating variable renewable sources such as offshore wind, leading to inefficiencies and instability. Although combining offshore wind with tidal energy and storage could strengthen resilience, such hybrid offshore systems have not yet been implemented in South Africa.

In coastal regions like the West Bank–East London area of Buffalo City Metropolitan Municipality, the lack of an integrated offshore hybrid Energy Management System (EMS) prevents effective coordination of wind, tidal, and storage resources. This gap results in energy underutilisation, persistent supply–demand imbalances and missed opportunities for improving grid reliability. The feasibility study therefore, investigates how an integrated offshore wind–tidal EMS could address these limitations and support South Africa’s transition to a cleaner, more stable energy system (Grobler et al., 2022).

1.4. Research aim

The aim of this study was to examine the economic feasibility, operational effectiveness, and feasibility of an offshore hybrid wind-tidal storage energy system integrated with a utility grid, with a focus on the Buffalo City Metropolitan Municipality's West Bank–East London area in the Eastern Cape Province of South Africa.

1.5 Research objectives

- i. Develop a comprehensive model of a hybrid wind–tidal storage energy system that integrates multiple renewable sources with energy storage.
- ii. Enhance the performance of grid-connected tidal power systems by applying advanced control techniques to improve system stability and responsiveness.
- iii. Minimize harmonic distortion in tidal power systems through optimized filtering methods to improve overall power quality.
- iv. Model and compare alternative control strategies for hybrid offshore systems combining wind and tidal energy, focusing on grid integration performance.
- v. Improve the power quality of offshore hybrid systems by implementing tailored voltage-oriented control strategies suited to South Africa’s electrical grid.
- vi. Optimize the sustainability and operational performance of offshore hybrid wind–tidal storage systems for off-grid coastal communities.
- vii. Develop and apply a cost-optimization framework for grid-connected offshore wind–tidal power generation systems using HOMER-based case studies.
- viii. Design and implement an energy management strategy based on Fuzzy Logic Control to maximize energy extraction efficiency and minimize operational losses in hybrid wind–tidal storage systems.

1.6. Research Questions

The following research questions guide this study:

- i. How can independent power producers (IPPs) collaborate with Eskom to leverage South Africa's ocean energy potential, thereby improving system reliability, stability, efficiency, and sustainability, while reducing operational complexity and electricity costs?
- ii. What is the impact of managing power flow from offshore hybrid wind–tidal turbines, serving both the grid and local loads, on the overall implementation cost of smart grid systems and the potential to accelerate marine energy adoption?
- iii. How does integrating offshore hybrid wind and tidal energy into the utility grid influence broader power system dynamics, particularly in terms of energy security, reduction of CO₂ emissions from conventional power sources, and mitigation of frequency-based load shedding?
- iv. Which technical parameters are most critical for maximising the value of wind-tidal hybrid systems with battery storage in grid applications?

This research addressed these questions by developing and optimising a comprehensive model for grid-connected hybrid offshore wind-tidal storage power systems to improve energy solutions and enhance overall system performance.

1.7. Significance of the research

This research is significant because it comprehensively investigates the critical role of Energy Management Systems (EMSs) in grid-connected offshore wind–tidal hybrid storage power systems. By optimising renewable energy production, improving grid stability, and maximising the utilisation of offshore resources, this study makes a substantial contribution to advancing hybrid renewable energy technologies in South Africa.

The study specifically focuses on the design and development of EMS solutions tailored for offshore hybrid wind–tidal systems with integrated battery storage. This directly addresses a key research gap, as no such systems have been implemented in South Africa to date. The outcomes also enhance understanding of EMS principles, operational mechanisms, and optimisation strategies, providing value to policymakers, researchers, and industry stakeholders.

Furthermore, the proposed EMS model introduces a resilient and economically viable framework for power distribution, storage management, and fault detection. The insights generated support decision-making for sustainable energy adoption and advance the broader transition toward cleaner, smarter, and more reliable power systems.

1. Scope of the Research

The scope of this study is limited to the feasibility assessment and modelling of grid-connected offshore hybrid wind–tidal storage systems in the West Bank–East London area of Buffalo City Metropolitan Municipality. MATLAB/Simulink and HOMER are used as methodological anchors to evaluate control strategies, cost optimisation, and energy management performance.

2. Limitations of the Research

This study does not extend to practical deployment or physical testing of offshore systems. Its findings are based on simulations, case studies, and modelling assumptions that reflect the specific technical and geographical context of South Africa's Eastern Cape coast. As such, while the results provide valuable insights for feasibility and planning, they should be interpreted as a foundation for future pilot projects and real-world implementation.

3. The Significance of the Study Can Be Summarised as follows:

- i. Bridging the research gap by addressing the absence of EMS frameworks tailored for offshore wind–tidal hybrid storage systems in South Africa.
- ii. Optimising renewable integration through improved energy efficiency, stability, and reliability using advanced control and energy management strategies.
- iii. Supporting sustainability goals by promoting clean, resilient, and environmentally friendly energy solutions aligned with global carbon reduction targets.
- iv. Informing stakeholders (government, IPPs, industry, academia) with actionable insights that support policy formulation and renewable energy adoption.
- v. Driving technological innovation by introducing optimised EMS models that enhance hybrid systems' performance, fault detection, and operational longevity.
- vi. Elevating power quality by applying advanced simulation tools and AI-driven energy management approaches.
- vii. Providing cost-effective solutions that reduce operational and maintenance costs, thereby improving the long-term economic viability of offshore hybrid systems.
- viii. Mitigating environmental impacts by offering a dependable alternative to fossil fuels and complementing solar energy with more predictable marine resources.
- ix. Advancing clean and smart grids by enabling decentralised generation models and enhancing South Africa's grid resilience.
- x. Streamlining modelling techniques by employing computationally efficient tools and algorithms that accelerate decision-making and optimisation.

1.8. Delineation of the research

This research holds considerable significance as it contributes to a comprehensive understanding of a novel intelligent energy management process in the context of grid-connected hybrid offshore power systems, specifically integrating battery storage. However, the delineation of this research is elucidated by addressing existing academic gaps and underscoring the complexities and implications of the proposed smart grid system.

- *Addressing academic gaps*

While several studies have delved into optimising the size, design, control, and economic viability of hybrid renewable systems encompassing multiple sources, such as wind turbines, solar modules, and diesel backups (Mohammed et al., 2019), the incorporation of hybrid offshore energy systems connected to the grid with a battery bank remains relatively unexplored. Previous research has often excluded critical components like diesel backup and the interplay of communication technologies. Therefore, focusing on these integral aspects, this research has managed to bridge that gap and provide comprehensive insights into the intricacies of such complex power generation systems.

- *Inclusive approach to hybrid offshore systems*

Unlike previous studies that may have overlooked the potential of integrating wind and solar applications along with the inclusion of diesel backups (Abdelaziz et al., 2018), this research acknowledges the holistic nature of offshore hybrid wind-tidal energy systems connected to the grid. This work recognises the pivotal role of battery storage and incorporates communication technologies, encompassing the full spectrum of this integrated energy ecosystem.

- *Essential role of energy forecasting*

The objective of this work is to pioneer an advanced EMS designed to optimise power distribution, oversee system operations, and effectively harness the potential of battery and offshore hybrid energy systems linked to the utility grid. This pioneering initiative is poised to play a pivotal role in shaping an intelligent, dependable, and environmentally sustainable energy management system tailored for grid-connected hybrid offshore power systems. Also, this encompasses the seamless integration of offshore hybrid energy sources and battery storage within the South African context.

1.9. Publications

The publications below have evolved from this research:

1. Kangaji, L., Orumwense, E. & Abo-Al-Ez, K., 2022. Modelling and simulation of tidal energy generation system: A systematic literature review. *International Journal of Advanced Technology and Engineering Exploration*, 9(92): 2394-7454. <http://dx.doi.org/10.19101/IJATEE.2021.875704>
2. Kangaji, M., Raji, A. & Orumwense, E., 2024. Optimizing sustainability offshore hybrid tidal-wind energy storage systems for an off-grid coastal city in South Africa. *Sustainability*, 16(21): 9139. <https://doi.org/10.3390/su16219139>
3. Kangaji, L., Orumwense, E. & Raji, A., 2025. Improving grid-connected tidal power systems through PWM inverters based on voltage-oriented control. *International Journal of Electrical Engineering and Applied Sciences (IJEEAS)*, 7(2). <https://ijeeas.utm.edu.my/ijeeas/article/view/6226>
4. Kangaji, L.M., Raji, A. & Orumwense, E., 2025. Cutting-edge progress in offshore wind and tidal stream power technology – State-of-the-art. *AIMS Energy*, 13(1): 188-230. <https://doi.org/10.3934/energy.2025007>
5. Kangaji, L., Orumwense, E. & Raji, A., 2025. Cost optimization model for a grid connected offshore wind and tidal power generation system using HOMER: A case study in Buffels Bay, South Africa. *International Journal of Electrical Engineering and Applied Sciences (IJEEAS)*. <https://ijeeas.utm.edu.my/ijeeas/article/view/ISSN:26007495>
6. Kangaji, L. M., Atanda Raji; Efe Orumwense (2025). Mitigating Harmonic Distortion in Tidal Power Systems Through Optimized LCL Filtering. 2025 33rd Southern African Universities Power Engineering Conference (SAUPEC), 1–6. <https://doi.org/10.1109/SAUPEC65723.2025.10944381>
7. Kangaji, L. M., Atanda Raji; Efe Orumwense (2025) 'Power Quality Improvement of Offshore Tidal-Wind Systems Using Voltage-Oriented Control in the South African Grid', Proceedings of the International Conference on Electrical, Computer and Energy Technologies (ICECET 2025), Paris, France, 3–6 July. IEEE. (Accepted for publication).
8. Kangaji, L.M., Raji, A. and Orumwense, E. (no date) 'Fuzzy Logic Controller Energy Management Strategy for Offshore Hybrid Wind-Tidal Storage Systems', Submitted to Discover Energy, Under review.
9. Kangaji, L.M., Orumwense, E. and Raji, A. (no date) 'Modelling and Control of Hybrid Offshore Energy Systems with LCL-Filters for Grid-Connected Voltage Source Inverters: A Comparative Study of Offshore Wind and Tidal Energy', Submitted to Journal of Electrical and Computer Engineering, volume. Under review.

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CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Integrating renewable energy sources, particularly offshore wind and tidal power, into grid-connected systems is critical due to rising energy demands and environmental concerns. Hybrid renewable energy systems (HRESs), offer a promising solution for achieving energy sustainability and reliability, and reducing greenhouse gas emissions. This chapter reviews current research on hybrid offshore wind-tidal energy systems, focusing on system design, energy management, control strategies, and storage integration, emphasising advanced control methods such as fuzzy logic controllers (FLCs).

2.2 Offshore renewable energy systems

Marine energy generation systems, driven by their abundant and eco-friendly resources, are becoming increasingly viable. Offshore wind turbines and tidal stream turbines share many design similarities, although tidal energy is far more predictable. This greater predictability makes hybrid systems more reliable and effective in energy harvesting. This section explores offshore wind and tidal turbines in depth, highlighting their unique components and resource dynamics.

2.3. Offshore renewable energy systems

Marine energy generation systems are gaining traction, driven by their abundant and eco-friendly resources. Offshore wind turbines and tidal stream turbines share significant design similarities, with tidal energy offering greater predictability than offshore wind patterns. This inherent reliability positions hybrid systems as a compelling option for future sustainable energy generation. The following section presents a comprehensive literature review of offshore wind and tidal turbines, delving into their components and resource dynamics.

2.4. South Africa's ocean regions

South Africa's extensive coastline spans 2,798 km, encompassing both the Indian Ocean and the Atlantic Ocean. A distinct jet stream divides these oceans, with strong currents such as the Agulhas Current reaching velocities of 60 to 150 cm/s and transporting massive amounts of seawater. The highest velocities are observed between coordinates 32.5°S, 29°E and 34.5°S, 25.5°E. These ocean currents, which can reach velocities over 2 m/s, offer significant

potential for marine energy generation. Additionally, the area around East London in the Eastern Cape has been identified for its considerable marine energy potential (Lumpkin & Johnson, 2013; Reinecke, 2013). These oceanic currents are often likened to rivers due to their significant flow, transporting immense quantities of seawater, sometimes reaching up to a staggering one million cubic meters per second ($100 \times 10^6 \text{ m}^3/\text{s}$). The currents' core velocities, particularly in the largest western boundary currents, can surpass 1 m/s and frequently exceed 2 m/s. These powerful currents extend over substantial dimensions, with widths exceeding 100 km and depths reaching depths of more than 2000 m (Schumann, 2013). The gravitational pull of wind and sunlight has generated significant potential in tidal, wave, and thermal power sources, estimated at approximately 22,000 and 87,600 TWh/year respectively (Borthwick, 2016). A noteworthy marine energy potential is observed in East London (Figure 2.1), a medium-sized city along South Africa's Eastern Cape coastline, far from major urban centres like Johannesburg, Durban, and Cape Town.

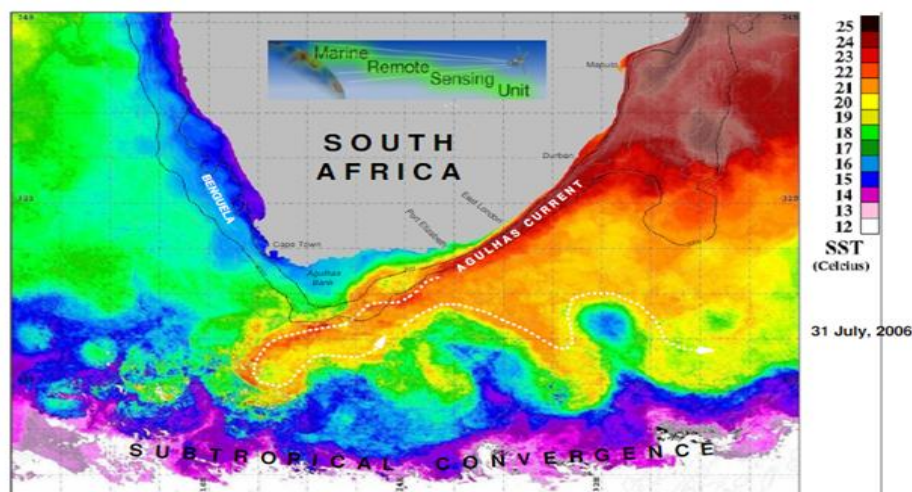


Figure 2. 1: Satellite image of sea surface temperature in South Africa Schumann (2013)

East London enjoys a temperate climate, which significantly favours optimal wave energy generation and maritime conditions. The annual precipitation around East London is projected at 593 mm, with the majority occurring during the summer months. Notably, July experiences a peak daily temperature of 20°C, while February witnesses a higher temperature of 26°C. July, known for its cooler weather, records average night-time temperatures of 9.3°C. The tidal range, ranging from low to high tides, can span up to 2 meters, though it typically averages around 0.5 meters. Waves, subject to wind dynamics, can attain heights of 4 to 5 meters (Reinecke, 2013; Schumann, 2013).

2.5. Offshore wind resources in South Africa

Offshore wind energy has grown substantially since its introduction in the 1990s, especially in Europe, where countries like the UK, Germany, and the Netherlands have expanded their installed capacity. Offshore wind is a reliable and abundant energy source due to stronger and more stable wind currents over the ocean. The global offshore wind capacity and projections suggest that it could contribute significantly to global electricity generation by 2030, (Camara et al., 2013; Majdi & Kilby, 2021). Europe currently has an installed offshore wind capacity exceeding 20 GW (McKenna et al., 2022).

Wind energy plays a pivotal role in renewable power generation, with offshore wind developments expanding rapidly. South Africa's offshore wind potential is estimated at an impressive 44.52 TWh annually at altitudes below 50 meters and 2,387.08 TWh at altitudes below 1,000 meters. In South Africa, a GIS-based multi-criteria evaluation has pinpointed key areas such as Struis Bay and Richards Bay for offshore wind farm development. Offshore wind power facilities have the potential to supply a significant portion of South Africa's electricity demand—contributing up to 15% at shallow water sites. However, installation costs can increase by as much as 800% at deeper ocean locations due to the complexities of deployment and maintenance. China's first pilot and commercial offshore wind projects began operation in 2007 and 2010, respectively. By 2018, China had installed 4,445 MW of offshore wind capacity, accounting for 19.83% of the global total and ranking third worldwide, behind the United Kingdom (34.41%) and Germany (27.57%). Although China leads globally in onshore wind power with 36.38% of installed capacity, its offshore wind sector still holds significant potential for growth. The on-grid tariffs for intertidal and nearshore offshore wind projects in China are 0.75 CNY/kWh and 0.85 CNY/kWh, respectively, considerably higher than the UK's 2017 Contracts for Difference (CfD) auction price of 0.52 CNY/kWh (£57.50/MWh). Moreover, by 2017, the National Renewable Energy Fund (NREF) faced a deficit of 112.7 billion CNY [13], placing a substantial financial strain on electricity consumers as illustrated in Figure 2.2 (Grobler et al., 2022).

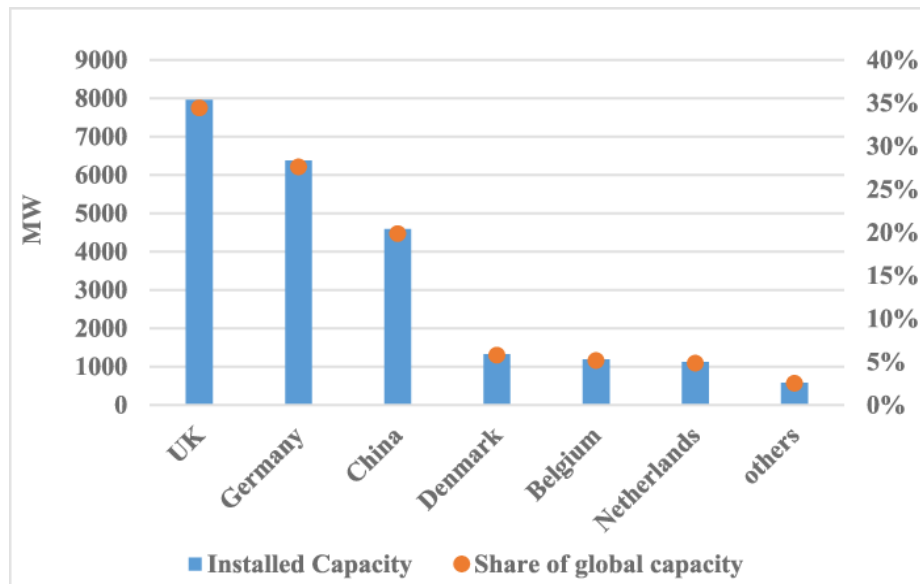


Figure 2. 2: Offshore wind installed capacity by nation up to 2019 Grobler et al. (2022)

The current utilisation of offshore wind (OSW) energy in regions requiring floating structures due to ocean floor depth contributes only marginally to the overall OSW capacity. By the end of 2019, only about 84 MW of OSW capacity had been installed. However, there has been a swift anticipated surge, mirroring the growth trajectory of traditional fixed-bottom OSW capacity. Examining projects with confirmed commercial operation dates (COD) until 2025, a notable upward trajectory becomes evident, as shown in Figure 2.3 (Grobler et al., 2022).

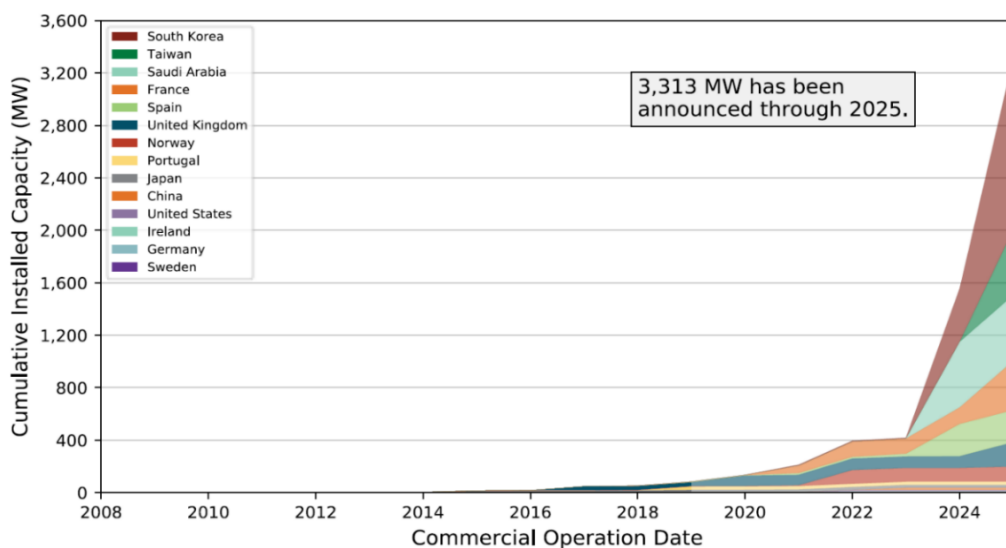


Figure 2. 3: Country-specific installed floating OSW capacity through 2025 Grobler et al. (2022).

2.6. Offshore wind farm site selection

South Africa has substantial potential for offshore wind energy generation, with an estimated annual capacity of 44.52 TWh for depths under 50 m and 2,387.08 TWh for depths under 1,000 m. A GIS-based multi-criteria evaluation has identified strategic locations within the South African exclusive economic zone for offshore wind farm development, including Struis Bay, Richards Bay, KwaDukuza, and Durban (Figure 2.4). The theoretical capacity of offshore wind energy could meet 15% of the nation's annual electricity demand at depths under 50 m and an astounding 800% at depths under 1,000 m, aligning with South Africa's electricity consumption of 297.8 TWh in 2018 (Rae & Erfort, 2020).

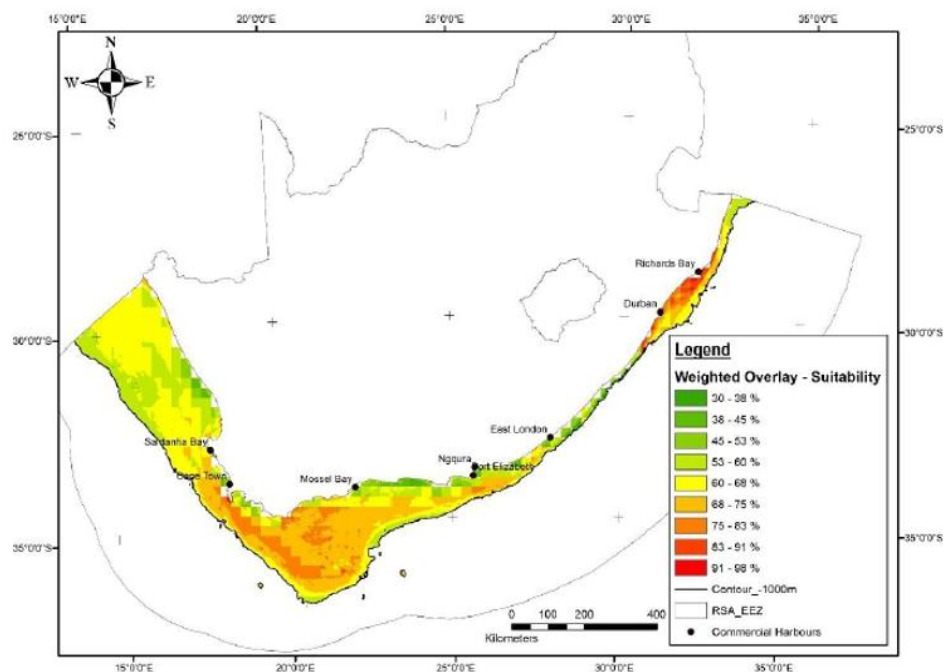


Figure 2. 4: Final sustainable map of offshore wind in South Africa Rae & Erfort (2020)

2.7. Offshore tidal current

Tidal turbines generate more energy than similarly sized wind turbines due to seawater's higher density, making tidal energy more predictable and reliable. A first-order model for hourly tidal velocities provides precise energy predictions over time, allowing optimisation of turbine placement and energy output across different time scales.

2.7.1. Growth and potential of offshore energy

Table 2.1 shows the growth of offshore energy across various regions worldwide from 2015 to 2020. Offshore energy technologies, such as tidal, wind, and wave systems, are becoming more integral to the global energy mix (Majdi & Kilby, 2021).

Table 2. 1: Offshore energy growth by continent and country (MW), 2015-2020 (Majdi & Kilby, 2021).

Continent	Country	2015	2016	2017	2018	2019	2020
	UK	5,094	5,340	5,772	7,892	8,480	8,480
	Germany	3,310	3,305	5,375	5,843	7,372	7,770
Europe	Belgium	713	713	878	1,556	1,556	2262
	Netherlands	376	518	1,118	1,118	1,118	1,118
	Denmark	1,269	1,269	1,264	1,294	1,701	1,701
	China	937	2,038	2,038	3,330	4,685	10000
	Taiwan	0	0	8	8	128	128
	South Korea	11	11	44	44	44	124
Asia	Japan	78	80	80	80	81	92
America	USA	0	0	30	30	30	30

2.7.2. Evolution of wind and tidal turbines

2.7.2.1. Evolution of wind turbines

Humans have long sought out energy sources, and wind was one of the earliest discovered, originally harnessed for navigation by the ancient Egyptians thousands of years ago. Later, wind power was adapted for daily use in grain grinding mills, with the first windmills created by the Persians around 2000 years ago for both milling grain and water lifting (Esteban et al., 2011). In 1846, Danish meteorologist Paul la Cour experimented with wind turbines to drive DC generators and produce electricity. Between 1887 and 1888, American inventor Charles Francis Brush built a wind turbine connected to a 12 kW generator to power his home, storing energy in batteries (Esteban & Leary, 2012).

2.7.2.2. Evolution of tidal turbines

Tidal energy has been used for centuries to produce mechanical power through water wheels installed along rivers and dams, often powering mills to grind grain. Tidal turbines were sometimes referred to as "submerged wind turbines" due to their similarities to wind turbines (Uihlein & Magagna, 2016a). Scientists have studied tides for millennia; in the 4th century

BCE, Pytheas and Euthymenes identified the moon's influence on tidal currents. This understanding was expanded upon over centuries, with Roman naturalist Pliny noting the effects of the sun and moon on tides (Khan et al., 2017).

Later, Johannes Kepler (1571-1630) and Galileo (1564-1642) questioned and refined these ideas. In 1687, Isaac Newton's laws of universal gravitation provided the first theoretical foundation for tidal movement, proposing that water's surface immediately responds to the gravitational forces of celestial bodies by forming an ellipsoid shape. While Newton's theory had limitations, as it assumed the ocean surface was level, it laid the groundwork for future study (Soukissian et al., 2017).

2.7.3. Classification of turbines

Wind and tidal turbines are categorised based on various research perspectives such as control, power output, and orientation perspectives. From a control perspective, they fall into two main categories (Rautenbach, et al., 2019):

- Fixed-speed controlled turbines
- Variable-speed controlled turbines

From the power output perspective, turbines are categorised into three groups:

1. Small-scale: nominal power under 40 kW
2. Medium-scale: nominal power ranging from 40 kW to several hundred kW
3. Large-scale: nominal power exceeding 1 MW

Lastly, from the orientation perspective, turbines are classified into:

- Horizontal-axis turbines
- Vertical-axis turbines, as shown in Figure 2.5.

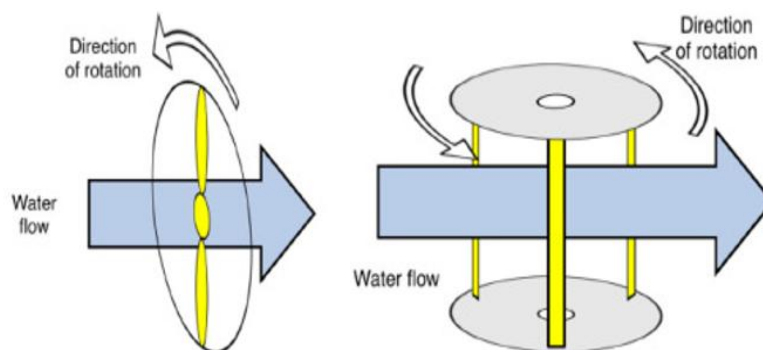


Figure 2. 5: Horizontal axis tidal turbine vs vertical axis tidal turbine Tatum et al. (2016)

Figure 2.6 illustrates a general diagram of a wind power system connected to the grid. The mechanical components include the tower, drivetrain, rotor blades, wind sensors, and brakes (Rotor et al., 2021). The electrical system consists of key elements such as the generator, electronic converters, harmonic filters on the grid side, transformers, cables, and the point of common coupling (Melikoglu, 2018). Additionally, the control system typically involves intelligent devices designed to ensure efficient and reliable interaction between the electrical and mechanical systems (Ali et al., 2021a).

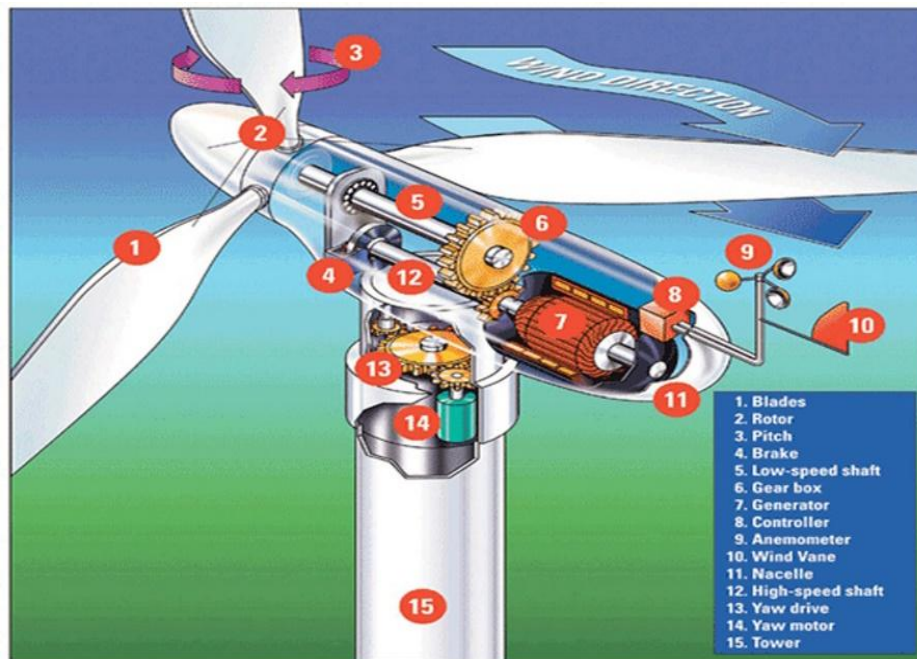


Figure 2. 6: Offshore wind energy system Ali et al. (2021b).

2.7.4. Offshore tidal current technologies

Tidal stream generators harness kinetic energy from water movement, offering greater reliability than wind-based systems. For example, the Pentland Firth tidal stream generator, which uses dual 20-meter rotors, produces up to 2 MW of power depending on current speed. These systems are usually anchored to the seabed and optimised for operation in water depths of 30 to 50 meters. Table 2.2 provides a list of prototype devices tested worldwide (Johnson & Pride, 2010; Laws & Epps, 2016; Liu et al., 2011).

Table 2. 2: Stream energy extraction prototype devices (Lande-Sudall et al., 2018; Nkwanyana et al., 2023).

Type	Device	Power Generation	Location	Manufacturer	Year
Axial Flow	Sea Gen	1.2 MW	UK	Marine Current Turbines	2008
Axial Flow	Alstom 1 MW*	1 MW	UK	Alstom	2013
Axial Flow	HS1000	1 MW	UK	ANDRITZ HYDRO Hammerfest	2011
Axial Flow	HyTide 1000	1 MW	UK	VOITH HYDRO	2013
Axial Flow	NENU 20 kW	20 kW	China	Northeast Normal University	2013
Cross Flow	TidGen	150 kW	USA	Ocean Renewable Power	2012
Axial Flow	ZJU 60 kW*	60 kW	China	Zhejiang University	2014
Axial Flow	OUC 50 kW*	50 kW	China	Ocean University of China	2014
Cross Flow	Haineng II	600 kW	China	Harbin Engineering University	2013
Cross Flow	DUT 15 kW*	15 kW	China	Dalian University of Technology	2013
Axial Flow	Zhejiang University Tidal Turbine	100 kW	China	Zhejiang University	2025
Axial Flow	Makai Ocean Engineering	2 MW	USA	Makai Ocean Engineering	2025
Axial Flow	ORE Catapult Tidal Turbine	5 MW	UK	ORE Catapult	2025

2.8. Key components of grid-connected hybrid offshore wind-tidal energy systems

The core components of a grid-connected hybrid offshore wind-tidal energy conversion system consist of mechanical and electrical components, and control systems, similar to those found in wind energy conversion systems (WECS), but specially adapted to harness both wind and tidal energy. These components work in unison to capture energy from both wind and tidal currents, converting it into usable electrical power (Ahmed et al., 2020; Mosi et al., 2019)

Mechanical components: This category includes essential elements such as the tower, nacelle, rotor blades, rotor hub, gearbox, pitch drives, yaw drives, wind speed sensors, drivetrain, tidal turbine blades, and mechanical brakes (Benzazah et al., 2018). In a hybrid system, tidal turbines are submerged and interact with water

currents, while wind turbines capture wind energy. Both require robust structural components to withstand harsh offshore conditions.

- **Electrical components:** The electrical components play a crucial role in converting mechanical energy into electrical energy and ensuring its efficient transmission to the grid. These components include the electric generator, power electronic converters, harmonic filters on both the generator and grid sides, step-up transformers, and the three-phase grid or collection point (Catapult Offshore Renewable Energy, 2015). Tidal turbines and wind turbines each have their own electrical generation systems, which must be integrated into the same grid.
- **Control systems:** Control systems are vital for the optimal operation of both wind and tidal energy components. They regulate turbine performance, ensuring that the turbines operate efficiently under varying wind and tidal conditions (Tang et al., 2012). Control systems also manage power electronics and grid interaction to maintain stability and power quality. The control mechanisms for tidal turbines are particularly important for coping with the predictable yet fluctuating nature of tidal currents (Ugalde-Loo et al., 2014a).

2.8.1. Offshore wind turbines and grid integration

Wind energy systems capture the kinetic energy of the wind and convert it into mechanical energy, which drives a generator to produce electricity. Figure 2.7 showcases a typical grid-connected wind system setup, highlighting key components such as rotor blades, wind sensors, generators, and power converters.

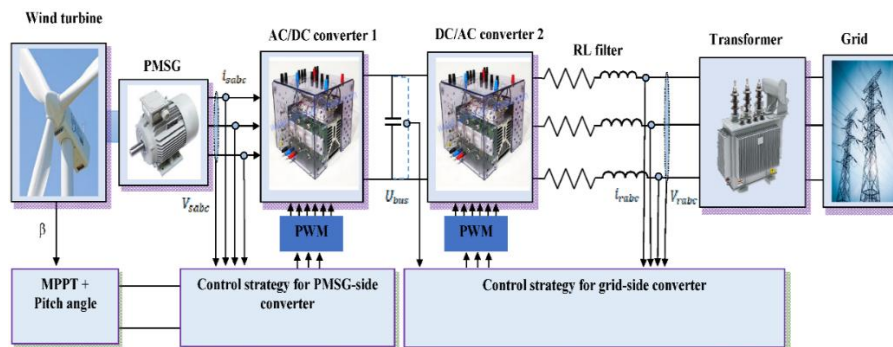


Figure 2. 7: Grid-connected energy system (McKenna et al., 2022).

2.8.2. Operational characteristics of offshore wind-tidal energy systems

Wind turbines in the system generate electricity when wind speeds reach or exceed the rated level, with blade pitch adjustments made to regulate power output if wind speeds surpass safe thresholds. In contrast, tidal turbines generate power based on water flow rates, which fluctuate in a predictable manner according to tidal cycles. Both wind and tidal turbines typically operate at low speeds and high torque (Jain et al., 2018). A multistage gearbox is employed to connect the low-speed, high-torque turbine shafts to the high-speed, low-torque generator shafts (Bajaj & Singh, 2020).

These gearboxes are essential for both wind and tidal turbines, though gearless or direct-drive technologies are becoming more popular due to their reduced maintenance costs and enhanced reliability (El-Naggar et al., 2023). Also the replacements of the gearbox simplifies the design but may require more advanced control systems. Fixed-speed wind turbines (FSWTs) offer a straightforward design but come with challenges such as uncontrollable reactive power output, increased mechanical stress, and limited power quality control (Ramsumar, 2015; Saeidi et al., 2016). These challenges are compounded in a hybrid system, where both wind and tidal energy sources must be balanced to maintain grid stability. Hybrid systems, however, provide the advantage of continuous energy generation, as tidal currents are more predictable than wind patterns, ensuring a more stable power supply (Jain et al., 2018).

2.8.3. Offshore tidal turbine technologies and grid integration

Water's kinetic energy is transformed into mechanical energy via tidal energy systems, which powers a generator to create electricity. A common configuration for a grid-connected wind or tidal system includes important parts or components such as generators, converters, rotor blades, and tidal sensors (Figure 2.8) (Ali et al., 2021; Benelghali et al., 2010; Ma et al., 2017).

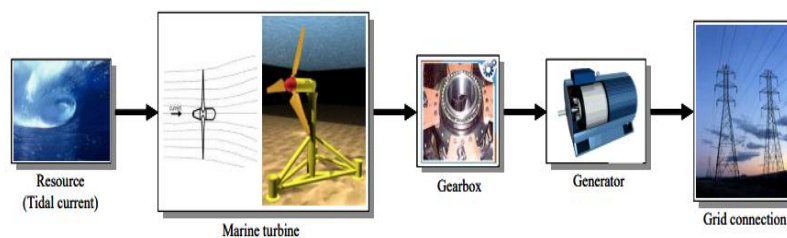


Figure 2. 8: The Tidal Stream conception (Benelghali et al., 2010).

2.9. Overview of the problem of hybrid offshore renewable energy system optimisation and control.

2.9.1. Operation below, around, and above rated wind and water speeds

- Operation below rated wind and water speeds this simply imply that the system functions efficiently at lower wind and water speeds, although power output remains below nominal capacity.

- Operation around rated wind speed this is when wind speeds are near the rated level, the system often reaches nominal power capacity, optimising energy production.
- Operation above rated wind speed this is when power curtailment becomes necessary to maintain system safety and stability if wind speeds surpass the rated limit. All modern wind turbines have power control mechanisms to prevent operational risks in high winds. The two primary control methods used are:
 - i. Pitch control – this involves adjusting the angle of the turbine blades to regulate power output and reduce load on the system.
 - ii. Stall control – this includes limiting power by creating aerodynamic resistance on the blades, thus naturally curtailing power in high-wind conditions.

These control mechanisms ensure that wind turbines operate securely across varying wind conditions, safeguarding both system integrity and energy production efficiency.

(Boersma et al., 2017).

2.9.2. Technical requirements for MW-WECS and TCS power converters

In early wind turbine models (Type 1), power converters were primarily used to establish an initial, stable grid connection and then disengaged after integration. However, modern wind energy conversion systems (WECS) and tidal conversion systems (TCS) in Types 3 and 4 turbines. This requires power converters that meet comprehensive technical and operational standards as indicated in Figure 2.9 (Wang et al., 2016).

Key requirements include:

- **Initial cost:** the upfront cost of power converters significantly impacts the overall cost of energy (COE), making it a priority for competitive renewable energy. Although converters account for just 7%–12% of a turbine's total cost, reducing these expenses can yield significant savings, especially in large-scale wind and tidal farms (Kangaji & Raji, 2024).
- **Reliability, modularity, and maintenance costs:** minimising maintenance costs, such as component replacements and labour, is critical for achieving a low COE. Studies reveal that power converters and electric generators experience some of the highest failure rates among turbine components, with average rates between 13% and 20% (Strasser et al., 2015). Failures lead to costly downtime and increase operational expenses, particularly impactful in offshore applications where reliability is crucial. Modular power converter designs are preferred, as they allow turbines to continue operating at reduced capacity even if one module fails, thus reducing downtime (Rinaldi et al., 2021).

- **Efficiency:** at the megawatt (MW) scale, high converter efficiency is essential for lowering COE. Generally, a 1% efficiency improvement can result in substantial cost savings across a large farm. Reducing power losses, which is a key to maintaining efficiency, can be achieved by using advanced, high-efficiency switching devices and optimising their configuration (Heptonstall et al., 2012).

Meeting these technical requirements is essential to ensuring the operational viability, cost-effectiveness, and reliability of power converters in MW-scale WECS and TCS, especially for the hybrid wind-tidal systems integrated into the grid (Mohanty et al., 2016).

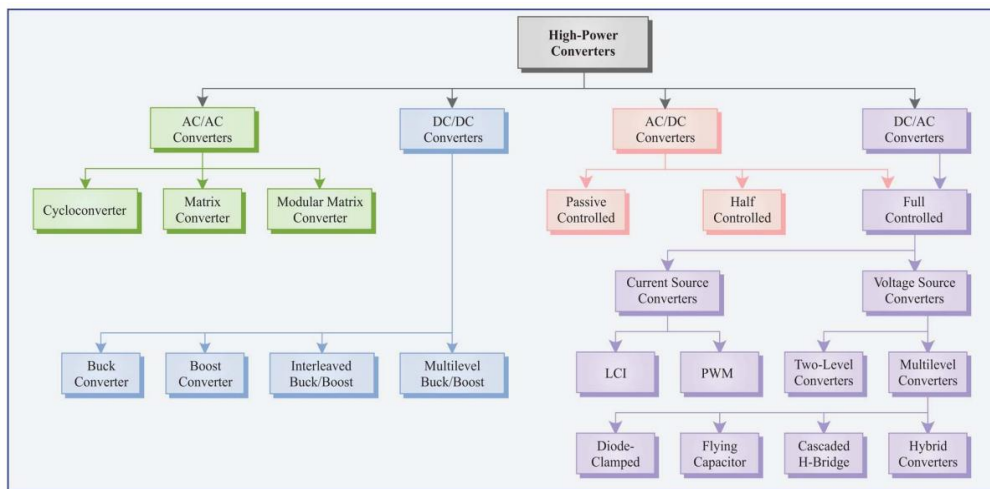


Figure 2. 9: General classification of state-of-the-art high-power converters (LCI: load commutated inverter, PWM: pulse width modulated) (Mohanty et al., 2016).

Table 2.3 outlines various generator-converter configurations used in offshore tidal and wind energy conversion systems. As power electronic converters become more complex, system costs tend to rise (Chhipa et al., 2022). Control design choices also impact costs, for example, using maximum power point tracking (MPPT) techniques rather than simpler approaches (Lin & Wu, 2021). Adding a DC-boost stage, although slightly increasing costs, simplifies grid inverter control, offering a streamlined approach to manage power flow (Tripathi et al., 2015). Similarly, replacing diode rectifiers with controlled rectifiers allows for more refined control over power transfer between the generator and the grid, though this comes at a higher cost (Sousounis et al., 2016). Balancing efficiency with cost is essential to maximise the performance and economic feasibility of wind and tidal energy conversion systems, especially in hybrid, grid-connected setups (Tiwari & Babu, 2016).

Table 2. 3: The various configurations of generator-converter systems (Tiwari & Babu, 2016).

Generator Type (Power Range)	Converter Configuration	Device Count (Semiconductor Cost)	Control Schemes
PMSG (kW)	Diode Bridge / SCR Inverter / Compensator	12 Controllable Switches (Moderate)	Basic firing angle control for a single converter
	SCR Rectifier / SCR Inverter	12 Controllable Switches (Moderate)	Firing angle control for both converters
	Diode Bridge / Hard-Switching Inverter	6 Controllable Switches (Low)	MPPT via stator frequency derivative; wind predictability control
	Diode Bridge / DC Boost / Hard-Switching Inverter	7 Controllable Switches (Low)	Vector control on inverter side; DC voltage via chopper duty ratio
	Back-to-Back Hard-Switching Inverters	12 Controllable Switches (Moderate)	MPPT and vector control on both converters
DFIG (kW–MW)	Back-to-Back Hard-Switching Inverters	8 Controllable Switches (Low)	MPPT-based generator control; inverter current with PI controllers
	Diode Bridge / SCR Inverter	6 Controllable Switches (Low)	Sliding Mode Control
	SCR Rectifier / SCR Inverter	12 Controllable Switches (Moderate)	Dual thyristor firing angle control
	Back-to-Back Hard-Switching Inverters	12 Controllable Switches (Moderate)	Vector control (rotor and grid side); SVM or PWM-based MPPT
	Matrix Converter	18 Controllable Switches (High)	Double Space Vector PWM; rotor and supply side vector control
IG (kW–MW)	Back-to-Back Hard-Switching Inverters	12 Controllable Switches (Moderate)	Vector control with fuzzy logic; model reference adaptive system using rotor slot harmonics
	Diode Bridge / DC Boost / Hard-Switching Inverter	7 Controllable Switches (Low)	Phase angle displacement and supply voltage control
SG (kW–MW)	Back-to-Back Hard-Switching Inverters	12 Controllable Switches (Moderate)	Control of real/reactive power and electromagnetic torque

2.9.3. Hybrid configurations that integrate both wind and tidal stream technologies

The integration of wind and tidal energy through shared infrastructure can substantially reduce costs by utilising common foundations, cables, moorings, and anchors (Tekobon et al., 2017). This configuration also benefits from enhanced stability through shared wave energy equipment. Combined wind-tidal systems mitigate electricity fluctuations, ensuring consistent power output, though further development of energy assessment technologies is essential (Lande-Sudall et al., 2018). Although hybrid wind-tidal configurations are still in their early stages of development, two notable designs have emerged. The Savonius Keel and Wind Turbine Darrieus (SKWID) system by Mitsui Ocean Development and Engineering Company (MODEC) is designed to support isolated islands. A combined Savonius current turbine and a

Darrieus wind turbine on a floating platform is illustrated in Figure 2.10 and 2.11 (Nkwanyana et al., 2023).

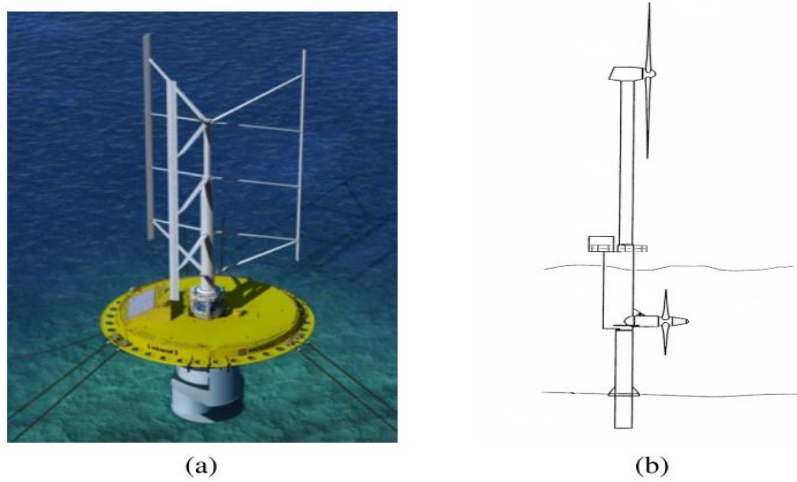


Figure 2. 10: (a) MODEC's SKWID – Savonius Keel and Darrieus wind turbine and (b) Marine Current turbine's patented turbine that combines air and water flow Roy et al. (2018a)

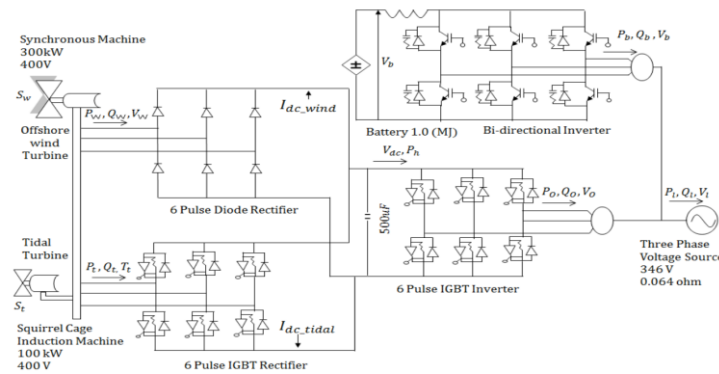


Figure 2. 11: Illustration depicting the schematic of a hybrid offshore wind-tidal (HOTT) system Roy et al. (2018a)

2.9.4. Hybrid offshore wind-tidal turbine (HOTT) systems with energy storage integration

The HOTT system's configuration with a battery energy storage system (BESS), shown in Figure 2.12, is generally known to stabilise active and reactive power fluctuations, especially under variable environmental conditions (Caraiman et al., 2012). The integration of wind and tidal sources with battery storage can effectively respond to real-time power demand while minimising grid disturbances. This configuration represents a significant advancement toward achieving consistent and reliable energy generation in offshore environments. Figure 2-14 displays the power traits of both wind and tidal turbines (Tekobon et al., 2017).

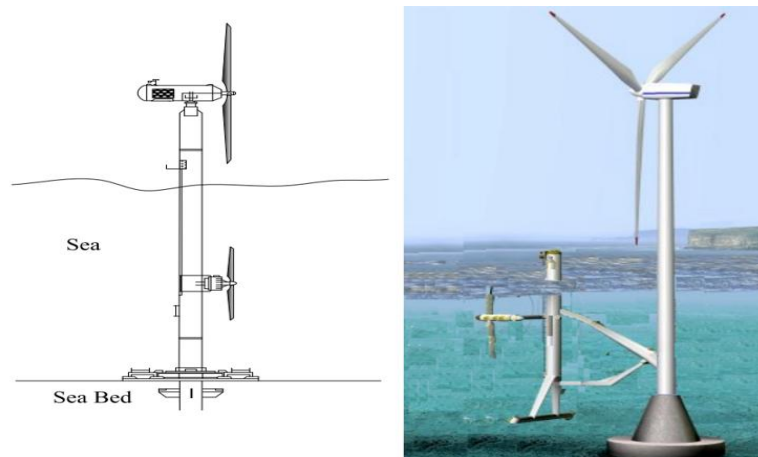


Figure 2. 12: Illustration depicting the concept of a Hybrid Offshore Wind-Tidal (HOTT) system (Rahman et al., 2014).

In order to connect these systems efficiently, it also requires careful consideration of capital and operational expenditures. An AC-DC-bus-based configuration was selected for this study due to its cost efficiency and simplified control systems (Tekobon et al., 2017). This structure encompasses the hybrid connection of offshore wind and tidal turbines with power electronics for energy quality and grid stability, as shown in Figure 2.13. The control structure of the PMSG-based hybrid energy harvesting system consists of two separate permanent magnet synchronous generators (PMSGs), two PWM-controlled AC/DC converters, a DC link, and a DC/AC converter (Chimurkar & Kothavade, 2016). Direct grid connection of the Permanent Magnet Synchronous Generator (PMSG) output is not feasible due to its variable voltage amplitude and frequency, which are incompatible with the fixed parameters required by the grid. Instead, a stable DC link is required to either supply power to the grid through an inverter or to support direct use in stand-alone applications (Unamuno & Barrena, 2015).

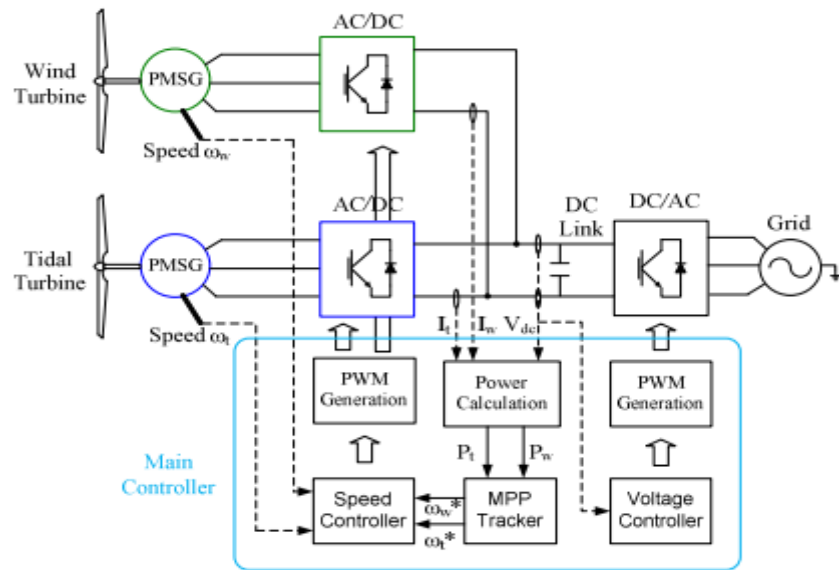


Figure 2. 13: PMSG-based hybrid wind/tidal turbine control structureDa & Khaligh (2009)

Numerous studies have explored hybrid configurations to address the inherent variability of renewable energy sources. One notable innovation is the HOTT system, which integrates offshore wind and tidal energy generation with a BESS to effectively manage power fluctuations (Rahman et al., 2011; Rahman & Shirai, 2008). The HOTT configuration leverages the complementarity between tidal currents and wind power, helping to stabilise power output (Rahman et al., 2014).

2.9.5. Advanced control strategies for generator-side power converters in variable-speed energy systems

The primary objective of the generator-side power converter controller is to regulate the electric generator's speed and/or torque by adjusting it according to predetermined references set by a higher-level controller. Figure 2.14 illustrates the different variable frequency control methods (Memon et al., 2018), categorising them into scalar and vector control approaches. The scalar control approach focus on the steady-state relationships, managing only the magnitude and frequency of voltage, current, and flux linkage vectors (Moreira et al., 2017). This method help to avoids interference with the space vector position during transients, making it ideal for applications where high dynamics are not essential (Biweta & Mamo, 2017). In contrast, the vector control approach relies on the transient relationships, allowing for precise control over the instantaneous position of voltage, current, and flux space vectors (Jain et al., 2018).

Vector control techniques adjust the position of space vectors to ensure proper orientation during both steady-state and transient conditions. One widely adopted method is field-oriented control (FOC), which employs current control loops within a synchronous reference frame

(Sanjuan, 2010), often utilising pulse width modulation or space vector modulation (Tiwari & Babu, 2016). Another popular approach is direct torque control (DTC), which integrates closed-loop control of both torque and flux to achieve precise performance (Ugalde-Loo et al., 2014b; Tiwari & Babu, 2016). This DTC approach employs bang-bang hysteresis controllers for fast and straightforward control. However, it comes with drawbacks such as the need for fast sampling times, variable switching frequencies, and high torque pulsations, which can be mitigated using DTC-SVM, blending features of FOC and DTC. This section outlines the implementation of FOC for permanent magnet synchronous generators (PMSGs), providing a dynamic model of the PMSG, introducing a block diagram of the controllers, and offering general guidelines for tuning them (Biweta & Mamo, 2017).

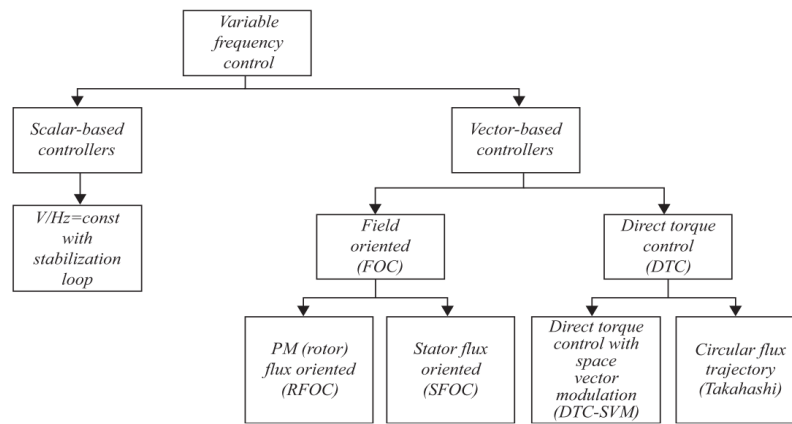


Figure 2. 14: Classification of control methods.

Voltage-oriented control (VOC) is particularly effective for managing the voltage and frequency of grid-connected inverters, making it a key technique in tidal power systems for regulating power output and enhancing system reliability (Kangaji et al., 2024a). A synchronous generator produces variable-frequency AC power, which is then converted into fixed-frequency AC power by the power converter (Ali et al., 2021a). The stator is connected to the grid through a back-to-back, four-quadrant AC/DC/AC converter, using insulated gate bipolar transistors, as shown in Figure 2.5 (Wang et al., 2018). Additionally, squirrel-cage induction generators (SCIGs) are employed, benefiting from advancements in power electronics. This configuration enables reactive power control and seamless grid integration, making it suitable for various generator types (Sousounis & Shek, 2017).

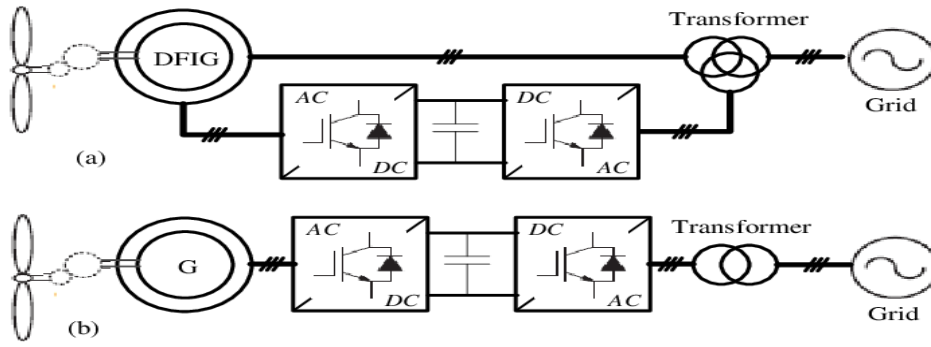


Figure 2. 15: Offshore wind turbine with a doubly fed induction generator (DFIG) operating at variable speeds, controlled by a partial-scale power converter Susperregui et al. (2022)

The interactions between grid impedance and inverter output impedance can significantly affect system stability. To mitigate instability, an impedance-based stability criterion for grid-connected inverters has been proposed (Moreira et al., 2017). Power quality is heavily influenced by current harmonics introduced by nonlinear loads in the distribution network (Khadkikar, 2012). These harmonics lead to voltage distortions, which can disrupt equipment operation across the grid (Wang & Chen, 2019). Disturbances at the point of common coupling (PCC) may cause issues such as motor overheating, transformer failures, cable instability, complications with capacitor compensation, and protection device malfunctions. Hence, disturbances often increase power losses and can also generate electromagnetic interference, disrupting communication systems (Mahela & Shaik, 2016). Recent studies have explored the interactions between DFIG wind farms, line-commutated converter (LCC) HVDC systems, and weak grids using impedance modelling, as shown in Figure 2.16 (Buła et al., 2022). Moreira et al. (2017) introduced an impedance controller that converted the q-axis impedance of a grid-connected inverter into positive resistance in the low-frequency range, enabling stable operation under weak grid conditions. Additionally, Susperregui et al. (2022) proposed an impedance reshaping control strategy utilising a symmetrical phase-locked loop (PLL) to eliminate resonance in DFIG-based turbines operating under weak grid conditions.

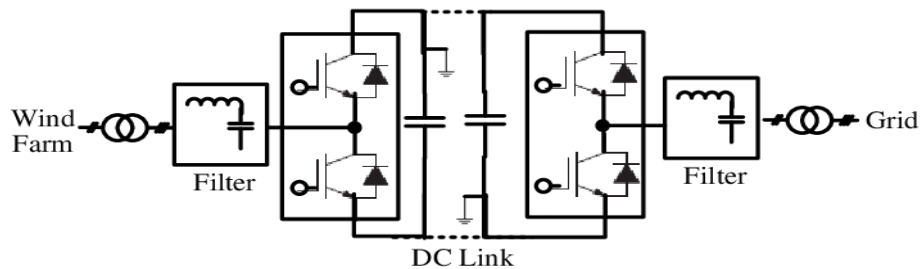


Figure 2. 16: VSC-based HVDC transmission scheme Lin & Wu (2021)

Variable-speed wind generators (VSWGs) have gained significant attention and are increasingly favoured in modern wind energy systems (Korompili et al., 2016). This preference stems from their advantages, such as reduced mechanical stress, lower noise levels, improved power capture, better control, and enhanced efficiency compared to fixed-speed models (Da & Khaligh, 2009). These VSWGs include various types of electrical generators such as switched reluctance generators, doubly-fed induction generators, and permanent-magnet synchronous generators (PMSGs) (Bracke et al., 2014).

The variable-speed wind turbine driven by a PMSG is typically connected to the grid through a full-scale frequency converter (FC), often composed of back-to-back voltage source converters (VSCs) with a shared DC link (Korompili et al., 2016). Maintaining grid stability is crucial, as challenges may arise from traditional wind turbine control methods. For example, the PLLs used in traditional turbines for grid synchronisation can undermine system stability under low short-circuit ratio conditions. Therefore, to address this challenge of the grid-forming wind turbine control strategies that employ self-synchronisation technology, rather than PLLs, are increasingly becoming the best option (Bhattacharya, 2014). For instance, grid-forming control (GFC) strategies for PMSG-based turbines enable maximum power point tracking (MPPT) functionality while maintaining grid stability (Soliman et al., 2018). Additionally, GFC strategies for DFIG turbines have been proposed to enhance the stability of sending terminals in LCC HVDC systems (Soliman et al., 2018). A commonly used control approach is the cascaded control scheme, which manages generator-side and grid-side converters or inverters, primarily through proportional-integral (PI) controllers (Aktaş & Kırçiçek, 2020). While PI controllers offer robustness and wide stability margins, they are also sensitive to nonlinear system dynamics and parameter variations (Zhao-Xia et al., 2019). In industrial applications, the complex tuning of these controllers is often necessary for handling nonlinear, higher-order systems (Soliman et al., 2018). As wind energy conversion systems (WECSs) continue to expand, frequency control has become increasingly vital for ensuring the reliable operation of power systems. Variable-speed turbines, which typically lack an inherent inertial response due to their converter-based interfaces, face challenges in maintaining frequency stability. These turbines often operate under MPPT conditions without power reserves, limiting their ability to provide spinning reserves for frequency regulation (Choi et al., 2016).

2.9.6. Control architecture and integration strategies for hybrid wind-tidal systems

Control and optimisation are crucial for maximising the performance and economic feasibility of hybrid wind-tidal energy systems. These systems present distinct challenges compared to conventional low-voltage networks with distributed energy resources (DERs) (Eid et al., 2016).

Traditional systems rely on generator rotor inertia for stability, whereas power electronics-based DERs lack inherent inertia, making power flow and voltage management more complex (Khadkikar, 2012). For hybrid systems, a three-tier control architecture is recommended, which includes:

- **Primary control:** maintains real-time active and reactive power balance.
- **Secondary control:** corrects voltage and frequency deviations and assists in grid resynchronisation.
- **Tertiary control:** manages long-term energy distribution.

The control bandwidth decreases from primary to tertiary levels, catering to the unique needs of electronically coupled DERS. Control methods for DERs are typically developed to match diverse operating conditions and achieve specific functions (De Azevedo et al., 2017). A basic control framework for electronically-coupled DERs in a hybrid AC system, where DERs like wind and tidal units function as grid-forming, grid-feeding, or grid-supporting components, as shown in Figure 2.17 (Roy & Pota, 2015).

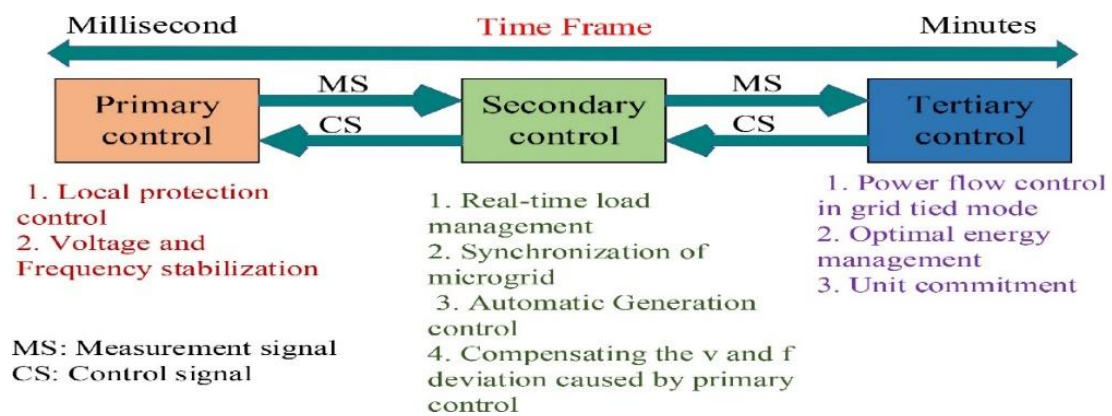


Figure 2. 17: Block diagram of control mechanism Hou et al. (2018).

A. AC-coupled systems

As illustrated in Figure 2.18, AC buses are employed to integrate distributed generation (DG) sources with AC outputs. On the other hand, DC sources require DC/AC converters (inverters), while AC sources can be connected to AC buses directly or through AC/AC converters when necessary. Similarly, DC loads are connected to AC buses via AC/DC converters (rectifiers), while AC loads connect directly or through AC/AC converters, depending on the requirements (Rao et al., 2019).

There are two types of AC buses:

- High-frequency AC buses (HFAC): used for connecting high-frequency AC power generation systems and high-frequency loads.
- Power-Frequency AC buses (PFAC): used for connecting DG sources and loads that operate at power frequencies (50–60 Hz).

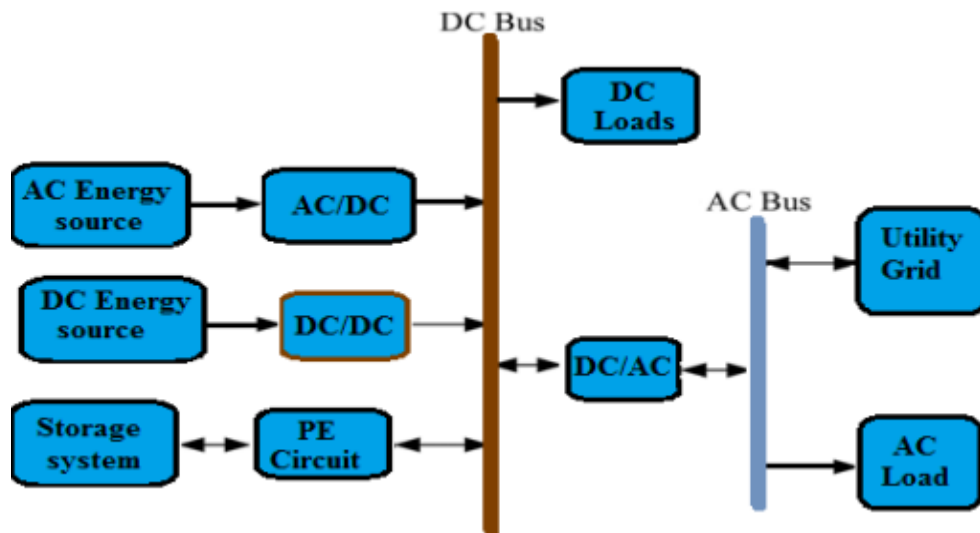


Figure 2. 18: Schematic diagram of a DC-coupled hybrid energy system Ali et al. (2021b)

Figures 2.19 (a) and (b) illustrate the general hybridisation and energy flow of DG sources using HFAC and PFAC buses respectively. In both configurations, AC/DC rectification is required to obtain DC power. Additionally, the utility grid can be connected to the HFAC system through a PFAC bus, using either a DC/AC or AC/DC converter, to which AC loads may also be connected (Yang, 2017).

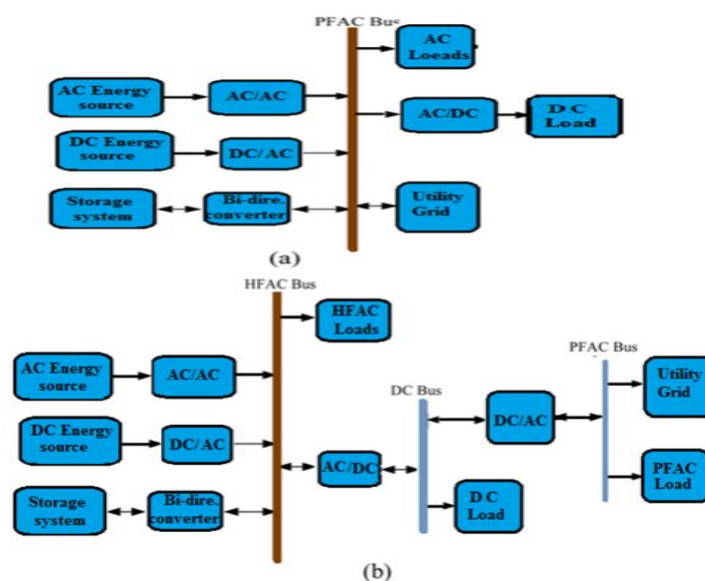


Figure 2. 19: Schematic of AC-coupled hybrid energy system: (a) PFAC; (b) HFAC Ali et al. (2021b)

In a hybrid-coupled configuration, both AC and DC sources and loads are connected, as depicted in Figure 2.20. This setup offers higher energy efficiency compared to the previous configurations (AC- or DC-coupled). However, it comes with increased complexity in terms of control (Sun et al., 2020).

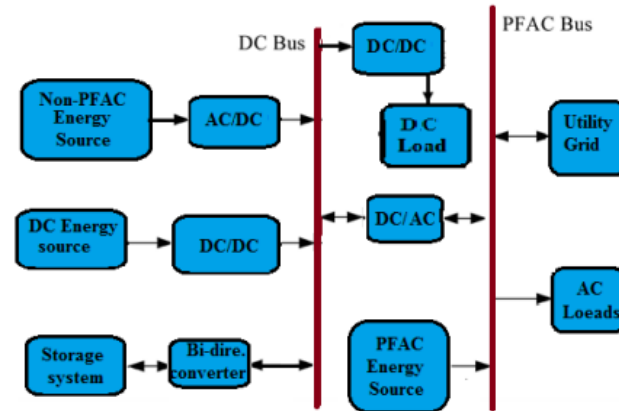


Figure 2. 20: Schematic diagram of hybrid-coupled energy system Ali et al. (2021b)

In today's energy landscape, two key transmission system technologies have emerged to support the long-distance transmission of offshore wind power plants (OWPP): a) AC collection-AC transmission; and b) AC collection-DC transmission (Figure 2.21). The traditional high-voltage alternating current (HVAC) transmission system, with its well-established and straightforward design, has become the dominant choice for many offshore wind farms due to its simplicity and proven reliability (Neumann et al., 2014).

The initially generated voltage typically hovers around 700V, and is elevated to a medium voltage level of 33 kV (which might escalate to 66 kV under certain circumstances). To effectively manage challenges related to over-voltage and charging currents in the subsea cable, a well-suited shunt reactor is employed to compensate for the transmitted power. This strategic application not only addresses these issues but also augments the overall transmission capacity (Camara et al., 2013; McKenna et al., 2022). Transmission is facilitated through the use of either an LCC or a voltage-source converter (VSC). In a VSC-HVDC system, both active and reactive power flow are influenced by several factors, including voltage amplitude, the phase angle between voltages, and transformer reactance (Wei et al., 2018).

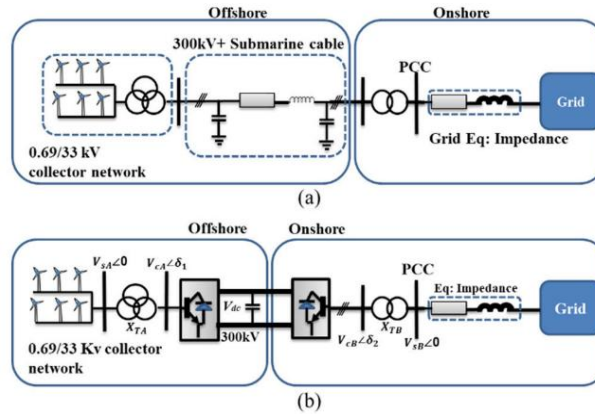


Figure 2. 21: In an offshore wind farm, the conventional configuration of (a): HVAC and (b): HVDC links (McKenna et al., 2022).

Recent advancements in VSC-based HVDC technology have expanded its capabilities, now supporting ultra-high voltage (UHV) transmission up to 800 kV. However, it remains less economical than LCC-based HVDC due to generally higher installation costs, lower power capacities, and increased power losses as a leading renewable source worldwide, spurring extensive efforts to improve offshore wind power transmission technologies to capitalise on this potential. Offshore wind farms, which generally experience higher and more consistent wind speeds than onshore sites, form the foundation of large-scale renewable energy projects. These farms typically rely on two main transmission strategies: AC collection-AC transmission and AC collection-DC transmission. The HVAC systems are prevalent in offshore wind transmission, scaling from voltages around 700 V up to 33 kV or more (Musasa et al., 2017). In contrast, HVDC systems – particularly voltage-source converter (VSC) configurations – are increasingly employed for efficient long-distance transmission, addressing issues like over-voltage and charging currents that can arise in extended connections (Wiegner et al., 2024). The widespread adoption of both HVAC and HVDC technologies in commercial high-power offshore wind transmission is illustrated in Figures 2.22 and 2.23, where cost competitiveness remains a significant consideration (Wang & Nguyen Thi, 2013; Planas et al., 2015).

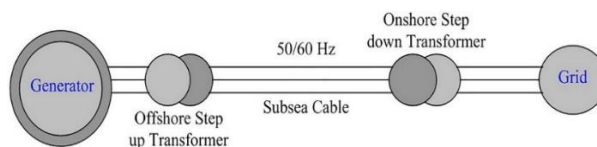


Figure 2. 22: HVAC transmission system design (Raza, 2017)

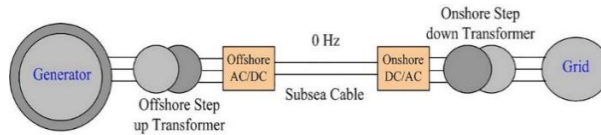


Figure 2. 23: HVDC transmission system layouts (Raza, 2017)

2.10. The role of reactive current in tidal and wind systems during grid faults

2.10.1. Classification of FRT methods for DFIG-WT

In a doubly fed induction generator wind turbine (DFIG-WT) system, the rotor side converter (RSC) plays a crucial role in controlling the rotor speed and managing the reactive power, whereas the grid side converter (GSC) ensures that the DC voltage is maintained at its rated level. This help to facilitate the seamless transfer of active power between the RSC, GSC, and the grid. Also, due to the direct connection of the DFIG stator to the grid, the system becomes highly vulnerable to grid faults, making fault tolerance an essential consideration. To improve the fault ride-through (FRT) capability of DFIGs, several strategies can be utilised. These include integration of protective devices, reactive power injection systems, energy storage devices (ESDs), and both conventional and advanced control techniques. A comprehensive summary of these various FRT classification methods, highlighting their effectiveness in enhancing system resilience during grid disturbances, is shown in Figure 2.24 (Moheb et al., 2022).

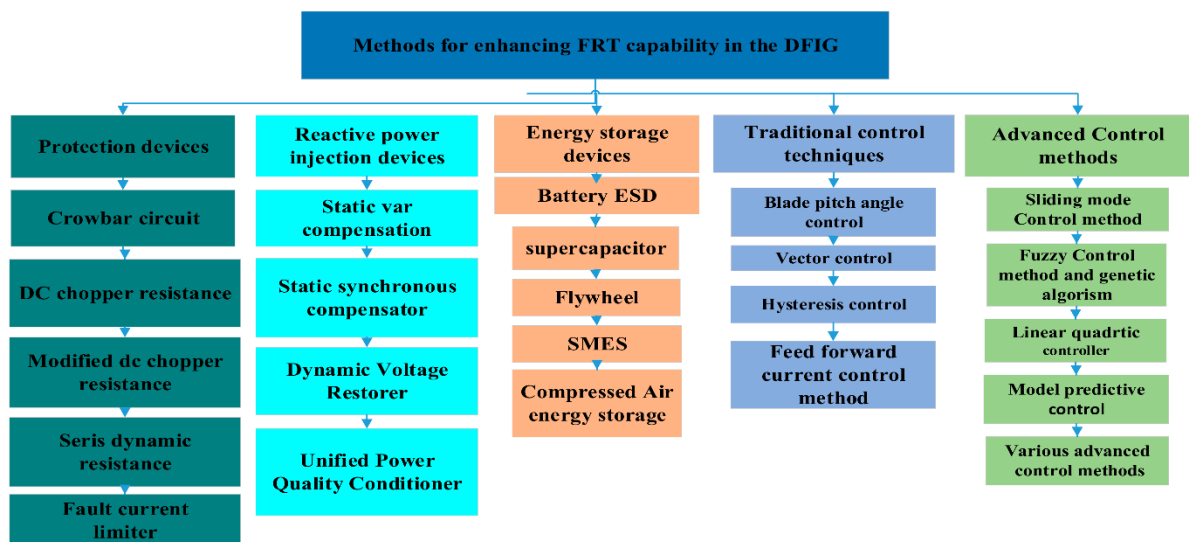


Figure 2. 24: Classifications of FRT hardware methods for DFIG Moheb et al. (2022)

Grid codes require that tidal and wind turbine (TWT) systems supply reactive current during grid faults to stabilise grid voltage. For example, based on the grid code requirements, the

FRT function should engage when grid voltage drops below 90% of its nominal value. In cases where grid voltage ranges from 50% to 90%, the generation system must provide 2% reactive current for every 1% voltage dip (Ikni et al., 2014). If grid voltage falls below 50%, the system is required to deliver 100% reactive current, meaning that the TWT system should supply full capacitive reactive power while generating zero active power output. Additionally, the transition from normal operation to FRT operation must occur within 20 milliseconds when grid voltage drops below 90% of its nominal level (Korompili et al., 2016).

2.10.2. Impact of transmission faults on type 4 and type 3 tidal and wind turbines

Both type 4 tidal and wind turbines (TWTs) offer a distinct advantage by completely isolating the generator from the utility grid, thereby protecting the generator, drive train, and gearbox from transmission faults, as illustrated in Figure 2.25. Upon activation of the electrical control system, the grid-side converter's active power output can be quickly reduced to zero (Kangaji et al., 2024a). However, the mechanical system responds more slowly than the electrical system, which results in the TWT generator continuing to inject active power into the power converter. According to the power balance theorem, the surplus energy – generated power exceeding what is injected into the grid – causes the net DC-bus voltage to rise exponentially in relation to the grid fault duration. This surge in voltage can potentially jeopardise the entire power conversion system (Gidwani & Tiwari, 2010).

In contrast, FRT compliance with type 3 turbines is more complex than with type 4 turbines, primarily due to the direct connection between the DFIG stator terminals and the grid. This connection results in uncontrolled dynamics for the DFIG stator during grid faults (Thakur, 2020). Since the rotor is electromagnetically linked to the stator, voltage spikes during FRT transients can lead to significant torque fluctuations. These fluctuations place considerable stress on the drive train, with the potential to cause gearbox failure. The DFIG-based TWTs, therefore, exhibit less controllability during grid faults than type 4 TWTs, underscoring the need for robust hardware protection (Yaramasu et al., 2015).

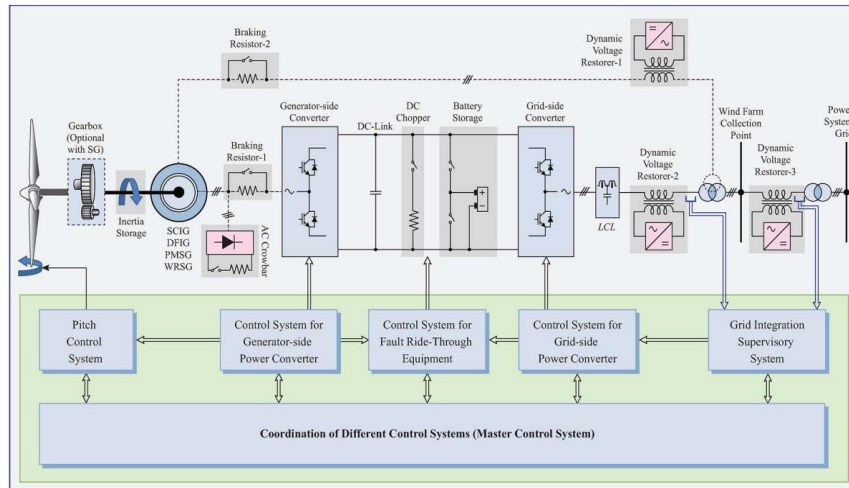


Figure 2. 25: Fault ride-through compliance methods for type 3 and type 4 WECS (Mahela et al., 2019)

2.11. Solutions for FRT compliance in tidal and wind systems

Strategies to ensure fault ride through (FRT) capability analysis compliance in type 3 and type 4 tidal and wind turbines, as well as hybrid tidal-wind farms, have been extensively studied in the literature. These strategies are essential for managing surplus energy during grid faults and ensuring system stability. Several approaches have been proposed which include the following:

1. Regulating active power generation – this involves controlling power output through a pitch control system to prevent excessive energy injection into the grid during faults.
2. Energy storage – surplus energy can be stored in systems such as the DC link, external energy storage devices, and the turbine-generator rotor inertia, helping to mitigate imbalances.
3. Energy dissipation – devices like DC-link choppers, AC crowbars, and braking resistors are used to dissipate excess energy, preventing overloading and protecting the system.
4. Compensation devices – these devices balance energy flow and stabilise the system during transient conditions.
5. Advanced control systems – control strategies implemented at the turbine, power converter, and tidal-wind farm levels enhance overall system performance during grid faults (Alasali et al., 2023).

However, among all these solutions, the crowbar remains a traditional and effective method for limiting fault currents. Upon fault detection, the crowbar introduces resistance into the circuit to protect the system. As illustrated in Figure 2.26, the crowbar consists of two conditional switches (Sawle et al., 2021). A fault detection algorithm triggers a signal

to control each switch. During a fault, the upper switch closes to insert resistance, thereby limiting the fault current. Under normal conditions, the lower switch is closed, allowing the regular current flow. Additionally, bidirectional power electronics switches manage both halves of the AC waveform, ensuring smooth operation (Szczesniak, 2019).

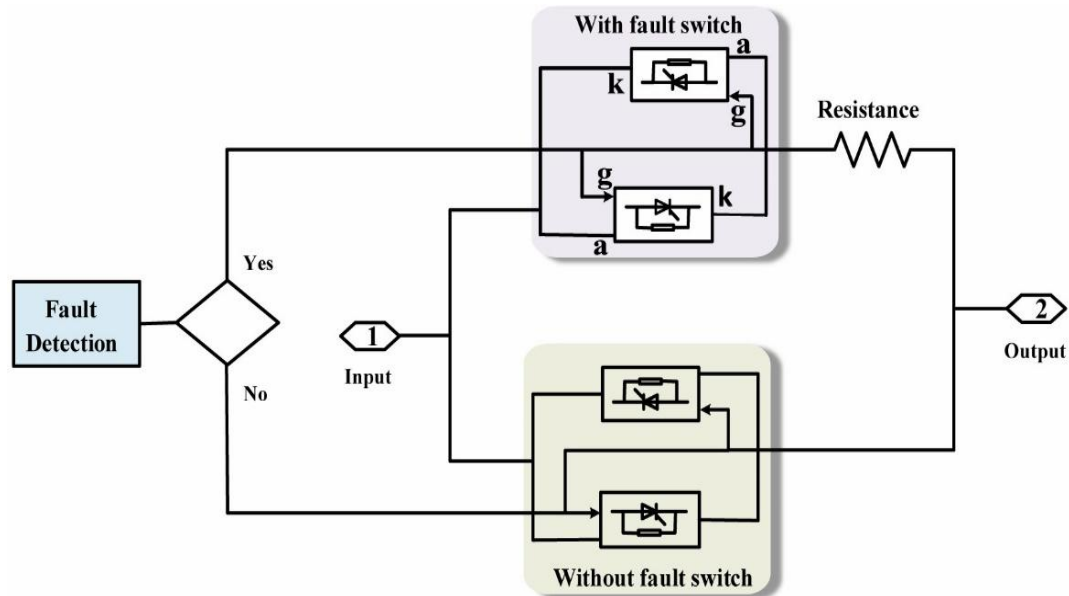


Figure 2. 26: Crowbar fault current limiting strategy Moheb et al. (2022)

2.12. Power limitation by pitch control system in tidal and wind systems

A simple yet effective approach for managing surplus energy during grid faults in type 3 and type 4 tidal and wind turbines is to reduce the power extracted from wind and tidal flows. Under normal operating conditions, the pitch angle adjusts at a rate of $5\text{--}10^\circ/\text{s}$. However, in response to grid faults or other emergencies, the pitch angle can be adjusted more rapidly, at rates of $10\text{--}20^\circ/\text{s}$. Despite these adjustments, the turbine-generator rotor's significant moment of inertia results in a slower response time for the pitch control system, as illustrated in Figure 2.27. This response typically occurs over several seconds, which is notably slower than the millisecond-level response times often required by grid codes (Sousounis & Shek, 2017). As a result, while the pitch control method alone may not ensure full compliance with grid codes or protect power converters, it serves as an important supportive measure when used in combination with other FRT enhancement techniques. This combined FRT enhancement approaches helps to improve the overall resilience of the system during grid disturbances.

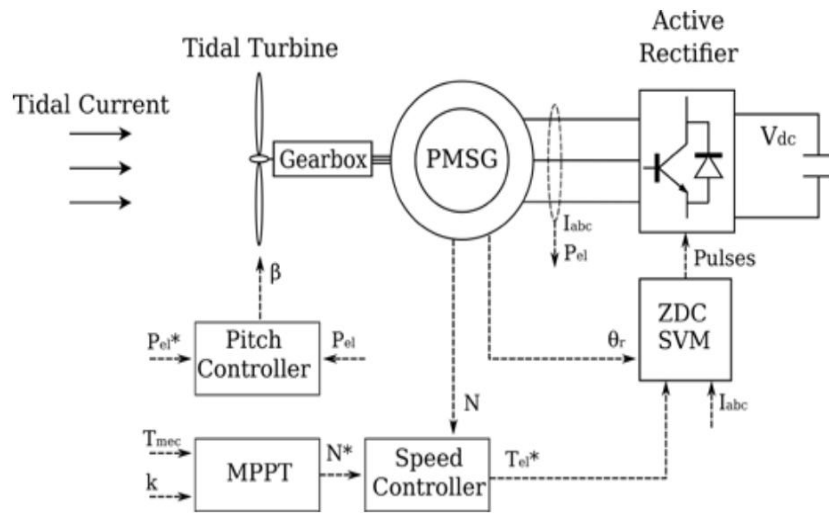


Figure 2. 27: Block diagram of the tidal current system Sousounis & Shek (2017)

2.13. Integration methods

Integrating offshore tidal and wind currents can stabilise power output, with hybrid systems leveraging power flow control mechanisms, such as those proposed by Caraiman et al. (2011) to mitigate wind's intermittency. Battery storage and grid integration techniques further support this stability, as indicated in Figure 2.28. For instance, tidal and wind farms are typically situated in remote locations, necessitating extensive transmission infrastructure and centralised grid connections to support large-scale production (Alam et al., 2020). These setups can create weak grids with a low short circuit ratio (Sepasi et al., 2023), which can lead to resonance issues that may threaten grid stability. Stable grid connections for tidal and wind turbines are essential for advancing renewable energy and maintaining power grid integrity (Li et al., 2022). Therefore, to achieve optimal dynamic and steady-state performance in tidal and wind energy conversion systems (TWECS), tidal and wind turbine systems utilise multiple control subsystems, alongside a master control system (Mazhar-UI-Haq et al., 2018). Under normal circumstances, controllers typically monitor variables such as tidal and wind speeds, directions, generator voltages/currents, and grid parameters, adjusting the system to maintain target values or stay within safe operational limits (Adhikari et al., 2017). When tidal and wind speeds exceed rated values, the master control system activates pitch control, passive stall, or active stall systems to adjust blade angles and prevent power output from exceeding the rated threshold (Ghefiri et al., 2018).

In hybrid systems that involve both DC and AC coupling, the DC segment connects various energy sources and storage technologies—such as wind, tidal, flywheels, and lithium-ion batteries—via bidirectional AC-DC converters (Behera & Pattnaik, 2022).

This ensures stable system performance regardless of the energy source, accommodating both intermittent and continuous energy flows from wind and tidal generation sources. Each distributed generation (DG) unit incorporates an energy storage module, managed by a bidirectional converter, to adjust operations based on the fluctuating nature of primary energy sources (Olivares et al., 2014). For example, Figure 2.29 illustrates how a tidal energy unit, when coupled with battery storage, operates through a bidirectional converter that regulates energy flow in response to variations in tidal power output. By integrating storage within the DC link, virtual inertia can be emulated, enhancing low-voltage ride-through capabilities and stabilising the grid during disturbances (Papari et al., 2019). This configuration allows the control mechanism for the grid-side inverter to be decoupled from the generator-side rectifier, facilitating the integration of virtual inertia alongside droop control functions on the grid-side inverter. Consequently, the design of electronically-coupled distributed energy resource (DER) units must consider the energy source type, load requirements, network configuration, and operational dynamics of both wind and tidal systems (Sepasi et al., 2023).

2.14. Electronically-coupled DER structures

Generally, DER in hybrid systems differ significantly in their interfaces. Conventional rotating generation units, such as fixed-speed tidal turbines, reciprocating engines, and small hydro turbines, are connected through mechanical generators. In contrast, electronically-coupled DERs use power electronics to synchronise their output with grid demands. This category includes variable-speed tidal turbines, internal combustion engines (ICEs), micro turbines, and distributed energy storage units (Eid et al., 2016). The use of power electronics in these DERs enhances system efficiency, provides active harmonic filtering, and allows for more flexible control of both active and reactive power. To facilitate the integration of DERs into the grid, various converter topologies are employed, each tailored to address specific grid requirements. These topologies play a crucial role in optimising the performance and stability of hybrid energy systems.

A. Grid-forming units

The DER units in hybrid systems exhibit varied interfaces, depending on their energy source and control requirements. Traditional rotating DG units, such as fixed-speed tidal turbines, reciprocating engines, and small hydro turbines, typically connect through mechanical generators. In contrast, electronically-coupled DERs use power electronics to synchronise their output with grid needs (Amenedo et al., 2021). These units include variable-speed tidal turbines, ICEs, micro turbines, distributed storage units, and electric vehicles. The tidal

turbines, for instance, vary in their integration with power electronics: fixed-speed units operate without an interface, partially rated variable-speed systems use power electronics for enhanced control, and fully rated systems with PMSG offer advanced capabilities (Yang et al., 2009). Additionally, power electronics enhance system efficiency and provide active harmonic filtering and flexible control of both active and reactive power. Various converter topologies, tailored to meet specific grid requirements, ensure seamless integration of wind and tidal power into hybrid systems. Control methods for DERs are designed to match the diverse operating conditions of wind and tidal systems and achieve specific functions. Figure 2.30 shows that a basic control framework for electronically coupled DERs in a hybrid AC system allows wind and tidal units to function as grid-forming, grid-feeding, or grid-supporting components, depending on the system's needs.

B. Grid-feeding units

Grid-feeding units, such as wind and tidal energy systems, play a vital role in adjusting both active and reactive power to meet dispatch requirements and stabilise power flow during fluctuations. To achieve this, various control strategies are employed. These control methods for grid-feeding DERs are typically categorised into three main approaches, namely current control (Unamuno & Barrena, 2015), direct power control (DPC), and AC voltage control (Tiwari & Babu, 2016).

Current control methods are based on techniques such as field oriented control (FOC), to regulate active and reactive power. Voltage-oriented control (VOC) and virtual flux-oriented control (VFOC) are approaches that allow synchronisation of control with the voltage integral rather than grid voltage, which effectively filters grid voltage fluctuations (Lyu et al., 2024). As shown in Figure 2.31, VOC systems generate current references through P and Q feedforward or feedback loops, with various controllers like PI, PR, and hysteresis controllers optimising performance (Olivares et al., 2014).

The direct power control (DPC) approach involves directly controlling active and reactive power without an inner current loop, simplifying the system and removing the need for coordinate transformations. This method is particularly beneficial for managing the dynamic response of systems with high renewable penetration, as shown in Figure 2.32 (Rathod & Subramanian, 2022). In a hybrid system with high DER integration, grid-feeding units must be capable of withstanding short grid disturbances and managing voltage transients during load switching, especially in islanded operations. Negative-sequence components may cause harmonic oscillations, requiring sophisticated algorithms for managing real power flow and ensuring system stability (Döring et al., 2018).

C. Grid-supporting units

Grid-supporting units operate by optimising power output from wind and tidal systems while providing ancillary services to improve power quality. Unlike grid-parallel units, which primarily focus on maximising power feed-in, grid-supporting units can also serve to mitigate power quality issues. For example, wind and tidal energy systems are increasingly being used as power quality conditioners, incorporating MPPT algorithms alongside repetitive AC voltage controllers to reduce harmonics and improve overall system stability (Olivares et al., 2014).

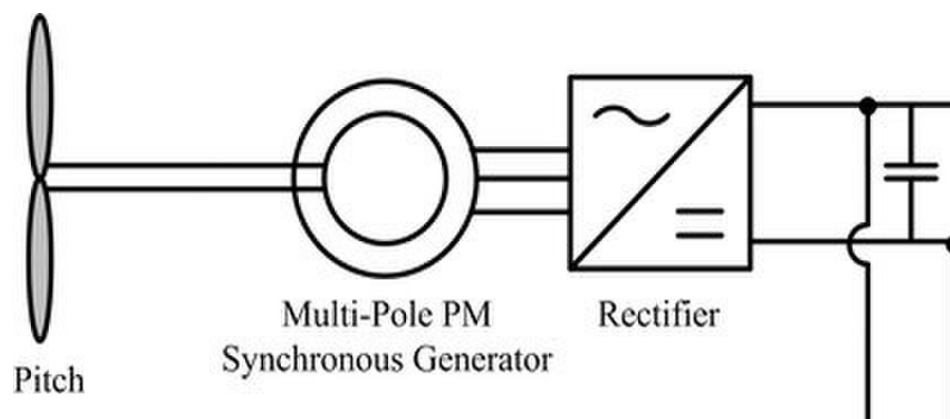


Figure 2. 28: Overview of three commonly used wind turbine systems Wu et al. (2021)

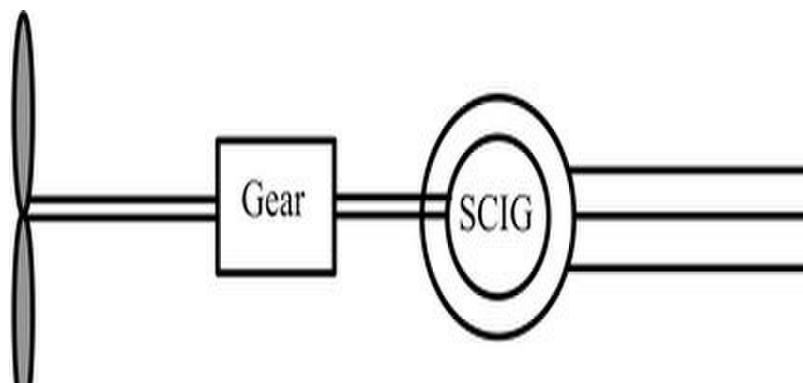


Figure 2. 29: Structure of a single-stage power conversion system for wind energy systems Kangaji et al. (2024b)

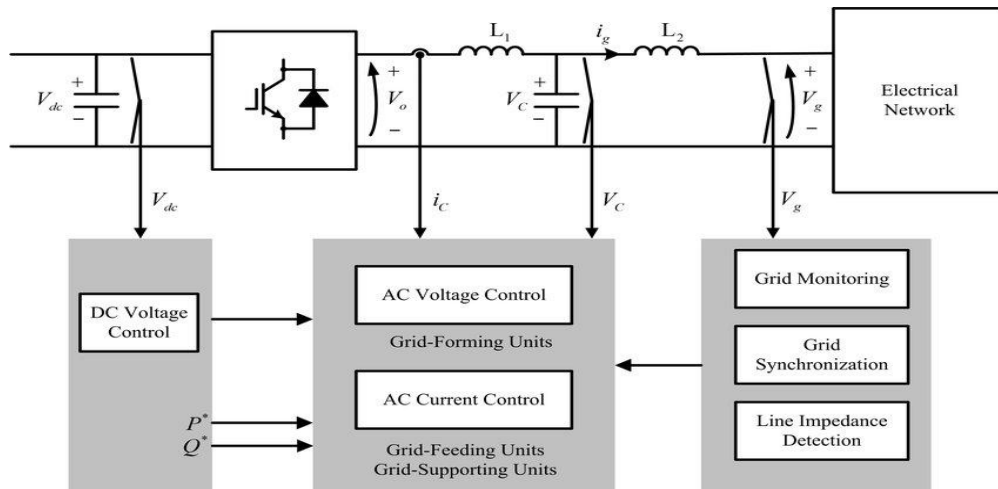


Figure 2. 30: General control system for an electronically-coupled der unit in an AC microgrid
Malik et al. (2017)

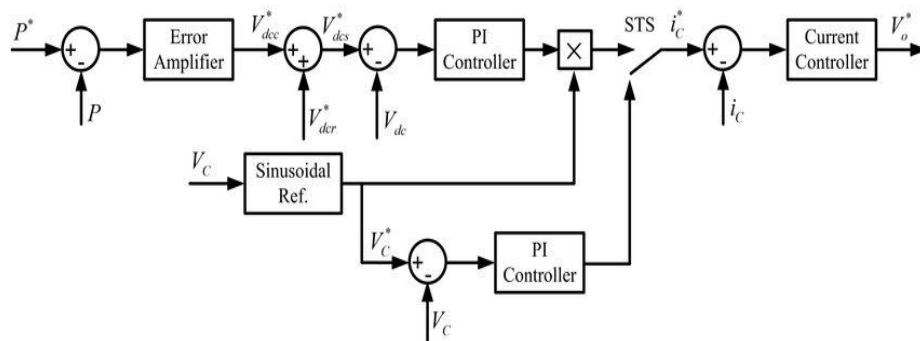


Figure 2. 31: Block Diagram of Voltage and Current control using a static transfer switch (malik et al., 2017).

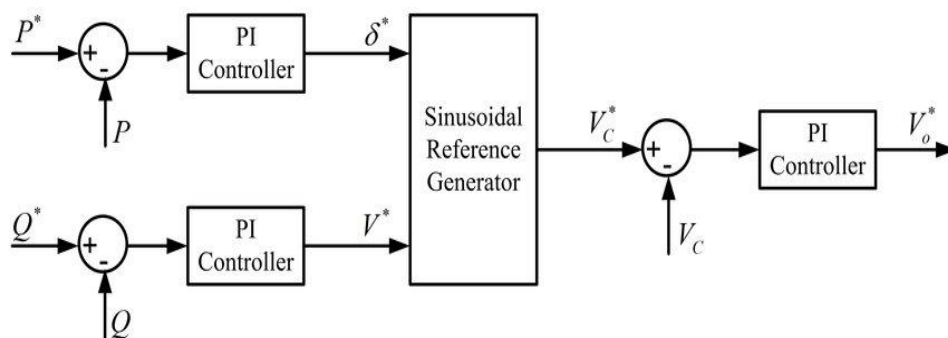


Figure 2. 32: Block diagram of basic direct Voltage control system method (olivares et al., 2014).

The combination of the intermittent nature of wind power with the predictability of tidal energy, are pivotal in advancing renewable energy integration. However, these systems require robust control strategies to manage the variability of power generation and ensure stable grid-connected operation. As shown in Figure 2.33, VOC system is the widely adopted approach for managing power flow and ensuring efficient energy conversion in such hybrid systems (Olivares et al., 2014). The VOC system generates current references through P-Q feed-forward or feedback methods, emulating the behaviour of synchronous machines and providing high dynamic and static performance. For the VOC system to achieve this, it incorporates the following key components:

- The PLL that synchronise the grid voltage phase angle with the control system, enabling accurate coordinate transformations.
- Current reference generation this one produces active and reactive current references to maintain power quality and balance grid demands.
- Synchronous frame controller This regulates active and reactive power independently in the rotating dq frame using proportional-integral (PI) controllers for precision (Kangaji et al., 2024b).
- Stationary frame controller this one operates in the $\alpha\beta$ frame, utilising advanced techniques like predictive or hysteresis control for rapid and robust performance.

These components collectively enable effective energy management in grid-connected hybrid wind-tidal systems, ensuring seamless integration and storage of renewable energy (Malik et al., 2017).

In microgrids, it is important that the hybrid systems handle grid disturbances and islanded operation challenges, such as voltage transients caused by load switching. This necessitates robust current controllers, including PI, proportional resonance (PR), hysteresis, and deadbeat controllers, as detailed in Prince et al. (2022). An alternative approach to VOC is the DPC method, which eliminates the need for current control loops or coordinate transformations by directly controlling instantaneous active and reactive power (p and q). The DPC method's simplicity and fast dynamic response make it a viable option for hybrid wind-tidal systems, as demonstrated in Figure 2.34, in voltage-based and virtual flux-based schemes. Comparative analyses of VOC, voltage-frequency-oriented control (VFOC), and DPC methods highlight their strengths in various applications. Advanced DPC techniques addressing variable switching frequency issues further enhance their applicability in hybrid energy systems (Xing et al., 2023).

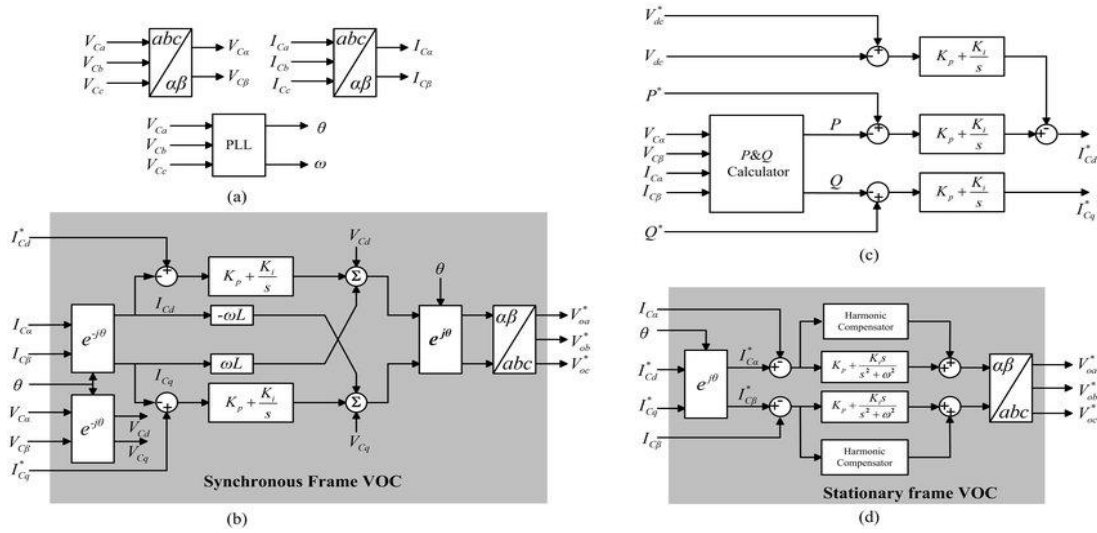


Figure 2. 33: (a) Phase-locked loop, (b) current reference generation, (c) synchronous frame-based voltage-oriented current controller, (d) stationary frame voltage-oriented current controller Prince et al., 2022)

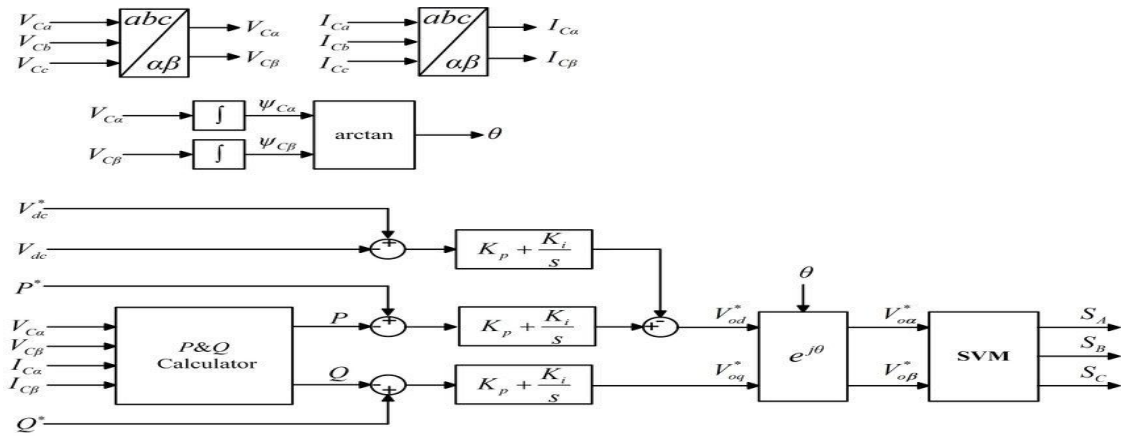


Figure 2. 34: Block diagram of the virtual flux-based direct power control scheme Xing et al. (2023)

The control system of a wind turbine plays a critical role in managing both safety and operational decisions. It continuously monitors various parameters and oversees turbine operations, ensuring optimal performance. The control system regulates multiple aspects of turbine functions, it also utilises specialised computers, switches, pumps, valves, and motors. Sensors are employed to measure essential conditions such as temperature, wind speed, rotor speed, and generator parameters, all of which contribute to efficient control. Redundancy is typically incorporated in safety-sensitive areas to enhance reliability. Controllers ensure the system's smooth operation by cross-referencing sensor readings and verifying the computer and control systems' functionality throughout the turbine (Sousounis & Shek, 2017).

An AC-coupled wind-storage hybrid system integrates distributed wind turbines with battery storage, connecting them to an AC bus, as shown in Figure 2.35. These systems commonly utilise an industry-standard PLL feedback control system to synchronise the phase of the generated power with that of the grid. On the other hand, the grid-side inverters are pivotal in aligning the voltage and phase of the AC waveform to match the grid's requirements, ensuring the safe and efficient integration of power from DERs.

The AC-coupled systems offer certain benefits over DC-coupled configurations. They use readily available legacy hardware and standardised equipment, making them easier to install. Additionally, in an AC-coupled setup, the battery's energy storage operates independently of the wind turbine output, enabling the system to be sized and managed based on specific energy needs and grid services. Also both units in an AC-coupled system can deliver maximum output simultaneously, resulting in a higher total capacity. This design can also reduce the frequency of charging and discharging cycles for the battery compared to a DC-coupled system, although this advantage may not hold if the system operates in an isolated mode. For type 3 and type 4 wind turbines, an AC-coupled wind-storage system needs two inverters, namely a unidirectional DC/AC inverter for the wind turbine (following the DC/AC converter) and a bidirectional DC/AC inverter for the battery to handle charging and discharging (Reilly et al., 2022).

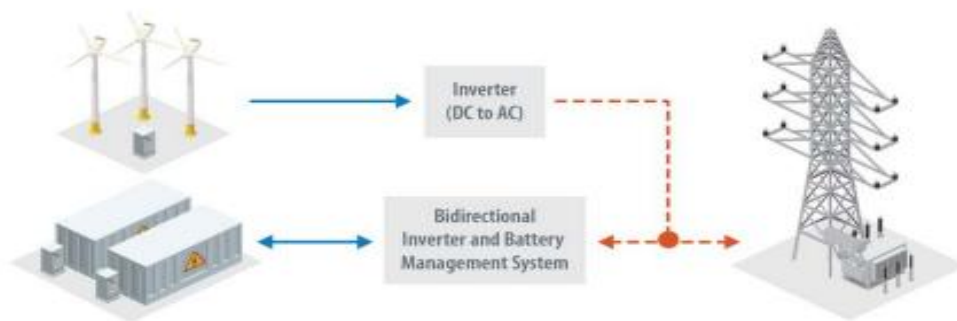


Figure 2. 35: Typical topology of an AC-coupled wind-storage hybrid system Reilly et al. (2022)

In a DC-coupled wind-storage hybrid system, the wind turbine and BESS are interconnected at the DC bus, with both components feeding into a shared inverter, as illustrated in Figure 2.36. The power generated by the wind turbine is first converted from AC to DC and then stored in the BESS, which is managed through a DC-DC converter. The grid-side inverter can be either unidirectional (DC/AC) or bidirectional, providing flexibility in controlling the direction of power flow. This configuration allows the battery to store energy exclusively from the wind turbine or from both the turbine and the grid. This significantly enhances the system's versatility and adaptability (Reilly et al., 2022).

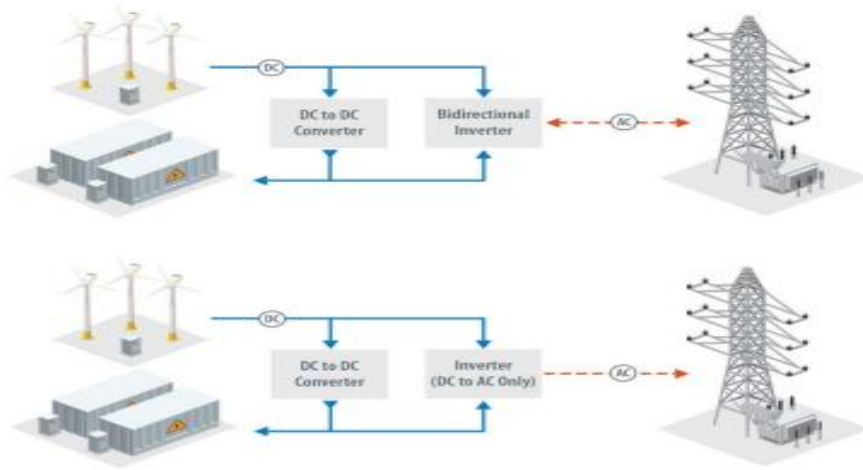


Figure 2. 36: Schematics of DC-coupled wind-storage systems Reilly et al. (2022)

2.15. Energy grid management, optimisation, and economic analysis of offshore hybrid tidal storage grid-connected systems

The primary objectives of offshore hybrid tidal storage grid-connected systems are to maximise safe instantaneous system load and minimise emissions from renewable power generation sources. Achieving these goals requires advanced optimisation techniques and efficient grid management. Several artificial intelligence (AI) techniques, including particle swarm optimisation (PSO), genetic algorithm (GA), and non-dominated sorting genetic algorithm II (NSGA-II), have been analysed and optimised for possible microgrid management (Alex et al., 2022; Zahraee et al., 2016).

Among these AI techniques, the NSGA-II algorithm is particularly effective for ensuring voltage and angle stability, in line with IEEE standards, while facilitating the integration of increasing levels of renewable energy. These algorithms balance system stability and performance while integrating diverse energy sources.

In the hybrid system where renewable energy sources such as wind, tidal, and wave energy serve as the backbone of the microgrid structure, HOMER optimisation tool plays a key role in continuously monitoring grid conditions and adjusting parameters to maximise safe bus loads while maintaining system reliability. Key indicators such as the fast voltage stability index (FVSI), line stability index (LSI), and line stability factor (LQP) are employed to assess and improve stability (Kangaji & Raji, 2024). This system ensures the grid remains efficient and sustainable, even under fluctuating conditions and varying energy demands. Figure 2.37 illustrates the proposed methodology for this study. The process started with the collection of essential data, including wind speeds, water flow rates, grid tariffs, battery specifications, and

other relevant tidal and wind parameters. Simultaneously, the energy demands of the coastal city were surveyed and categorised. Once all the necessary data and component specifications were gathered, the next phase focused on system design and detailed component modelling. The proposed energy management system (EMS) was developed to align energy supply from available sources with the demand load. Finally, the EMS was evaluated using HOMER software, enabling a comprehensive techno-economic analysis to assess the system's performance, efficiency, and cost-effectiveness.

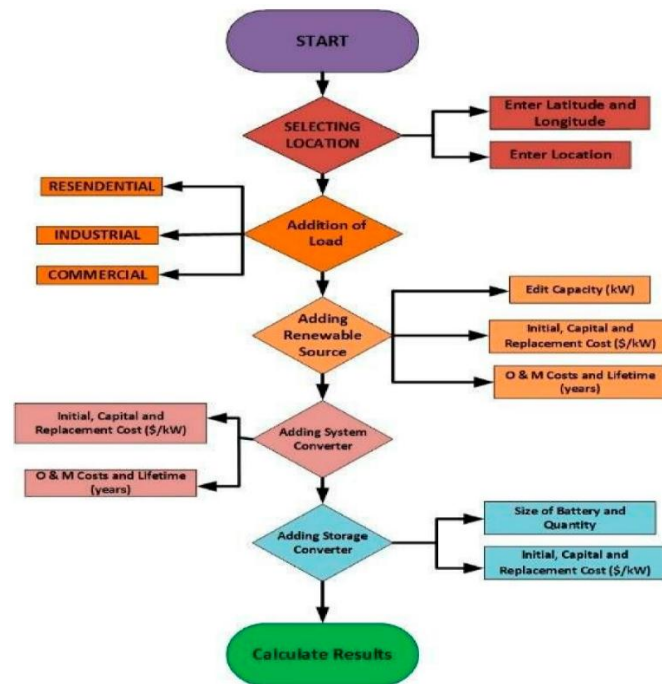


Figure 2. 37: Offshore hybrid tidal wind generation system optimisation general model.

In recent years, a notable evolution has unfolded in the realm of AI algorithms, significantly impacting the optimisation of high-renewable energy systems (HRES). The AI's prowess derives from its ability to emulate human-like cognitive processes within machines. In the domain of AI, traditional methods offer a distinct advantage by presenting potent solutions to intricate, nonlinear problems. Moreover, AI exhibits a pragmatic resolution for the intermittent and insufficient data challenges inherent in HRES, stemming from the unpredictable nature of solar and wind turbine contributions (Zia et al., 2018). In a recent study conducted by Mohapatra et al. (2020) the AI manifested its utility through the application of various GA algorithms. These optimisation techniques collectively formed a valuable toolbox for enhancing HRES performance and functionality. Each algorithm contributes a unique

approach, aligning with specific problem characteristics and refining the system's efficiency (Mohapatra et al., 2020). The amalgamation of AI's computational prowess with diverse optimisation methodologies propels the HRES field forward and aligns with the growing complexities of renewable energy integration. As HRES continue to play a pivotal role in sustainable energy transitions, the synergy between AI algorithms and optimisation techniques offers a promising trajectory towards robust and adaptive energy solutions.

2.15.1. Offshore hybrid wind tidal energy management strategies

Research in distributed generation (DG) emphasises the importance of strategic planning and implementation in distribution networks. Key aspects such as accurate component sizing and optimal placement are essential to reduce power losses and boost voltage stability (Zia et al., 2022a). Before integrating hybrid energy systems, addressing voltage regulation, frequency stability, and total harmonic distortion is crucial. Due to marine current variability influenced by swell effects, maintaining power quality can be challenging. Thus, the energy storage systems (ESSs) have shown great promise in stabilising power output and improving reliability (Vita, 2019). One of the innovative solutions involves hybrid energy storage systems (HESSs), which combine super capacitor banks (SCB) with vanadium redox flow batteries, which not only effectively capture energy from marine currents but also significantly enhance power quality. A time-series fuzzy logic controller plays a vital role in managing SCBs by preventing overcharging and over-discharging while balancing the state of charge (SOC) (Han et al., 2021).

Advanced machine learning-based management techniques have been developed to support efficient power redistribution in offshore hybrid systems. These approaches address harmonic compensation, line constraints, and voltage and frequency stabilisation at the power management level. At the control level, precision adjustments for voltage and frequency further ensure operational stability. This additional layered control strategy enhances the performance of the EMS while maintaining stability across all management levels. Figure 2.38 shows how the EMS integrates these strategies to enable seamless operation of the hybrid wind-tidal energy storage system (Han et al., 2021).



Figure 2. 38:Energy management strategies of MG (Zia et al., 2018)

Effective control and optimisation are crucial for maximising the performance and economic viability of hybrid wind-tidal systems. To ensure this is achieved, some methods such as artificial neural networks, genetic algorithms and fuzzy logic control are employed.

2.15.2. Artificial neural networks

Artificial neural networks (ANNs) basically involve the advanced energy management in microgrids which increasingly relies on innovative approaches, such as supervised neural networks, to enhance efficiency and sustainability. One of the prominent applications of ANN is the microgrid supervised neural network model, which accurately calculates controllable residential loads by combining conventional generator (CG) costs with penalties for energy curtailment. This application provides a holistic optimisation model that performs better than a traditional EMS by integrating unit commitment with optimal power flow. Despite its computational demands, ANN minimises energy use and peak demand, and enhances the load factor, showcasing demand response benefits on various metrics, including energy efficiency and load management (Zia et al., 2018).

Furthermore, predicting the CG power output based on demand requires sophisticated models like ANN and adaptive neuro-fuzzy inference systems, which both surpass traditional methods in accuracy. A model predictive control (MPC)-based EMS further enhances microgrid efficiency, optimising energy trading, peak demand battery use, and maximising local wind energy consumption. Another breakthrough is the hybrid intelligent algorithm, which combines Monte carlo simulations, ANN training, and GA optimisation to predict the performance of hybrid power systems effectively, reducing computational effort and yielding insights into non-reliable hybrid operations (Zahraee et al., 2016). In the PV and solar thermal systems, radial basis neural networks provide accurate power forecasts, enhancing thermal storage through precise heat load management. However, while batteries in residential settings offer benefits, high investment and maintenance costs remain a drawback (Zia et al., 2018).

2.15.3. Genetic algorithms

Inspired by natural selection, genetic algorithms (GAs) provide robust solutions for complex optimisation problems. The GAs are particularly effective in optimising energy systems by handling nonlinearity, discontinuity, and non-differentiable equations, making them ideal for applications in hybrid HRES (Zahraee et al., 2016). The GAs have been widely used to optimise configurations such as PV-wind systems, off-grid battery setups, and PV-pumped hydro-storage (Zia et al., 2018). Additionally, GAs have demonstrated their effectiveness in optimising power flow and reducing operational costs in microgrid management. Additionally, their ability to optimise both local and global solutions makes them a versatile tool for enhancing energy system performance (Mohapatra et al., 2020).

2.15.4. Fuzzy logic control (FLC)

For a standalone hybrid system, a combination of FLC with the cuckoo search algorithm represents a novel optimisation approach. This method uses battery state of charge (SOC) and net power flow as inputs, managing power rates for batteries, PV panels, and diesel generators. Fine-tuned with data on solar irradiance, temperature, and load profiles, this system minimises loss of power supply probability (LPSP), excess energy, and levelised energy cost. Notably, this approach outperforms PSO in controller efficiency (Zahraee et al., 2016). In-home microgrids, a combination of FLC with neural networks for an EMS effectively smooths power profiles, curbs grid oscillations, and extends battery life by maintaining SOC around 75% capacity (Zia et al., 2018). Also, fuzzy logic energy management systems (FLEMS) are especially adapted for managing complex hybrid energy inflows, proving efficient in grid-connected wind-tidal systems with storage (Ghefiri et al., 2018). Linear control methods like proportional integral derivative (PID) controllers are often inadequate for nonlinear tasks

like MPPT, whereas FLC excels in managing load voltage, frequency, and energy optimisation, despite some complexities (Ali et al., 2021; Malik & Yadav, 2021).

Techniques like ANNs are widely used in handling non-linear statistical modelling, which further enhance renewable energy system performance (Jamal et al., 2021). To improve hybrid system performance, various optimisation methods are applied, including graphical techniques, probabilistic modelling, iterative and multi-objective methods, and AI techniques (Table 2.4) (Vigneysh & Kumarappan, 2016). In parallel, progressive control methodologies rooted in artificial intelligence, such as FLC, have gained traction across a myriad of applications, including renewable energy converters. To address this, an adept control strategy that ensures both conversion efficiency and robustness amidst varying tidal speeds is scrutinised.

Table 2. 4: A summary of the optimisation techniques

Optimisation approach	Optimised factors	Notice
Artificial Intelligence	Hybrid solar-wind-offshore	Using evolution methods (Zia et al., 2018), (Zahraee et al., 2016).
a. Genetic algorithm b. Particle swarm c. Simulated annealing d. Artificial neural network network e. Hybrid model	System with banks	
Iterative Method a. Hill climbing b. Dynamic programming	Hybrid solar-wind system	Using LPSP to determine Different conditions of solar-Wind combination -(Jyoti Saharia et al., 2018)
c. Linear programming d. Multi-objective		
Graphical construction Probabilistic methods Deterministic methods Software based a. HOMER	Battery and PV array Efficiency of hybrid system Standalone PV with battery	Usually applied for 2 factors By using statistical method of data gathering Based on equations applied for finding value When applying fixed factors Software Software based. Using an input file with all the essential data based on a software application (Li et al., 2020; Li et al., 2020; Yeter et al., 2022).

Numerous studies have explored intelligent strategies for integrating DG into power grids, with a primary focus on reducing both investment and operational costs while improving system reliability (Li et al., 2020; Yeter et al., 2022). Recent advancements emphasise the growing role of AI in hybrid energy systems, particularly within demand response applications. Artificial intelligence addresses common challenges in load shifting and the inefficiencies of conventional demand response methods (Thirunavukkarasu et al., 2022; Ye et al., 2020; Angeloudis et al., 2017). AI-driven energy management systems have been specifically designed to optimise the coordination of diverse energy sources, such as tidal and wind generators, flat-plate collectors, electric and thermal loads, energy storage systems, and even fossil fuels. These systems integrate these sources seamlessly into grid operations, enhancing flexibility and efficiency across the grid (Kazmi et al., 2017; Zhou, 2022a; Ye et al., 2020; Sanguesa et al., 2021).

The AI applications in energy management extend to areas like weather prediction, occupancy analysis, energy usage monitoring, and energy price signal interpretation, which together contribute to utility cost savings and improved system reliability (Prodan & Zio, 2014; Good et al., 2017; Yu et al., 2021; Strasser et al., 2015). Through data collection and analysis across diverse formats – numerical data, text, images, and videos – AI optimises energy consumption and reduces peak demand loads. Despite substantial progress, the literature reveals ongoing challenges in managing hybrid energy systems, particularly concerning initial investment and operational efficiency in dynamic load distribution (Pandžić, 2021). Proposed methods range from basic scheduling of renewable energy sources without considering real-time status to advanced computational intelligence techniques that adapt to system conditions for enhanced cost savings and operational stability (Ahmad et al., 2022). Renewable energy's inherent intermittency poses further complexities in integrating these resources into grid and microgrid applications, necessitating robust management strategies (Zhou et al., 2023; Zhou, 2022a; Theo et al., 2017; Gandhi et al., 2020; Sanguesa et al., 2021). The complexity associated with renewable energy resources in hybrid energy systems can be effectively addressed by integrating diverse AI techniques that could ensure more reliable and cost-effective system management without compromising power supply reliability (Yoldaş et al., 2017).

2.16. The design of an EMS methodologically involves defining clear objectives

The design of an EMS involves setting clear objectives to optimise the behaviour and power distribution within microgrids (MGs). Key functions and optimisation algorithms are applied to control power flow between MG components, based on variables like energy tariffs, weather data, and energy demand forecasts. While recent studies have introduced various methods to optimise MG operations, most focus on balancing operational costs with benefits over set timeframes by integrating economic factors such as grid tariffs and user comfort preferences (Dhara et al., 2024). The EMS's primary role is to coordinate power flow between sources, loads, and storage units to achieve objectives like minimising operational costs or maximising revenue through DG bids and electricity market prices. Effective EMS design considers MG power structures, accounting for controllable power distribution across all elements within the system (Yasin & Alsayed, 2021).

2.16.1. Optimisation methods and control techniques

Once EMS requirements are defined, various methodologies are used to achieve efficient design across different MG configurations and objectives. For example, Pena-Aguirre et al. (2020) employed stochastic dynamic programming and local forecasting techniques within an EMS for a grid-connected MG, including both diesel and renewable sources, to extend ESS lifespan. Similarly, Arcos-Aviles et al. (2018) integrated predictive control techniques to adjust ESS settings, compensating for energy forecast deviations in MGs. The FLC is often favoured in EMS designs due to its flexibility with diverse input data types. Also, FLC has been applied across various hybrid energy systems to manage energy distribution based on real-time data, making it adaptable for standalone MGs as well (Xing & Jia, 2023; Moghaddas-Tafreshi et al., 2019; S. Das et al., 2021; Kuznetsova et al., 2014). For instance, Marzband et al. (2016) developed a DC microgrid EMS using FLC to prioritise renewable energy sales while maintaining battery charge levels to prolong battery life. In another study, Javidsharifi et al. (2020) incorporated FLC in an EMS design, accounting for factors like daily energy prices and demand levels to enhance affordability, though few of these EMS designs directly address smoothing power profiles as a primary objective (Vivas et al., 2022).

2.16.2. Multimodal and centralised models

Recently, a multimodal EMS was introduced to adapt to varying residential prosumer needs. Through utilisation of weather and price data from three US locations, this EMS demonstrated reduced annual power costs and improved battery SoC, supporting diverse lifestyle-driven energy objectives beyond basic cost reduction. Additionally, Saha et al. (2022) proposed a centralised model to optimise both water and energy use in buildings, using machine learning algorithms. Their findings show that accurate predictions can aid decision-makers in evaluating EMS scenarios under economic and carbon reduction objectives before full-scale implementation (Motevasel & Seifi, 2014).

During the planning phase, decision-makers can use these forecasts to assess the current status of any energy management model under different economic and carbon emission reduction scenarios. According to the literature analysis, current hybrid EMSs mostly concentrate on cost reductions without regulating the degree of DG penetration into the grid (Alex et al., 2022). Due to frequency excursions brought on by changes in DG supply and load fluctuations, this frequently results in grid instability. Without the inherent inertia of power plant synchronous generators, the majority of DG sources integrate with the grid via power electronics inverter interfaces. The widespread incorporation of renewable DGs into grid networks has been hindered by this problem. Therefore, when designing EMS for hybrid grid/renewable DG systems, it is crucial to prioritise overall system reliability to ensure optimal performance under varying conditions.

In summary, several key gaps outlined below have been identified in the current literature regarding EMS and DG:

- Limited research in commercial settings: most studies focus on residential and industrial setups, with little attention given to commercial environments.
- Lack of attention to feed-in tariffs (FiT): few studies, particularly studies from developing countries, have considered FiT, despite evidence showing that FiT schemes can lead to significant energy cost savings.
- Safety concerns for microgrid (MG) components: only a limited number of studies address the safe operation of various MG components, such as batteries and load management systems.
- Focus on total load, not load classification: most research studies concentrate on total load management, and overlook the benefits of load classification, which could help reduce installation and replacement costs and enhance grid stabilisation.

- Energy Management (EM) design focusing primarily on cost reduction - Most studies emphasise cost reduction, particularly in demand-supply pricing, with insufficient attention given to the operational and maintenance costs associated with EMS.

The primary power source for coastal cities in South Africa is typically the conventional grid system. However, as the demand for cost-effective and sustainable energy solutions increases, alternative power sources are being integrated to create a more diversified energy mix. The high costs associated with peak energy demand, the risk of power outages, and the penalties for exceeding maximum demand have all contributed to the rising popularity of hybrid energy systems in EMS solutions (Prodan & Zio, 2014; Garrido et al., 2013; Padilla-Medina et al., 2020). Despite this progress, many existing hybrid EMSs face significant challenges, particularly the uncontrolled integration of renewable DG sources, which can undermine grid stability and reliability (Amirante et al., 2017).

To address these challenges, this study proposes an EMS that incorporates offshore hybrid wind and tidal energy sources, alongside storage solutions. This system is designed to effectively manage multiple energy sources and a variety of commercial building loads. The objective is to design an offshore hybrid system (wind/tidal/battery) that is well-suited for regions with abundant wind resources and consistent tidal flow throughout the year. However, designing optimal hybrid renewable power generation systems is complex, given the unpredictable and weather-dependent nature of most renewable energy sources. Figure 2.38 illustrates the general process for optimising such a hybrid generation system. Various optimisation techniques and mathematical models have been employed to design these hybrid systems, including PSO, GA, fuzzy logic algorithms, cascade analysis, and ANN. For this study, a fuzzy logic PID controller was implemented (Ghefiri et al., 2018), to optimise system performance.

This research also addresses long-duration applications, such as reducing output variability, relieving transmission congestion, providing backup for power generation shortfalls, and minimising load violations. The complexity of these requirements makes sizing the system particularly challenging. Factors such as resource variability, load fluctuations, technological constraints, system lifespan, and cost all influence system design. Sizing energy storage for isolated loads, especially in standalone systems, is particularly challenging due to the need for long-term backup, compared to grid-connected systems (Yahyaoui & de la Peña, 2022). A simplified sizing method, integrated with an energy management strategy, is proposed as shown in Figure 2.38. This strategy is demonstrated through an offshore hybrid tidal-wind-

storage grid-connected energy system, although it is applicable to other hybrid renewable energy systems as well.

The EMS monitors peak and off-peak periods to identify the most appropriate power sources for operating the loads, ensuring that user comfort is maintained without delays. The FLC continuously tracks load demand and the battery's charge/discharge state to manage system power without interrupting supply. The grid is assumed to be the primary energy source available at all times. The controller decides whether to use the grid or the hybrid tidal-wind/battery system to power the loads, taking into account factors such as time, cost, and the battery's state of charge. During off-peak periods, the EMS and dispatch controller primarily use the grid to operate most loads, relying on the tidal-wind/battery system for only essential loads during peak periods. Once the battery reaches a pre-determined charge threshold, the controller can increase the number of heavy loads powered by the tidal-wind/battery system, regardless of the time of day.

2.16.3. Offshore hybrid tidal wind energy grid structure and operation

Offshore hybrid wind-tidal energy grid systems represent a collaborative and integrated power solution, combining grid-tied, interconnected coastal loads with hybrid tidal-wind-storage systems. Each microgrid within this setup includes a tidal energy generator, a wind energy generator, a battery energy storage system (BESS) utilising lithium-based storage, and an aggregated load that represents coastal energy consumption patterns (Sudhakar et al., 2020). The BESS, in coordination with the utility grid, plays a crucial role in balancing energy consumption and generation. Each microgrid is equipped with its own EMS designed to optimise the use of DERs and maintain a stable and reliable power profile. The EMS ensures that energy generation from tidal and wind sources is efficiently integrated into the system, while also smoothing any fluctuations in grid power. Furthermore, the two microgrids are interconnected, enabling seamless power exchange between them to enhance system reliability and efficiency.

In each microgrid, P_T represents the tidal power, P_w wind power, P_{Bat} is the battery power, P_{grid} is the power exchanged with the distribution network. Positive battery power ($P_{BAT} > 0$) indicates a discharging process, while negative battery power ($P_{BAT} < 0$) indicates a charging process. Similarly, positive (P_{GRID}) signifies a power deficit in the microgrid, while negative (P_{GRID}) indicates a surplus of generated power.

2.16.4. Operation of the grid-connected hybrid tidal wind energy systems

Each microgrid operates in coordination with its EMS to minimise grid power peaks and mitigate abrupt fluctuations. This helps to smooth the power exchange between the grid and the microgrid. When the grid power profile remains stable, the EMS monitors the energy rate-of-change (ERoC) within the microgrid to assess energy fluctuations and predict future battery SoC behaviour. By using FLC techniques the EMS continuously adjusts and optimises the grid power profile for each microgrid within the system. This ensures a more reliable and efficient integration of renewable energy sources and enhances the overall stability of the power system. This enhanced structure and operational strategy improve the efficiency and reliability of microgrid systems, ensuring a stable and sustainable energy supply for residential areas (Arcos-Aviles et al., 2020).

$$P_{grid}(n) = P_{AVG}(n) + P_{FLC}(n) \quad (1)$$

$$P_{AVG}(n) = \frac{1}{M} \sum_{k=n-M}^{n-1} P_{LG}(k) \quad (2)$$

$$P_{LG}(n) = P_{LOAD}(n) - P_{Hyb}(n) \quad (3)$$

Where nn is the current sample, MM is the number of samples per day, P_{LG} is the microgrid power balance, P_{AVG} is the average microgrid power balance, and P_{Hyb} is the output of the FLC block. This block is responsible for smoothing the grid power profile while ensuring the BESS operates within safe limits to extend battery life.

On the other hand, the constraints of the BESS, specifically the maximum and minimum state of charge (SOC) values, SOC_{MAX} and SOC_{MIN} respectively, are defined by considering the depth of discharge (DOD) of the lead-acid battery bank:

$$SOC_{MIN} \leq SOC(n) \leq SOC_{MAX} \quad (4)$$

$$SOC_{MIN} = (1 - DOD).SOC_{MAX} \quad (5)$$

Alternatively, the battery power P_{BAT} correlates directly with the SOC of the BESS. The EMS outlined by Malik & Yadav (2021), Einan et al. (2017) and Han et al. (2016) delineates the battery power and assesses the current battery SOC in the following manner:

$$\Delta SOC(n) = \frac{100}{C_{BAT}} \cdot P_{BAT}(n-1) \cdot T_s \quad (6)$$

Where C_{BAT} represents the battery-rated capacity and η denotes the battery efficiency, with $\eta C \eta C$ for charging and $1 \eta D \eta D 1$ for discharging, and Tsh signifies the sampling period. Each microgrid operates according to the block diagram illustrated in Figure 2.39, which is based on the microgrid ERoC, $P_{AVG}(n)$ defined in Equation (6), and the BESS's state of charge. It is important to note that $P_{AVG}(n)$ represents the local prediction of the battery SOC's future behaviour if the grid power remains unchanged. A comprehensive description of each block is depicted in Figure 2.39.

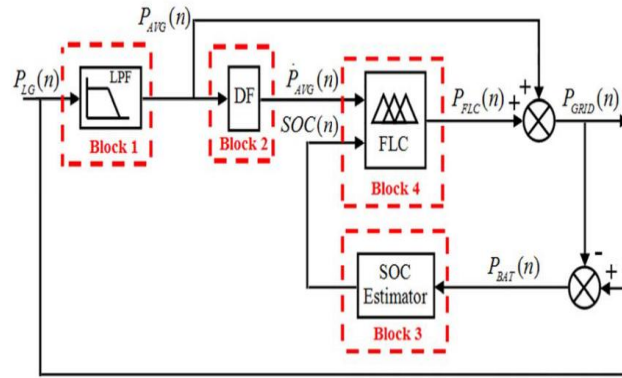


Figure 2. 39: Block diagram of the fuzzy-based EMS based on microgrid energy rate-of-change (Arcos-Aviles et al., 2017).

2.17. Fuzzy-based power exchange management

2.17.1. The adjustment of all parameters involved in the fuzzy Logic Controller

The optimisation of the hybrid renewable energy system was accomplished by addressing the objective function while considering all constraints, such as high reliability, state of charge, and minimal pollution. This study emphasises optimising the cost of energy and the total net present cost, factoring in numerous constraints like high reliability, battery SOC, optimal system sizing, and planning for future expansion (Mohammed et al., 2019). A procedure was conducted offline to adjust various parameters of the FLC, such as the number of membership functions per input/output, mapping methods, and rule-base structure (Zahraee et al., 2016). This adjustment process, outlined in Velik & Nicolay (2014) and García et al. (2013) was targeted to minimise a predefined set of quality criteria. These criteria encompass metrics like PG_{MAX} (maximum power delivered by the grid in one year), PG_{MIN} (maximum power fed into the grid in one year), MPD (maximum power derivative of P_{GRID} in one year), APD (yearly average power derivative of P_{GRID} , P_{VR} (power variation range of P_{GRID}), and PPV (grid power profile variability). This comprehensive set of criteria, detailed in, served as an evaluation framework for assessing the performance of an EMS, where achieving lower values would indicate an improved EMS (García et al., 2013).

Advantages of the FLC:

- **Robustness:** the FLCs are robust enough to cope with variations in system parameters and external disturbances, making them suitable for hybrid systems operating in unpredictable offshore environments.
- **Simplicity:** FLCs do not require precise mathematical models and can be easily implemented using heuristic rules. This simplicity is advantageous in complex hybrid systems where modelling all interactions may be impractical.
- **Adaptability:** FLCs can be easily adapted to changes in system configuration or operating conditions by modifying the rule base or membership functions, allowing for flexible control strategies.

2.17.2. Limitations and challenges of FLC

- **Computational complexity:** Although FLCs are relatively simple to design, they can become computationally intensive and challenging when dealing with large rule bases or multiple inputs and outputs.
- **Tuning difficulties:** designing effective membership functions and rule bases for FLCs requires expert knowledge and experience. Improper tuning can lead to suboptimal performance or instability in the system.

2.18. Challenges and gaps in current research

Despite significant advancements in the development and implementation of hybrid offshore energy systems and control strategies, several challenges explained below, still remain and need to be overcome:

1. **Performance metrics and traditional power plants:** traditional power plants are characterised by their robust performance capabilities such as active/reactive power control, voltage/frequency regulation, short-circuit capabilities, and black start functionality (the ability to restart independently after a shutdown). There is an increasing expectation that high-power wind energy conversion systems (WECS) will mimic these capabilities of conventional power units.
2. **Policy and grid code requirements:** the integration of wind turbines and wind farms into power systems will increasingly require attention to various regulatory and operational standards. Power system operators will need to focus on ensuring wind farms meet stringent requirements for supply security, reliability, and power quality. Consequently, grid codes are

expected to evolve, covering critical aspects such as frequency support, active/reactive power control, short-circuit power levels, voltage variations, flicker, harmonics, and overall system stability. The evolving fault ride-through (FRT) requirements will be particularly influential in shaping the design and operation of high-power wind turbines, particularly in dealing with asymmetrical grid fault conditions. Furthermore, research will be needed to assess WECS performance under various generator-converter configurations and wind farm interconnection methods. Also, while full-scale voltage source converters (VSCs) easily meet FRT requirements, other converter configurations such as current source converters (CSCs) and partial-scale VSCs require further attention in terms of design and operation.

3. Interconnection of onshore and offshore wind farms: currently, most wind turbine connections to the grid are made using parallel AC configurations with HVAC transmission. However, as offshore wind farms expand into the gigawatt range and deeper-sea locations, the challenges related to cost, size, reliability, and efficiency of interconnection methods become increasingly important. Hence, high voltage direct current (HVDC) transmission systems are set to replace HVAC methods due to their technical and economic advantages, particularly for offshore applications, as they eliminate the need for bulky transformers. Also, even though, DC collection systems are still under research, they are expected to play a significant role in future offshore wind projects. Significant advancements in power converter technologies for HVDC applications will also be crucial for this transition.

4. Evolving trends in control theory: control theory has emerged as a crucial field for optimising the performance of modern wind turbines and wind farms. Control systems have also become central to the continued development of wind energy through enabling WECS to achieve optimal operation, enhance energy conversion efficiency, reduce operational costs, extend turbine lifetimes, and minimise downtime.

5. Control of power converters and wind generators: precise control of power converters and generators is essential for maximising the energy extracted from wind. In the WECS, generator-side converters often employ techniques such as vector control or field-oriented control (FOC) for squirrel-cage induction generators (SCIG), DFIG, and PMSG. Generally, these methods/techniques aim to regulate generator currents, torque, flux, and active/reactive power independently. Also, advanced MPPT algorithms, such as optimal tip-speed-ratio control, power signal feedback control, and hill climbing, play a crucial role in maximising wind energy capture. Grid-side converters in type 3 and 4 WECS utilise decoupled VOC or DPC, which regulates active and reactive power through dq-axis grid current regulation. Finite control-set model predictive control (FCS-MPC) has recently emerged as a promising method for controlling power converters and wind energy systems. This approach eliminates the need for traditional linear regulators and modulators. Although FCS-MPC introduces higher computational demands, modern digital signal processors make it cost-effective for large-

scale applications. Further advancements in control techniques, such as model predictive control, H1 control, sliding mode control, and AI-based control, are expected to drive innovation in wind energy systems (Yaramasu et al., 2015b).

6. High capital costs: the initial investment required for offshore hybrid systems, including infrastructure and storage, is considerably higher compared to traditional single-source energy systems. This represents a significant barrier to the widespread adoption of hybrid systems in energy markets.

7. Grid integration challenges: the variability and intermittency of renewable energy sources complicate the seamless integration of hybrid systems into existing grids. To address these challenges, advanced control methods and accurate forecasting techniques are essential for maintaining grid stability and ensuring reliable power delivery.

8. Environmental and regulatory concerns: the deployment of offshore wind and tidal energy systems may pose environmental risks, particularly disruption of marine habitats and ecosystems. Therefore, proper regulatory frameworks balancing the promotion of renewable energy with the protection of the environment will need to be ensured to address these concerns,

9. Complexity in control systems: while advanced control strategies such as FLCs and other novel approaches offer substantial improvements in system performance, their design and implementation can be complex. Thus, further research is needed to simplify such control architectures to ensure that these systems remain efficient, cost-effective, and easy to operate while still achieving optimal performance.

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CHAPTER 3 SUMMARY: CUTTING-EDGE PROGRESS IN OFFSHORE WIND AND TIDAL STREAM POWER TECHNOLOGY – STATE-OF-THE-ART

Chapter three explores methods for advancing offshore wind and tidal stream power technologies, focusing on the latest innovations and their potential to address global energy and environmental challenges. As the demand for clean, sustainable energy intensifies, these marine energy technologies are increasingly recognised for their ability to harness renewable resources from the ocean. However, significant gaps remain in understanding their technological readiness, integration potential, and pathways to overcome existing barriers. This chapter provided a comprehensive review of these cutting-edge advancements, offering insights into the current state of offshore wind and tidal stream power systems. The chapter delves into recent breakthroughs in turbine design, materials, and hybrid systems that integrate both wind and tidal energy. The chapter also presents a detailed analysis of the methodologies employed in recent research, including an extensive synthesis of project reports, industry developments, and academic studies. The review evaluates the progress in turbine efficiency, the scalability of these technologies, and their reliability, highlighting the significant strides made in these areas. Key findings from the research include considerable improvements in turbine performance and the increasing integration of hybrid systems. These systems, which combine wind and tidal energy, offer promising solutions to maximise marine resource utilisation while enhancing energy conversion efficiency and stability. Despite these advancements, this chapter also identifies and elaborates on persistent challenges, such as high capital costs, environmental concerns, and the competition from more established renewable energy sources like solar and onshore wind. The chapter concludes by emphasising the transformative potential of hybrid systems as a way to optimise marine energy production and improve energy supply stability. The findings underscore the need for continued innovation, research, and investment to overcome existing barriers and unlock the full potential of offshore wind and tidal stream power. These insights are crucial for guiding future research directions, informing policy decisions, and shaping investment strategies in the rapidly evolving field of marine renewable energy.

Review

Cutting-edge progress in offshore wind and tidal stream power technology—State-of-the-Art

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Abstract: The growing global demand for clean and sustainable energy has underscored the critical importance of offshore wind and tidal stream power technologies in addressing energy and environmental challenges. While these technologies hold significant potential to harness marine energy resources, gaps remain in understanding their readiness levels, integration potential, and pathways to overcome existing barriers. This study aims to bridge these gaps by providing a comprehensive review of the latest advancements in offshore wind and tidal stream power systems, focusing on innovations in turbine design, materials, and hybrid systems that combine wind and tidal energy. The methodology involves an extensive review and synthesis of recent research, project reports, and industry developments to evaluate the current technological state, challenges, and opportunities. Key findings include notable progress in turbine efficiency and hybrid system integration, which collectively improve energy conversion efficiency, scalability, and reliability. However, the study identifies persistent barriers such as high costs, environmental impact, and competition with more established renewable energy sources like solar and onshore wind. This paper emphasizes the importance of hybrid systems as a transformative approach to maximizing marine resource utilization and enhancing energy supply stability. The findings have significant implications for guiding future research, fostering innovation, and informing investment strategies in the marine renewable energy sector.

Keywords: hybrid wind-tidal energy systems; marine renewable energy; voltage source converter (VSC); tidal power integration

1. Introduction

The growing demand for electricity and the urgent need to reduce carbon emissions have intensified global efforts to develop renewable energy sources. Offshore energy systems, including wind, ocean currents, and wave energy, are key contributors to these efforts [1]. Offshore wind energy, for example, demonstrates 48% greater sustainability than onshore wind, according to life cycle analysis (LCA) [2]. However, the high cost of electricity from offshore wind remains a major obstacle to widespread adoption [3]. Ocean renewable energy (ORE) technologies, such as wave energy, tidal stream energy, and ocean flow energy, are gaining attention as viable additions to the renewable energy mix [4]. Emerging technologies such as salinity gradient engines and ocean thermal energy conversion (OTEC) also show promise [5]. Tidal energy stands out for its predictability and significant potential, with an estimated global capacity of 3000 GW, including 1000 GW in shallow waters. By 2021, Europe had installed 30.2 MW of tidal stream systems, indicating growing feasibility and scalability [6].

Although less advanced than offshore wind or wave energy, tidal stream systems have the potential to produce around 20 TWh per year [7]. Nevertheless, tidal stream and offshore wind systems have not yet reached full economic viability. At £140/MWh for offshore wind and £305/MWh for tidal stream energy, electricity strike costs are still expensive [8]. The UK, with its vast tidal energy resources, could generate over 4 TWh annually using current technology, with future projections reaching 94 TWh per year and an installed capacity of 36 GW [9,10].

Ocean energy (OE), or “Blue Energy”, encompasses power derived from waves, currents, thermal gradients, and salinity gradients [11]. Among these, offshore wind energy is the most advanced and commercially viable. It is considered the most promising marine renewable energy (MRE) category for large-scale maritime applications. Tidal current energy converters (TCECs), including horizontal-axis turbines, vertical-axis turbines, and oscillating hydrofoils, have seen advancements in blade design, control strategies, array configurations, and environmental impact studies [7,12].

The technology readiness level (TRL) of tidal energy has progressed from laboratory-scale development to the pre-commercial stage [13]. Offshore energy systems include current turbines, wave energy converters, tidal stream generators, and offshore wind turbines, with tidal stream energy being more predictable due to less variability over extended periods. These systems are crucial for maritime electrification and military operations, though research has often focused on specific applications rather than holistic integration [14].

Combining multiple renewable energy sources with storage creates a reliable, eco-friendly, cost-effective energy solution. The integration of wind and tidal energy, in particular, presents a significant opportunity, but this requires collaborative research efforts to develop efficient and reliable systems [15,16]. This paper reviews recent advancements in offshore wind and tidal stream technologies, focusing on innovations that improve energy efficiency, scalability, and reliability. It also highlights ongoing challenges, such as cost competitiveness, and discusses future trends that could drive a wider adoption of these renewable energy solutions.

Section 2 provides an overview of energy policies and underscores the importance of electrical generators as key components of ocean energy converters. Section 3 examines four configurations of low-voltage (LV) converters commonly used in marine energy systems. Section 4 focuses on using synchronous generators in tidal current energy converters (TCECs) and classifies marine current turbines based on their interaction with water motion, noting areas where categories overlap.

Section 5 concludes by exploring hybrid configurations that combine offshore wind and tidal stream technologies. These configurations have the potential to maximize resource utilization and address energy supply challenges. This review aims to help researchers, policymakers, and industry stakeholders better understand the current state and future potential of offshore renewable energy systems. Unlike previous studies that focus on offshore wind or tidal energy individually, this review highlights the integration of hybrid systems that combine these technologies. It examines how the synergy between wind and tidal power can optimize resource use, enhance energy stability, and tackle cost and environmental challenges. By focusing on these hybrid solutions, the study provides practical insights to drive the transition to more sustainable offshore energy systems.

2. Electrical generators are crucial components in ocean energy converters

2.1. Introduction

The European Green Deal prioritizes energy transition to achieve climate neutrality by 2050, while also addressing biodiversity loss and pollution. To meet energy and climate goals, the EU has set 2030 targets to boost renewable energy use [11].

The vast potential of oceanic energy resources has long been overlooked. However, a significant shift is occurring. There is now a growing focus on harnessing eco-friendly energy from the ocean, marking an important development in the energy sector [15,16]. This shift is driven by the belief that wind and tidal energy could significantly contribute to meeting global electricity demands [17]. Astonishingly, the combined energy from wind and tides exceeds current global energy consumption by a factor of 300. However, despite this immense capacity, these resources have remained largely unused, as shown in Figure 1 [18]. This work explores tidal stream energy fundamentals and turbine classifications [19]. However, the current state of marine energy has not yet met the criteria outlined in the Sustainable Development Scenario (SDS), which mandates an annual growth rate of 23% until 2030. On the other hand, countries such as Canada, the UK, China, and Australia have advanced marine energy projects from 10 kW to 1 MW (IEA 2020b) [19].

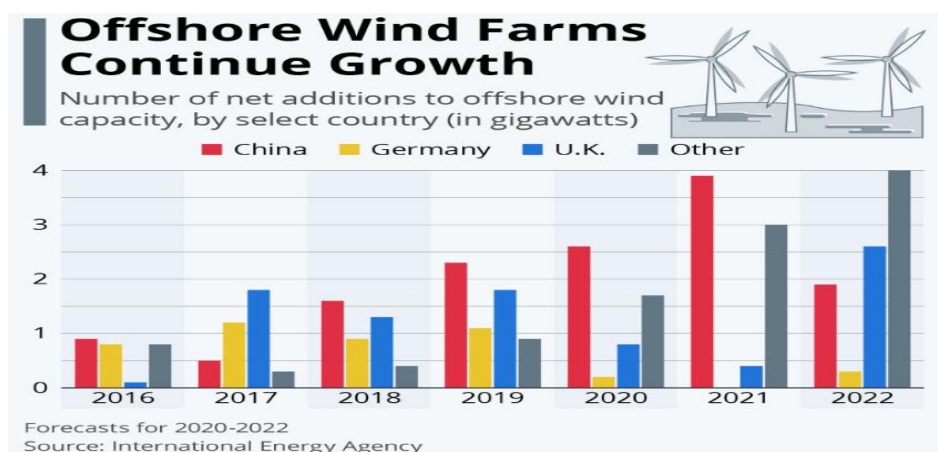


Figure 1. Cumulative global capacity of offshore energy from 2016 to 2022 [20].

Renewable marine energies include wind, wave, tidal, and ocean currents and innovative approaches like ocean thermal energy conversion (OTEC) and osmotic power, which harness energy from temperature variations and salinity gradients, respectively [18]. Evidence of wind energy's expansion manifests in installed capacity statistics. China leads the pack, boasting a substantial 237 GW of wind power, closely trailed by the US with approximately 105 GW [21]. Europe remarkable progress, with installed capacity soaring from 1.48 GW in 2008 to a formidable 25 GW in 2020. Offshore renewable energy (ORE) is a type of renewable energy that can be harnessed from various sources, including wind (both bottom-fixed and floating), ocean energy (tidal and wave), and floating solar technologies. These technologies are currently at different stages of development (see Figure 2) [21].

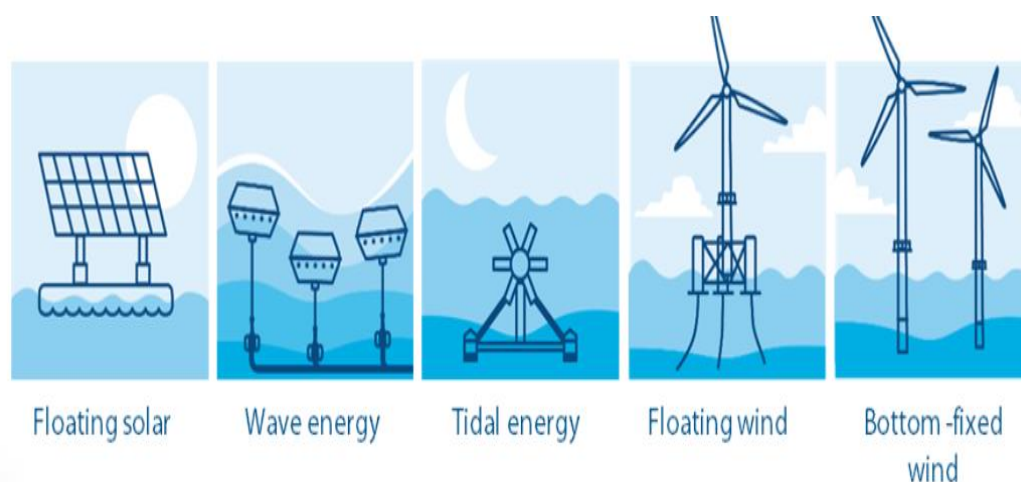


Figure 2. Overview of ORE technologies [18].

2.2. Comparisons between onshore and offshore power systems

The term *offshore*, particularly in the context of tidal stream power, has multiple interpretations that need clarification in this review [22].

As defined by the International Convention for the Safety of Life at Sea, offshore includes internal waters, territorial seas, contiguous zones, exclusive economic zones, and international waters. For this review, offshore power systems (OffPS) are defined as systems located in water, submerged beneath saline layers, or positioned deep within the subsea. While some principles might apply to freshwater environments like rivers and lakes, the focus remains on marine, subsea, deep-sea, offshore islands, and maritime environments [23].

Although OffPS shares some similarities with land-based power systems, they encounter unique technical challenges and risks. Figure 3 illustrates the key factors that shape the distinct resilience and reliability of offshore power system components. Offshore systems, especially those on floating platforms, must withstand oscillations from waves, exposure to moisture, and the corrosive effects of saline water [24]. Onshore high-voltage transmission towers are unsuitable for these conditions due to the harshness of the deep-sea environment. Additionally, subsea cable installation differs significantly from that of overhead land-based cables, with the added benefit that subsea lines are immune to lightning strikes. Consequently, the interaction between the subsea ecosystem and offshore power systems differs substantially from onshore systems [25].

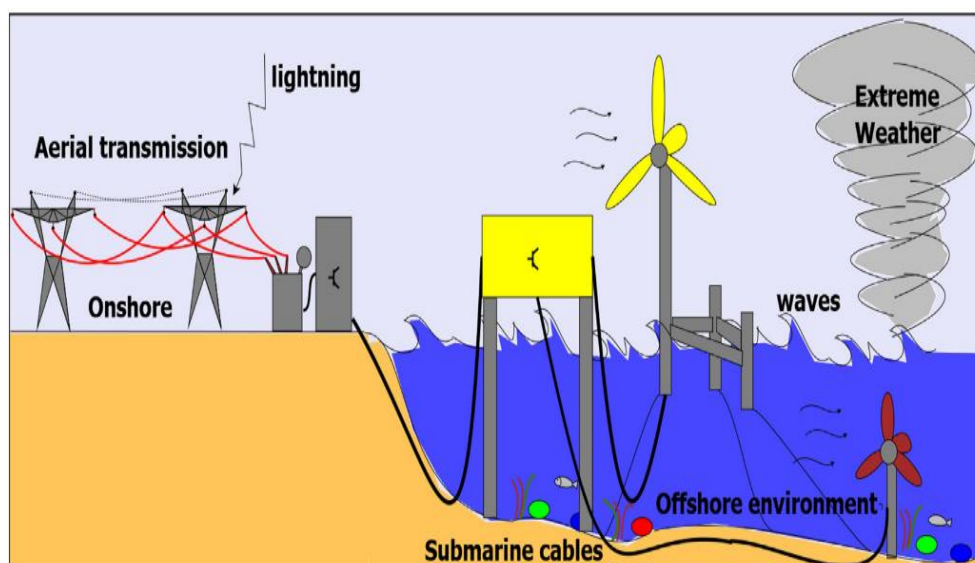


Figure 3. Contrasts between onshore and offshore power systems in terms of transmission [26].

2.2.1. Generalized offshore power system architecture

A comprehensive offshore power system (OffPS) framework integrates several interconnected subsystems at sea, as shown in Figure 4. These subsystems include power generation, transmission, distribution, consumption, energy storage, intelligence, and environmental considerations [11]. The generalized architecture in Figure 4 serves as a reference for this research, organizing OffPS into seven key components: power generation, transmission, distribution, consumption, energy storage, offshore intelligence, and environmental factors. Each plays a crucial role in managing the flow of electricity—from production to transmission, storage, and conversion [27]. Beyond wind power, tidal stream energy is increasingly vital to OffPS, particularly in areas with strong tidal currents. Notable examples include the Pentland Firth in Scotland and South Africa's Agulhas Current along the Western Cape. These locations benefit from predictable and reliable tidal cycles, offering a consistent energy source that complements the variability of wind and tidal power [28]. This creates a more balanced and resilient renewable energy mix. Energy storage has gained prominence as it mitigates the intermittency of wind and tidal energy sources [24]. Larger wind turbines also help by capturing more energy, reducing overall installation and maintenance costs compared to smaller units. Wind turbines are typically installed across vast areas, forming wind farms connected to national grids. These farms can be located onshore or offshore, though offshore installations often involve higher initial and maintenance costs due to the need for robust foundations and submarine cables. Similarly, offshore tidal turbines face challenges from underwater currents and corrosive seawater, requiring durable construction [29]. While onshore wind farms are more accessible and cost-effective, offshore wind and tidal farms demand advanced transmission technologies. These include series/parallel AC/DC configurations as well as high-voltage AC (HVAC) and high-voltage DC (HVDC) systems, essential for connecting offshore systems to the grid. However, the rapid integration of wind and tidal energy into electrical grids raises concerns about stability, security, and efficiency. As a result, many countries have updated grid codes to govern the connection of large-scale renewable energy projects [30].

The offshore intelligence subsystem plays a critical role in managing, maintaining, and automating OffPS by processing data from all other subsystems, ensuring smooth operations and reliability [18]. The environmental subsystem interacts with natural forces such as weather, hurricanes, tsunamis, and powerful tidal currents, as well as artificial elements like vibration-isolation systems and submarine hulls that protect against deep-sea pressures. These structures also serve as ground terminals and voltage references for OffPS grounding systems [31]. Internal interactions within OffPS form a complex network of data and power connections. Figure 4 illustrates these interactions, with dashed lines representing data flows and solid lines indicating power connections [32]. This conceptual network does not correspond directly to physical systems but provides a broad depiction of how offshore systems function, incorporating the diverse capabilities of wind and tidal energy installations in locations like the Pentland Firth and the Agulhas Current [33].

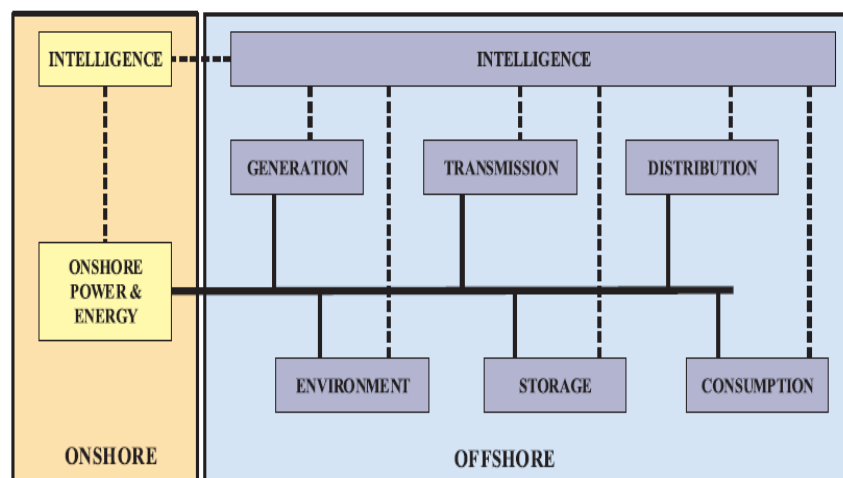


Figure 4. Overall structure of an offshore power system and its various interconnections depicted in the generalized architecture [24].

The following sections delve into an exhaustive exploration of each subsystem in finer detail. Offshore power generation involves the conversion of energy sources into electricity exclusively within the offshore environment [24]. While several energy sources, such as solar, wind, and fossil fuels, exist in both onshore and offshore contexts, some are unique to the oceans, such as waves and tides [34]. These offshore power generation systems are categorized based on their energy source and can include connections to auxiliary systems such as subsea structures and platforms. In this context, these external systems are considered part of the offshore environment, distinct from the primary power generation, transmission, distribution, consumption, energy storage, and intelligence processes [35].

2.3. Overview of offshore technology in development

The development of offshore renewable energy technologies has primarily focused on designing efficient energy conversion systems to harness the kinetic energy of natural resources like wind and tidal currents, which turn the rotor to drive the generator, transforming tidal kinetic energy into electrical power. Unlike wind turbines, tidal systems must contend with the unique challenges of

underwater environments, such as water density resistance and marine corrosion [26]. However, the predictability of tidal cycles provides a stable and reliable energy source, making tidal energy a valuable component of the renewable energy landscape [36]. The following section explores the components and design considerations involved in the power conversion chain for tidal current energy systems.

2.3.1. Power conversion chain design for tidal current energy systems

Tidal stream turbine systems share similarities with wind turbines in both design and operation, allowing for effective comparisons in reliability assessment and drivetrain configurations. Although comprehensive data on tidal stream turbine failures are scarce, the available documented cases provide valuable insights into performance challenges [3]. These turbines are typically classified as either vertical-axis or horizontal-axis, with the latter being more common in tidal energy applications [6].

A horizontal-axis tidal stream turbine consists of key components, including rotor blades, a drivetrain, and a generator. The turbine captures the kinetic energy of tidal currents through its rotor blades, converting the water's momentum into mechanical energy [6]. This mechanical energy is then transferred via the drivetrain to the generator, where it is transformed into electrical power. The energy transfer may occur directly through a direct-drive system or via a gearbox that adjusts rotational speed for optimal power conversion [37].

The tidal current energy conversion (TCEC) system is a sophisticated assembly designed to convert tidal currents into electrical power. This system typically includes a turbine, a pitch control system, and an advanced drivetrain. The drivetrain system, as shown in Figure 5, contains components like the main drive shaft, bearings, gearbox, coupling, brake, and generator, all of which are crucial for efficient energy conversion [37].

A key factor to consider is the density of water, which is approximately 800 times greater than air, making tidal energy systems operate under unique conditions. These systems are generally optimized for flow speeds of approximately 3 m/s, which is the velocity at which the system reaches maximum power output [38]. The design of the turbine blades and pitch control must be tailored to the specific site conditions, including tidal speeds exceeding 2.25 m/s and water depths between 25 and 50 m. For efficient power generation, turbines require large swept areas and strong tidal currents, which are relatively rare and typically found in specific geographic features like narrow straits [38].

Key control mechanisms in tidal energy conversion systems include:

- Blade pitch control: Adjusting the blade pitch allows for precise regulation of power capture and mechanical loads. Hydraulic actuators or servo pitch motors facilitate these adjustments, enabling the turbine to adapt to changing tidal conditions.
- Generator torque control: Managing the generator torque is critical for optimizing the conversion of mechanical energy into electricity, allowing for efficient power generation.
- Yaw control: While more commonly used in wind turbines, yaw control systems in tidal turbines may help align the rotor with tidal currents, enhancing energy capture and overall system efficiency [26].

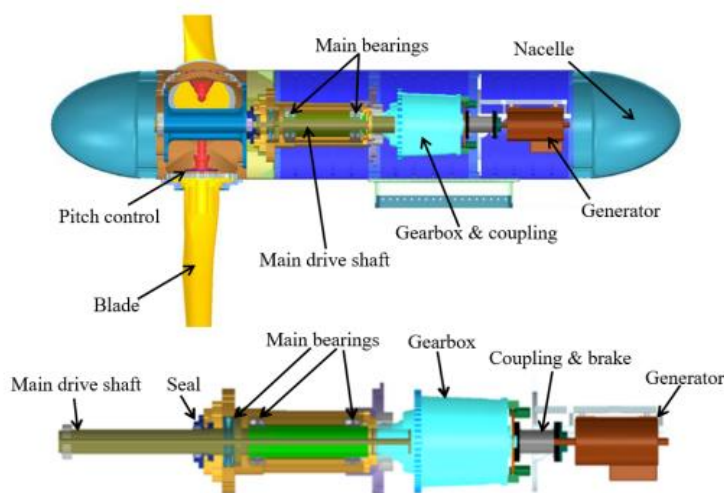


Figure 5. Power conversion chain of TCEC [39].

Gearbox failures have long been a significant challenge in the energy sector, leading to substantial downtime and repair costs [40]. Although much of the focus has been on wind turbines, tidal stream turbines encounter similar issues related to gearbox reliability [23,41]. Gearbox components are standardized, accessible, and cost-effective, yet they are pivotal to the efficient operation of tidal energy systems. Gearboxes, based on mature technology, are widely used across various sectors, including transportation and manufacturing. These components are essential and typically exhibit a higher mean time to repair (MTTR) compared to other subsystems [41]. The extensive theoretical and practical knowledge available for geared systems offers valuable insights for designing geared tidal turbines. By integrating advancements in gearbox design, condition monitoring, and maintenance practices, it is possible to significantly improve the reliability of tidal stream systems and mitigate potential failures [42]. Optimizing tidal stream energy systems requires leveraging these advancements in gearbox technology and maintenance strategies. Such improvements will enhance system performance and reduce downtime, thereby increasing the overall efficiency and reliability of tidal current energy systems [43].

At the core of the power conversion process lies the mechanical transmission system, which facilitates the transfer of kinetic energy from the tidal current to the generator. The design and configuration of this system directly impact the efficiency and reliability of tidal energy conversion. The next section delves into the key role of mechanical transmission, including gearbox designs and alternatives such as direct-drive systems, which are increasingly favored in offshore applications.

2.3.2. Mechanical transmission

In tidal stream energy systems, the gearbox is a crucial component of the mechanical transmission system. Tidal stream turbines typically operate at low rotor speeds due to the slow movement of tidal currents [44]. To convert this low-speed rotational energy into higher speeds required for electricity generation, a gearbox is used. The gearbox increases the rotor's speed from the low revolutions per minute (rpms) generated by the tidal currents to the higher rpms needed by the generator [45]. In some tidal stream systems, particularly those utilizing multi-pole synchronous generators connected to the

grid via a power converter, the gearbox may be omitted. These generators are capable of operating efficiently at lower speeds, making a gearless design feasible. This approach is particularly beneficial for offshore applications, where minimizing maintenance is essential due to the challenging environment [46]. By eliminating the gearbox, the system reduces mechanical complexity and maintenance requirements [47]. For tidal turbines with smaller rotor diameters, gearboxes may also be unnecessary. Smaller rotors can achieve higher rotational speeds given the tidal currents, which may directly match the generator's requirements. This enables the use of a direct-drive system, simplifying the mechanical design and reducing maintenance needs. Direct-drive tidal stream turbines are increasingly used in standalone DC applications and battery charging systems [48].

The nacelle houses all critical equipment for the tidal turbine, including the drivetrain components (rotor shaft, gearbox, and bearings), electrical generator, power electronics, and control systems. It connects to the support structure via bearings, allowing for rotation to maintain optimal alignment with the tidal currents. The strategic placement of the drivetrain and associated components within the nacelle ensures efficient operation and facilitates maintenance [49].

2.3.3. Hydrodynamic model and maximum power extraction

Tidal stream turbines (TSTs) harness energy from tidal currents, which are driven primarily by the gravitational forces of the moon and sun. Unlike wind, tidal currents are more consistent and predictable. To understand energy extraction from tidal streams, consider the flow of water through the rotor disk, which represents the swept area of the turbine [34]. The mass flow rate of water ($\frac{dm}{dt}$) through the rotor disk is dependent on the water density [ρ] and the flow velocity U [m/s]. For a uniform flow velocity across the rotor's swept area (A), the mass flow rate is given by [44]:

$$\frac{dm}{dt} = \rho \cdot A \cdot U \quad (1)$$

The instantaneous kinetic power available from the tidal stream is calculated using:

$$P = \frac{1}{2} \rho \cdot A \cdot V_{\text{flow}}^3 \quad (2)$$

where V_{flow} is the free stream velocity of the tidal current. TSTs cannot extract all the available power due to the need for some residual flow behind the rotor. The theoretical maximum for power extraction is governed by the Betz limit [50].

The primary objective of TSTs is to maximize power extraction from tidal streams. The power delivered to the rotor and the torque developed can be expressed as follows:

$$P = T\omega \quad (3)$$

where ω represents the angular velocity of the turbine and T is the torque on the shaft. The angular velocity can be determined by:

$$\lambda = \frac{\omega r}{V} \quad (4)$$

where r is the turbine radius, λ is the tip-speed ratio, and V_{flow} is the stream velocity. The torque on

the turbine shaft is given by:

$$T = \frac{1}{2} \rho C_T C V_{rel}^3 \quad (5)$$

where C is the blade chord length, V_{rel} is the relative velocity, and C_T is the torque coefficient [34]. Operating the turbine at variable speeds allows for optimal power extraction across a range of tidal flow speeds [49]. Figure 6 shows the characteristic curve for optimal power extraction and illustrates how the turbine's performance aligns with varying tidal flow speeds [51].

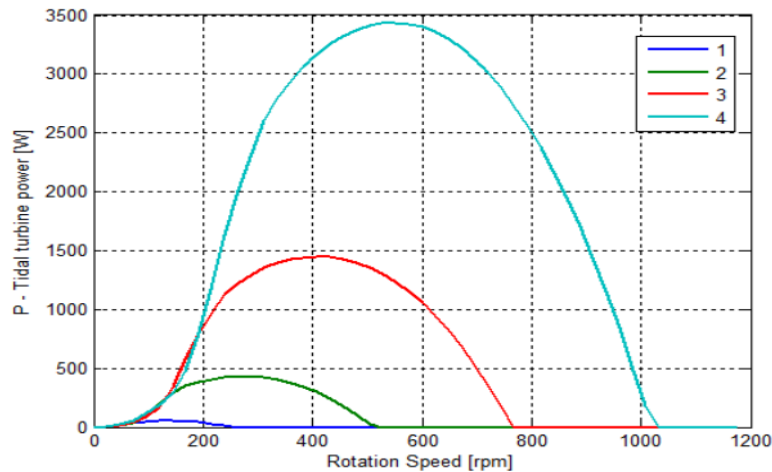


Figure 6. Power characteristics of tidal turbine [49].

The next section presents a hydrodynamic model and discusses strategies for maximizing power extraction from tidal currents.

2.3.4. Tidal stream turbines and offshore variable-speed wind turbines

The recent development of larger tidal stream system turbines has led to a shift from fixed-speed to variable-speed operation. This shift addresses grid code requirements and reduces mechanical loads [50]. Figures 11 and 12 present configurations employing a permanent magnet synchronous generator (PMSG) and a full power converter (FPC), relevant to TSTs [41,52]. By routing all turbine power through converters, the dynamic operation of the PMSG is decoupled from grid frequency variations, ensuring stable grid operation despite fluctuations in tidal stream speed [53]. While the hydrodynamic model focuses on maximizing power extraction from tidal currents, integrating this energy into the grid requires additional components, such as voltage transformers. These transformers ensure that the power output meets the required voltage levels for safe and efficient transmission. The next section examines the role of voltage transformers in tidal energy systems and their significance in grid integration.

2.4. Voltage transformer

The voltage transformer adjusts the turbine's internal voltage, typically between 690 and 1000 V, to match the collector grid voltage, commonly rated at 33 or 36 kV. This transformation incurs power losses that are converted into heat, necessitating dissipation via the cooling system [53]. Many tidal stream turbine systems neglect to fully account for these transformer losses in their control and management systems. Recent developments show that newer and larger turbines are incorporating advanced controllers to mitigate these losses [41,52]. While the voltage transformer plays a critical role in adjusting turbine output to match grid voltage, ensuring optimal energy capture and conversion requires additional subsystems for efficient turbine operation. Among these, the yaw drive is essential for maintaining the turbine's alignment with changing tidal or wind directions, thereby maximizing energy generation. The following section explores the functionality and importance of yaw drive systems in renewable energy technologies.

2.4.1. Yaw drive

The yaw drive is vital in modern horizontal-axis wind turbine yaw systems. It actively adjusts to keep the rotor aligned with changing wind directions, optimizing energy production. A wind vane measures wind direction at the nacelle's rear [53]. Yaw angle errors lead to reduced energy capture, with power losses proportional to the cosine of the yaw error [53,54]. In addition to optimizing turbine alignment, safety mechanisms like the mechanical brake are integral to the reliable operation of tidal stream turbines, especially during emergencies or maintenance. This section examines the mechanical brake's role in ensuring system stability and safety.

2.4.2. Mechanical brake

The mechanical brake is crucial in tidal stream turbines, serving as an emergency backup if other braking systems fail. Positioned between the gearbox and the generator, it also prevents unexpected turbine activation during maintenance. The mechanical brake engages after other braking methods have reduced the turbine speed, minimizing wear [52]. The following section discusses advancements in power electronic converters and their critical role in tidal energy systems.

2.4.3. Power electronic converter

Advancements in power electronics have significantly enhanced the operation of renewable energy [52]. Power electronic converters are essential for interfacing tidal stream and wind turbines with the grid. As tidal turbines operate at variable speeds, their generator's electrical frequency fluctuates, requiring decoupling from the grid frequency via these converters [51]. This decoupling enables turbines to operate efficiently across varying speeds, enhancing power capture compared to fixed-speed models. Common configurations include gear-coupled double-fed induction generators (DFIGs), where power electronics manage rotor voltage and frequency, or direct-coupled synchronous generators (SGs), with power electronics controlling stator voltage and frequency. Both configurations may use brushless field excitation or permanent magnet excitation [47].

Effective variable-speed operation requires a control system tailored to the specific tidal stream turbine, ensuring maximum power extraction while maintaining stable grid voltage and frequency [54]. As switching frequencies increase to develop more compact and efficient equipment, emissions in the 2–150 kHz frequency spectrum, known as super harmonics, become more pronounced [55]. Key power converters include inverters, rectifiers, DC/DC converters, and DC/AC inverters [56]. Building on the advancements in power electronic converters, integrating these systems into variable-speed turbine configurations has significantly enhanced the efficiency and flexibility of energy systems. The direct-in-line variable-speed turbine with a full-scale power converter represents one such innovative design, addressing key challenges associated with fixed-speed systems. The next section examines the advantages and trade-offs of this configuration in detail.

2.4.4. Direct-in-line variable speed wind turbine with full-scale power converter

In fixed-speed systems, the generator connects directly to the grid (see Figure 9), maintaining a steady rotor rotation determined by grid frequency, gear ratio, and generator pole pairs [16]. Fixed-speed configurations are generally straightforward, reliable, require less maintenance, and are cost-effective [57]. However, they present several drawbacks:

- Limited energy capture: Power extraction depends on the rotational speed of the prime mover and environmental conditions. Variable-speed solutions can improve efficiency by 5%–20% across varying conditions.
- Mechanical stress: Fixed speeds cause torque pulsations, leading to mechanical strain. Systems using squirrel-cage induction generators experience less mechanical stress due to slip compliance during transients.
- Power quality: Mechanical power fluctuations affect both the drive train and the grid, leading to degraded power quality. Fixed-speed systems, particularly those with low-inertia drive trains, can generate noticeable electrical power fluctuations.
- Reactive energy compensation: Squirrel-cage induction generators consume reactive energy, often requiring additional compensation components.

Converters, which serve as interfaces between the load/generator and the grid, are crucial for ensuring reliability, efficiency, and cost-effectiveness. They consist of power electronic devices, driving circuits, protection systems, and control circuits [58].

Currently, two main types of converters are used: grid-commutated and self-commutated converters [59]. Grid-commutated converters, which use thyristors and multiple pulses, generate integer harmonics but lack reactive power control [60]. Variable-speed solutions offer several advantages over fixed-speed systems:

- Decoupling: Power electronics decouple the grid from the generator.
- Enhanced power take-off: Improved alignment between the resource and prime mover speed enhances power take-off.
- Energy storage: The rotor and drive train can act as a flywheel, storing or delivering energy and reducing power fluctuations.
- Reduced stress mechanical stress: Variable-speed systems reduce mechanical stress due to inherent mechanical compliance.
- Full power control: Both active and reactive power can be controlled.

However, variable-speed solutions entail higher costs due to power electronics. Common configurations include fully controllable back-to-back converters in either a double-fed induction generator setup or a full-converter configuration [61]. In the DFIG arrangement shown in Figure 7, the rotor winding connects to the grid via a bidirectional power converter, which typically comprises 30%–40% of the rated power. This configuration enables variable-speed operation and control over active and reactive power within specific limits but requires slip rings, increasing maintenance needs [62].

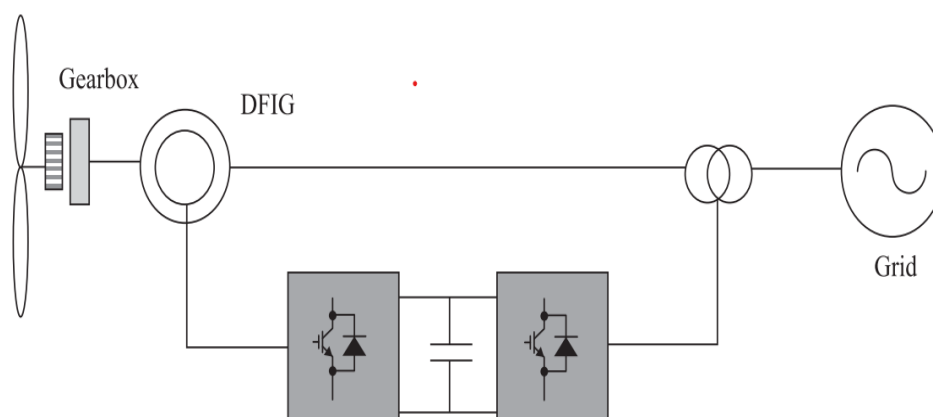


Figure 7. DFIG topology.

Power converters are critical components in tidal stream energy systems, acting as interfaces between the generator and the grid to manage bidirectional power flow [49]. Key considerations for these converters include reliability, efficiency, and cost. They consist of power electronic devices, drive systems, protection circuits, and control mechanisms [59]. The primary converter types used are grid-commutated and self-commutated converters. Grid-commutated converters, utilizing thyristors, produce integer harmonics and lack reactive power control capabilities [61].

Variable-speed systems present several advantages over fixed-speed configurations in tidal stream turbines:

- **Grid decoupling:** Power electronics enable the decoupling of the generator from the grid, providing greater operational flexibility.
- **Enhanced power take-off (PTO):** By aligning turbine speed with tidal flow conditions, power extraction is optimized.
- **Energy storage:** The rotor and drive train can act as a flywheel, storing or delivering energy to mitigate power fluctuations.
- **Reduced mechanical stress:** Variable-speed operation reduces mechanical stress due to the inherent mechanical compliance of the system.
- **Comprehensive power control:** Both active and reactive power can be precisely managed.

Presently, the most common configurations involve employing a fully controllable back-to-back converter, either within a double-fed induction generator setup (refer to Figure 8) or in a full-converter configuration (refer to Figure 9) [61]. Despite these benefits, variable-speed systems incur higher costs due to the advanced power electronics required. Common configurations involve fully controllable back-to-back converters, either in a double-fed induction generator (DFIG) setup or a full-converter

arrangement [63]. In the DFIG configuration, the rotor winding connects to the grid via a bidirectional power converter, typically accounting for 30%–40% of the rated power. This setup facilitates variable-speed operation and enables control over both active and reactive power within specified limits. However, the requirement for slip rings in this arrangement can increase maintenance demands [62].

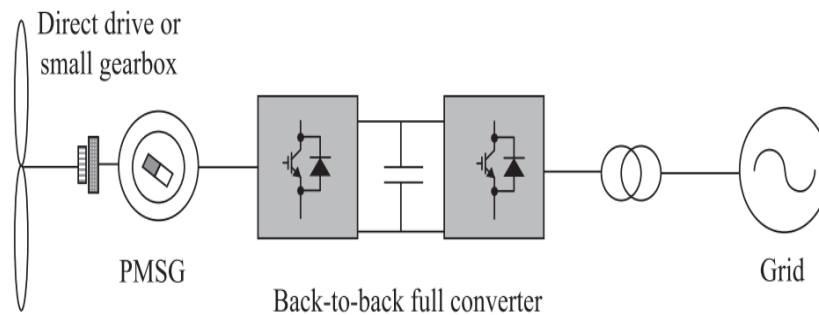


Figure 8. Full converter topology.

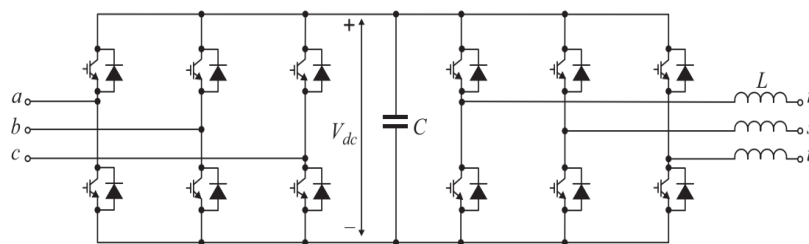


Figure 9. Back-to-back converter.

Power converters are fundamental to the operation of both variable-speed and fixed-speed tidal turbines, acting as interfaces between the generator and the grid. They ensure bidirectional power flow, maintain grid stability, and enable precise control of active and reactive power. In the next chapter, we delve deeper into the design, types, and functionality of converters used in tidal stream energy systems, highlighting their role in improving efficiency and reliability.

3. Converters

This section examines four LV converter configurations, each tailored to specific tidal stream turbine grid connections, typically utilizing standard voltages of 690 and 575 V. Power converters are essential components in tidal stream energy systems, serving as interfaces between the generator and the grid. They enable efficient power conversion, regulate energy flow, and support grid stability in variable operating conditions. The following subsections detail the key converter configurations employed in tidal stream turbines, beginning with the widely adopted full-scale back-to-back two-level voltage source converters (BTB 2L-VSCs).

3.1. Full-scale BTB 2L-VSCs

Figure 10 illustrates a typical Type 4 tidal conversion system (TCS) using full-scale back-to-back (BTB) two-level voltage source converters (2L-VSCs) [63]. These consist of a voltage source rectifier (VSR) and a voltage source inverter (VSI), connected by a DC-link capacitor [64]. Both the VSR and VSI are realized through low-voltage insulated gate bipolar transistors (LV-IGBTs), arranged in a matrix configuration. The DC-link unit, consisting of capacitors arranged in series or parallel, achieves the required voltage and capacitance. This link decouples the generator from the grid, preventing generator transients from impacting grid stability [65].

This mature converter topology is used in approximately 90% of Type 4 tidal stream turbines rated below 0.75 MW and supports a range of tidal stream generators like permanent magnet synchronous generators (PMSG), wound rotor synchronous generators (WRSG), and squirrel cage induction generators (SCIG). The converter's power rating is typically matched to the generator output, so a 0.75 MW generator connects to a 0.75 MW converter. The VSR controls the generator's torque and speed, while the VSI manages the DC-bus voltage and grid reactive power [66].

To minimize switching losses and enhance power density, the VSR and VSI operate with a switching frequency between 1 and 3 kHz. LCL filters are used on the grid side to reduce harmonic distortion in grid currents [67]. Although not shown, generator-side harmonic filters are also required [68]. The entire converter system—filters, rectifiers, DC-link, and inverters—is housed in a cabinet located in the turbine nacelle [69]. After filtering, the AC output is transmitted through cables to a step-up transformer at the tower's base. These low-voltage, high-current AC cables, though costly and prone to transmission losses, benefit from mass production, reducing overall expenses [70].

An example of a widely used commercial converter module is Semikron's SKiiP, known for its compact design and high power density [71]. It integrates heat sinks, semiconductor switches, and gate drivers into a single unit. While full-scale BTB converters are commonly used in small-scale tidal systems for their simplicity and effectiveness, larger systems often employ partial-scale converters to reduce costs and improve flexibility. The next section explores partial-scale BTB 2L-VSC configurations, which are specifically designed for semi-variable speed tidal systems [72].

3.2. Partial-Scale BTB 2L-VSCs

Figure 11 shows a Type 3 tidal conversion system that uses BTB converters in semi-variable speed tidal systems [73]. In this configuration, the stator is directly connected to the grid, while the rotor is linked to the power converter [74]. The converter's power rating is typically around 30% of the generator's total capacity. For example, a 2.5 MW doubly-fed induction generator (DFIG) would use a 0.75 MW converter [75]. The full-scale and partial-scale converters regulate active and reactive power, control DC-link voltage, and maintain grid power factor [76].

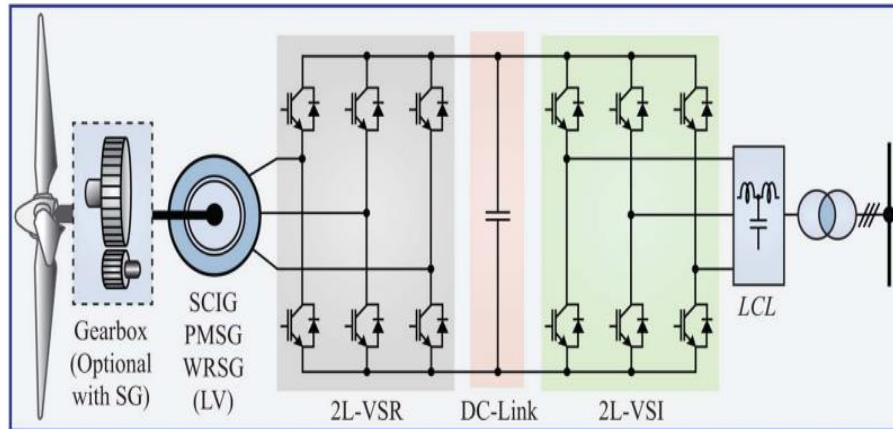


Figure 10. Type 4 TCS with two-level BTB voltage source converters (mainstream commercial power converter configuration) [63].

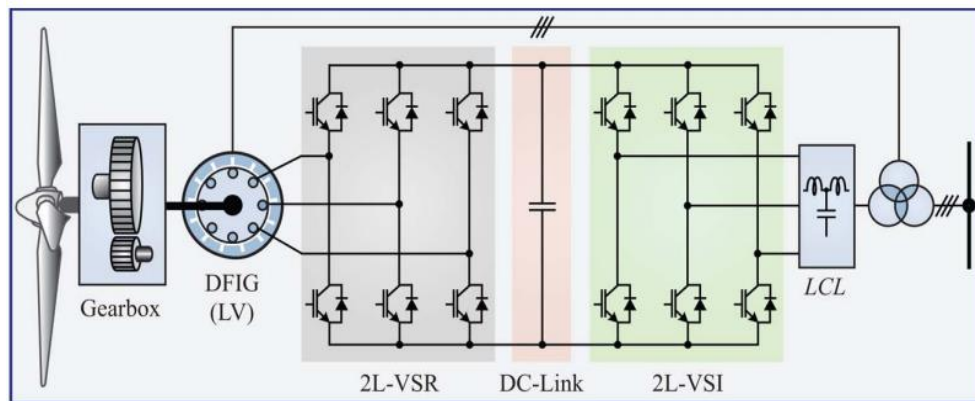


Figure 11. Type 3 TCS with two-level BTB voltage source converters [63].

As the power demands of tidal stream turbines increase, more advanced converter configurations are required. Parallel BTB VSC systems with a common DC-link provide a scalable solution for turbines with power ratings exceeding 0.75 MW.

3.3. Parallel BTB 2L-VSCs with common DC-link

For larger tidal turbines with power ratings above 0.75 MW, multiple BTB VSC modules can be connected in parallel, accompanied by harmonic filters, as shown in Figures 12 and 13 [77]. In the case of Type 3 and Type 4 turbines, connecting VSC modules in parallel increases the current-carrying capacity [78]. This parallel configuration allows for power ratings of 1.5 MW for Type 4 turbines and up to 5 MW for Type 3 turbines [79]. A common DC-link across the converters helps reduce costs and space requirements [80].

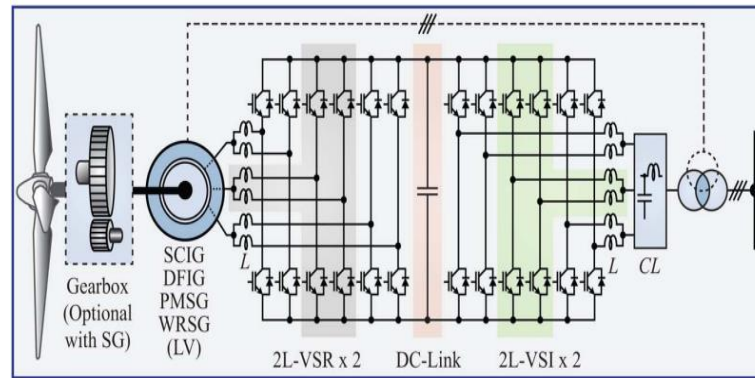


Figure 12. Type 3 and 4 TCS with parallel connected BTB 2L-VSCs and common dc-link [81].

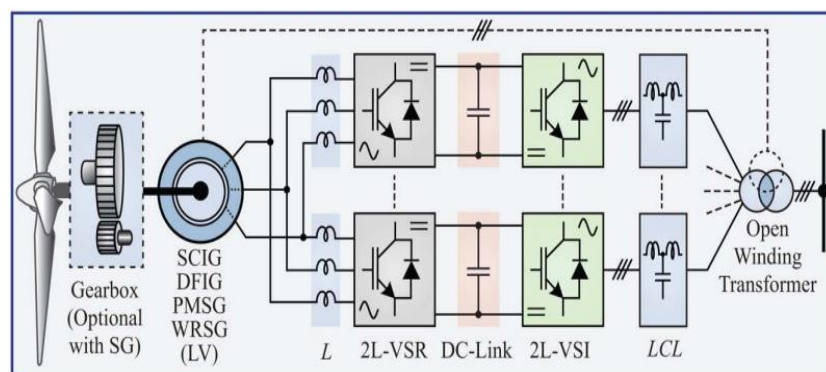


Figure 13. Type 3 and 4 TCS with parallel connected BTB 2L-VSCs, individual DC-links, and open winding transformer [81].

Self-commutated converters, which use pulse width modulation (PWM) and IGBTs, control both active and reactive power [82]. While PWM converters can meet reactive power demands, high-frequency switching generates harmonics, necessitating harmonic filters on both generator- and grid-side converters [83]. Generator-side harmonic filters reduce distortion in the generator's current, thus minimizing magnetic core and winding losses [84]. Grid-side filters ensure compliance with grid harmonic standards [85].

Finally, the grid-side harmonic filter output connects to a three-phase grid via a step-up transformer, switchgear, and circuit breaker [86]. In some cases, the converter can operate at collection point voltage levels, eliminating the need for a step-up transformer [87]. Efficient energy transfer from tidal stream turbines to the grid depends not only on converter technology but also on the grid connection layout. Properly designed grid connections ensure reliable transmission of energy over long distances while maintaining power quality and stability. The next section discusses grid connection layouts and their critical components, such as transformers, AC filters, and DC cables [88].

3.4. Definition of grid connection layout

In modern tidal stream energy systems, two primary transmission approaches are utilized for long-distance power transfer: a) AC collection-AC transmission and b) AC collection-DC transmission, as

shown in Figure 13 [16]. The most used method is high-voltage alternating current (HVAC) transmission, depicted in Figure 14(a). HVAC is widely adopted due to its straightforward design and well-established technology. Typically, the generated voltage in tidal stream turbines is around 700 V, which is then stepped up to medium voltage levels such as 33 kV or, in specific cases, 66 kV, to facilitate transmission [17].

To handle over-voltage and charging current issues in subsea cables, shunt reactors are employed for power compensation. This ensures improved transmission capacity and efficiency, enabling smooth and reliable transfer of energy from offshore tidal systems to onshore grids [89].

3.4.1. Transformers and phase reactors

In tidal stream energy systems, a trio of single-phase transformers is employed to match the AC bus voltage with the input requirements of the power converter [89]. These transformers are equipped with tap changers for precise voltage control, enabling adjustments as needed. The design simplicity is attributed to the reduced harmonic content inherent in voltage source converter (VSC) high-voltage direct current (HVDC) systems [90]. This lower harmonic distortion eliminates the need for complex filtering solutions, leading to a more straightforward transformer configuration [91].

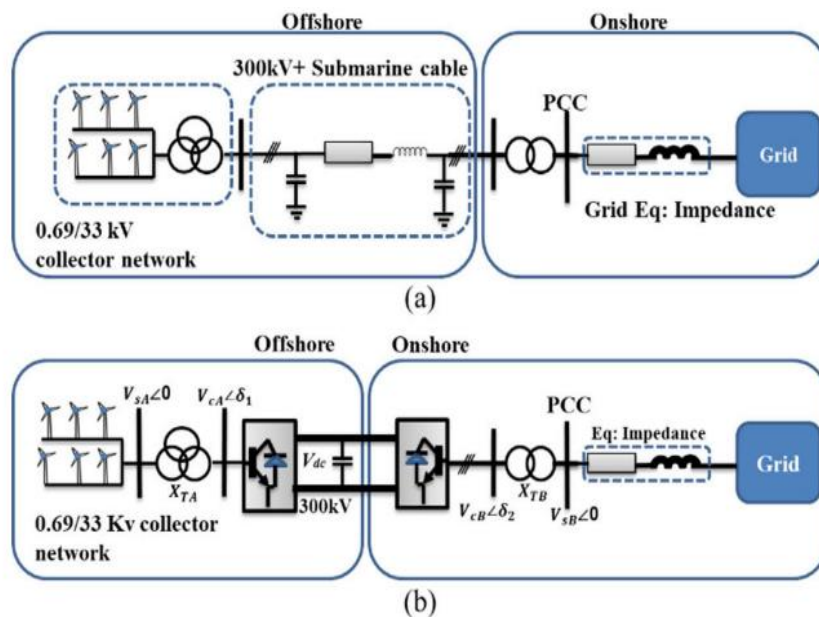


Figure 14. Standard (a) HVAC and (b) HVDC connections in offshore wind farms with elevated voltage levels [92].

3.4.2. AC filters

In tidal stream energy systems, managing high-order harmonics in AC output currents and voltages is critical [92]. These harmonics must be controlled to avoid interference with the AC system, as uncontrolled harmonics can cause equipment malfunctions or disrupt communication signals [89]. To achieve this, transmission systems use either passive or active high-pass filters. These filters help maintain nearly sinusoidal currents and voltages in the AC system. Thanks to their low harmonic

distortion and lack of need for reactive power compensation, these filters can be designed to be compact and simple [90].

3.4.3. DC cables and breakers

DC cables and breakers are essential components within the DC transmission system, working alongside DC links and earth electrodes. The development of DC cable technology has been driven by challenges in conventional cables, which are often heavy, difficult to install, and prone to faults [91]. Modern DC cables feature improved insulation, reduced power losses, lighter designs, and greater flexibility, making them suitable for applications such as submarine or overhead links [93]. In addition, hybrid DC breakers have emerged as a promising alternative to traditional mechanical or electronic switches. These hybrid breakers offer faster response times, enhanced efficiency, and greater reliability, with modular designs that allow easy adaptation to specific voltage and current demands [94].

3.4.4. DC capacitors and filters

DC capacitors and filters are critical in mitigating DC voltage ripple caused by the switching process in the converter's IGBTs [34]. To achieve this, the system uses two identical stacks of DC capacitors, each connected to a pole and grounded [90]. Additionally, DC filters can be applied on the transmission side to reduce interference with nearby metallic circuits. Thanks to the low harmonic content in the currents and voltages of VSC HVDC systems, these filters can be designed to be compact and straightforward [95].

3.4.4.1. HVDC system configurations

HVDC converters (Figure 15), which consist of rectifiers and inverters, provide flexibility in their interconnection through DC links, supporting various configurations [33]. These configurations include mono-polar HVDC systems, which can utilize ground return, metallic return, or a grounded midpoint [88]. Other configurations are back-to-back HVDC systems, bipolar HVDC systems (with variations such as bipole [95], bipole with metallic return, or bipole with series-connected converters), and multi-terminal HVDC systems, as shown in Figure 16 [96].

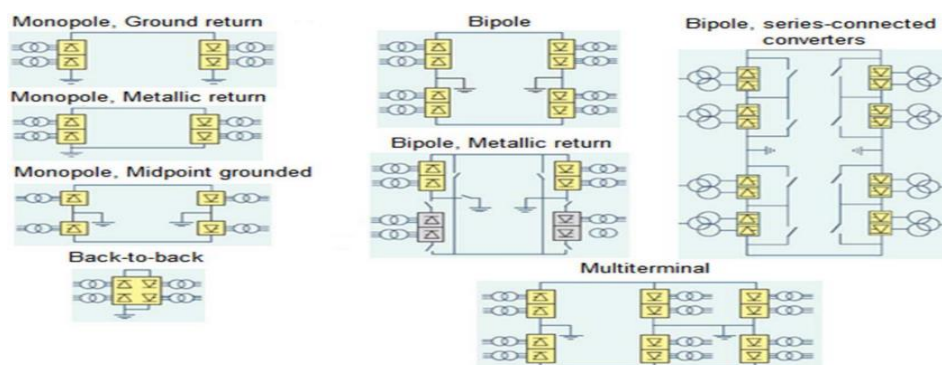


Figure 15. Different configurations of HVDC systems [97].

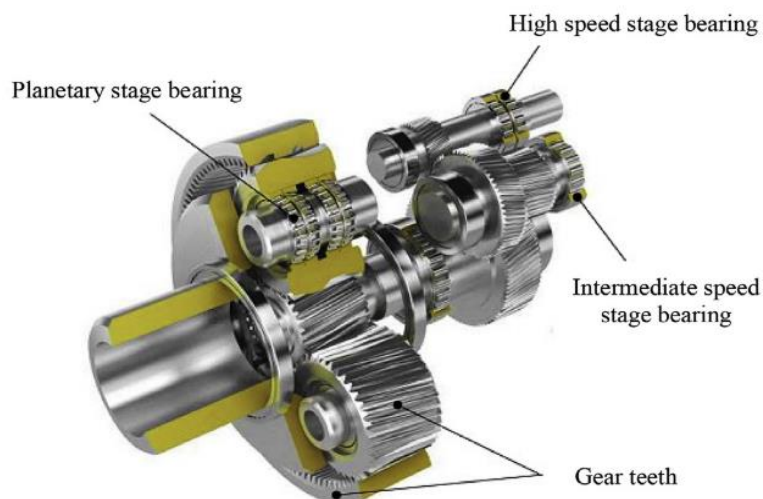


Figure 16. Typical planetary gearbox [26].

While power converters and grid connection layouts are vital for transmitting energy from tidal turbines to the grid, the mechanical transmission system is equally important for converting tidal flow into rotational energy for electricity generation. The following section focuses on mechanical transmission, including gearbox configurations and emerging trends in direct-drive systems.

3.5. Mechanical transmission

The gearbox is a crucial element of the mechanical transmission system. In large-scale wind turbines with significant rotor diameters, the rotor's rotational speed is typically low (approximately 18–50 rpm), which is insufficient for the efficient operation of generators that typically run between 1200 and 1800 rpm [45]. To address this mismatch, a gearbox is installed between the rotor's output shaft and the generator's input shaft, as shown in Figures 17 and 18, increasing the rotor speed to the required rpm for optimal power generation [47]. However, in systems utilizing multi-pole synchronous generators that are connected to the grid via a power converter, which electrically isolates the generator from the grid, the gearbox can be eliminated. This gearless configuration is particularly beneficial in offshore applications, where reduced maintenance is essential [49].

For wind turbines with smaller rotor diameters, the gearbox may also be unnecessary. A smaller rotor diameter results in a shorter distance traveled per revolution, potentially leading to a higher rotational speed that is compatible with the generator's requirements. This allows for a direct connection between the rotor and generator, similar to systems utilizing power converters. Smaller direct-drive wind turbines are commonly employed in standalone DC applications, such as battery charging [53].

The nacelle houses all of the turbine's key components, including the drive system (comprising the rotor shaft, gearbox, and bearings), the electrical generator, power electronics, yaw drive, mechanical brake, and control system, as shown in Figure 5. Since the nacelle must rotate to align with the wind direction, it is connected to the tower via bearings. The manufacturer's design choice to position the drive system and associated components above this rotational bearing is depicted in Figures 20–22 [98].



Figure 17. Geared tidal stream turbines: (a) Sea Gen tidal stream turbine (© Simec Atlantis Energy) [99].

According to the NREL gearbox reliability database, wind turbine gearbox reliability has improved substantially since 2013. Despite facing logistical challenges and a higher mean time to repair (MTTR) for offshore tidal turbines relative to onshore wind turbines, these advancements are significant [11]. Currently, gearbox failure rates are below 15%, with bearing failures representing 76% of these failures, while electrical system failures account for more than 25% [36]. The analysis highlights a notable decline in reliability for both standard and optimized gearboxes when compared to other industrial gearbox applications relevant to tidal stream turbines indicated in Figures 19 and 20. This decline is attributed to specific implementation factors; however, future gearbox designs remain unaffected [94]. This finding emphasizes the importance of both optimization and maintenance in improving gearbox reliability [100].

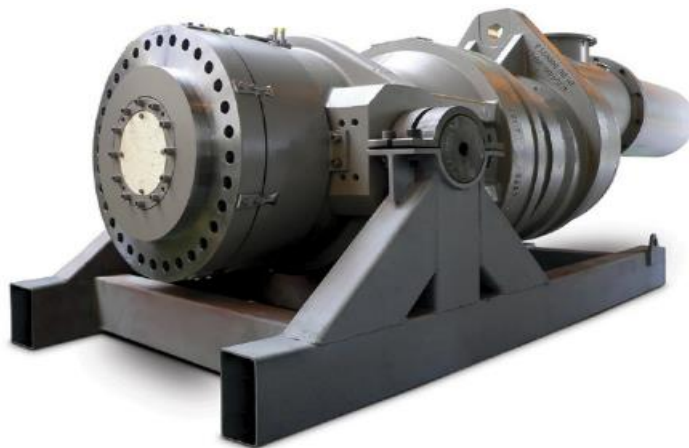


Figure 18. 650 kW planetary gearbox coupled with the generator of the MCT Sea Gen tidal stream turbine [101].



Figure 19. 1.5 MW planetary gearbox from the Mey Gen project [101].



Figure 20. 500 kW planetary gearbox employed in the TGL EMEC demonstrator project [102].

3.5.1. Addressing gearbox challenges

Addressing gearbox challenges in offshore tidal stream turbines necessitates adherence to rigorous operational and maintenance protocols. Effective lubrication is essential for optimal gearbox and transmission performance [6]. It mitigates friction, prevents excessive wear and heat generation, and preserves the integrity of critical components, such as gears, bearings, and seals. Lubrication issues can arise from contamination, degradation, leakage, or insufficient lubricant levels, potentially leading to increased noise, vibration, elevated temperatures, corrosion, and premature component failure [41]. To enhance gearbox reliability and longevity in challenging offshore environments, it is imperative to implement proactive measures to address these issues before they lead to failures [46]. Another prevalent maintenance challenge in tidal stream turbines involves alignment and balance issues. Proper alignment entails the precise positioning of shafts, gears, and bearings, while balance ensures the even distribution of mass and forces across rotating parts [57]. Misalignment and imbalance, often caused by improper installation, adjustment, or wear, can increase stress, vibration, noise, and accelerated component wear. These issues may also affect the efficiency and accuracy of power transmission [102].

Significant attention has been given to various configurations of permanent magnet generators for tidal stream turbines. The rim-driven concept is a notable option for direct-drive drivetrain systems, akin to the Open Hydro design (see Figure 21) [103]. In the rim-driven topology, the generator is positioned on the outer edge of the turbine, offering potential hydrodynamic efficiency advantages over a POD system, where the generator is housed within a nacelle [104]. Research has increasingly focused on various configurations of permanent magnet generators for tidal stream turbines. One promising approach is the rim-driven design, similar to the Open Hydro concept (see Figure 22) [105]. By positioning the generator on the turbine's outer edge, this design has the potential to improve efficiency compared to traditional nacelle-based systems [106].

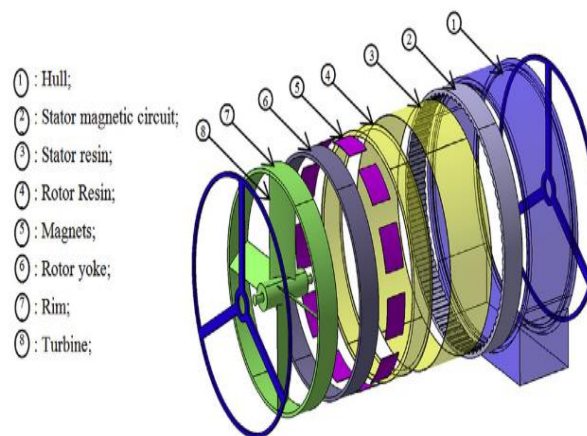


Figure 21. The rim-driven concept using a radial flux permanent generator [6].

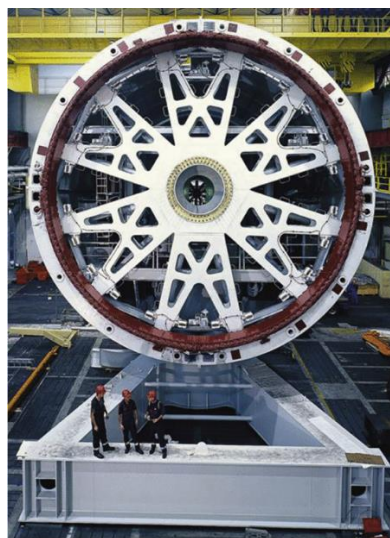


Figure 22. The concept of rim-drive utilizing a radial flux permanent generator [6].

4. Synchronous generators in tidal current energy converters (TCECs)

Marine current turbines can be classified in several ways, often with overlapping categories. This study focuses on categorizing these devices based on their interaction with water motion. The primary

classifications are:

- Horizontal-axis turbines
- Vertical-axis turbines
- Oscillating hydrofoil

To enhance the marine current velocity passing through the turbine and improve power capture, ducted structures are employed. These structures use the Venturi effect to channel flow toward the rotors, applicable to both horizontal and vertical turbines. This design approach increases the marine current speed in front of the rotor, potentially enhancing power output by up to 40% compared to turbines without ducts [6]. Additionally, it reduces turbulence and minimizes adverse effects on the rotor.

In tidal current energy converters (TCECs), turbines are equipped with two distinct types of synchronous generators: axial-flux and radial-flux direct-drive permanent magnet (DDPM) generators. The choice between these generators depends on the specific configuration requirements. Axial-flux generators are commonly used in pod-type structures, while radial-flux generators are employed in rim-driven configurations, as illustrated in Figure 23(a) [38]. For large-diameter radial-flux DDPM generators, a hollow center turbine structure, shown in Figure 23(b), is advantageous [106]. Radial-flux DDPM generators have traditionally been favored due to their development from induction generators [107]. However, axial-flux DDPM generators offer distinct benefits, such as increased compactness and power density, making them superior to conventional radial-flux DDPM generators in certain applications. Both axial and radial-flux DDPM generators, used in direct-drive systems, have garnered significant attention in both academic and industrial research [108].

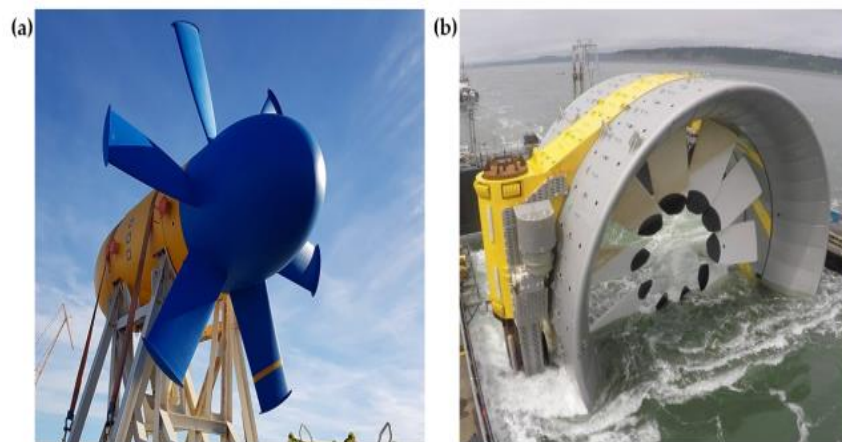


Figure 23. The pod-type structure exemplified by the Sabella D10-1000 tidal current turbine. (b) The rim-driven structure harnessed by the Open Hydro tidal current turbine [38].

Mechanical transmission systems deliver rotational energy to the generator, where it is converted into electrical power. The type and configuration of the generator plays a crucial role in determining the efficiency and reliability of tidal current energy converters (TCECs). The next section delves into synchronous generators, which are widely used in TCECs for their high efficiency and adaptability to variable-speed operations [108].

4.1. Single open-rotor horizontal-axis devices

A prevailing trend within major tidal energy device developers involves the utilization of a shared design foundation—the three-bladed, axial rotor concept indicated in Figure 24. This design approach, informed by the extensive operational expertise garnered from the wind industry, has become a prominent choice. Norway established a 300-kW grid-connected model in 2003. They have also commenced the development of their HS1000 1 MW turbine, scheduled for deployment by 2010. This innovative turbine is entirely submerged and follows a fixed yaw concept, meaning it remains stationary while its blades rotate with the tide's change. Consequently, the blades are required to have a symmetrical cross-section. The drivetrain is expected to incorporate a gearbox and a high-speed induction generator [109].

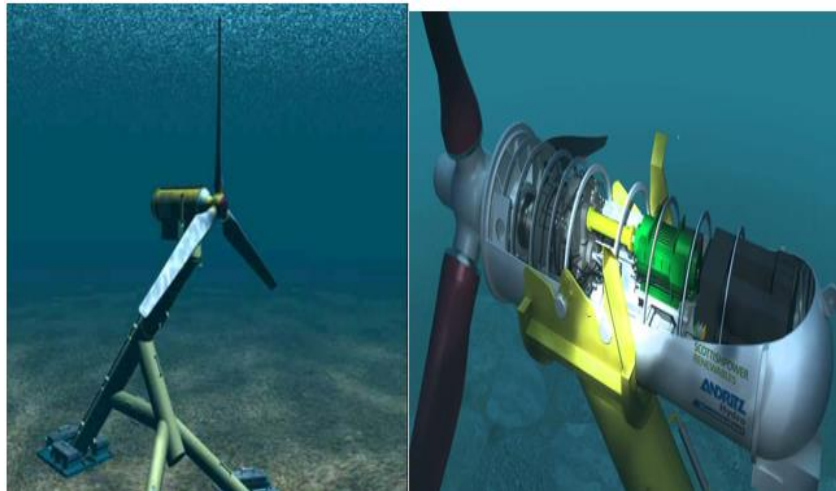


Figure 24. Single open-rotor horizontal-axis device (© Hammerfest Strøm AS) [109].

The turbine incorporates a robust system with multiple layers of redundancy, ensuring continuous operation even during faults or failures. It features an advanced condition monitoring system that predicts potential issues, enabling proactive maintenance [38]. Designed for a 25-year operational lifespan, the turbine includes three scheduled servicing intervals at 6¼ years. With a total mass of 150 tons, it can be installed and retrieved using standard dynamically positioned (DP) construction vessels. Figure 25 illustrates this design, which integrates established wind sector principles with emerging tidal energy technologies [38].



Figure 25. The in-stream tidal turbine known as AR1500, which is anchored to the seabed, originates from SIMEC Atlantis [109].

The Sea Gen turbine, developed by Marine Current Turbines (MCT), was the world's first commercial-scale tidal turbine. Commissioned in July 2008 in Strangford Lough, Northern Ireland, it marked a significant advancement in tidal energy. The Sea Gen project, featuring two 600 kW turbines, had a total capacity of 1.2 MW and required a £12 million investment [38]. The model has been generating 5 GWh of power, meeting the annual energy needs of 1,500 households, as shown in Figure 26. Throughout its operational life, Sea Gen contributed 11.6 GWh to the grid before decommissioning in July 2019 [110]. Installed in May 2008, it was transported to Strangford Lough's mouth by barge, weighing 1000 tons with a 43 m wingspan. Designed by Peter Fraenkel, it operated like an *underwater windmill*, harnessing tidal currents to rotate its rotors. Built at Harland and Wolff shipyards in Belfast, Sea Gen was secured to the seabed in 14 days. It initially produced 150 kW of electricity during commissioning in July 2008, reaching full capacity by November 2008 [111].

With a mobile cross arm on a single 3 m diameter supporting pile, Sea Gen's twin rotors activated when tidal currents exceeded 1 m/s, achieving rotor tip speeds of approximately 12 m/s—approximately one-third of wind turbine speeds. The twin blades operated at a constant 14 rpm, driving a gearbox system [111].

The project, in partnership with ESB Independent Energy, supplied power to about 1,500 homes, with grid connection managed by Northern Ireland Electricity [20]. Deploying Sea Gen in the energetic tides of Strangford Lough presented unique technical challenges. As a pioneering underwater windmill, Sea Gen set a new precedent in tidal energy. Strangford Lough was a notable tidal hotspot in UK and Irish waters, alongside Anglesey, the Pentland Firth, and the Channel Islands [111].

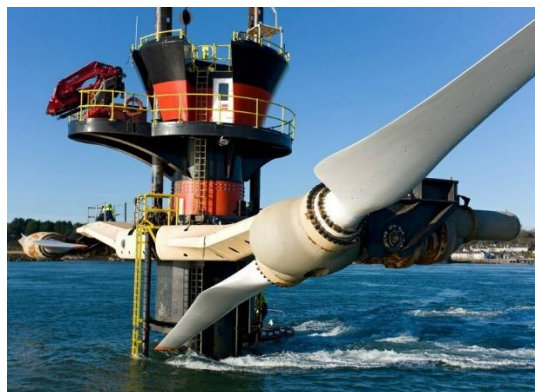


Figure 26. Sea Gen [111].

In the summer of 2011, Atlantis Resources Corporation (now SAE Renewables) deployed its AR1000 tidal turbine at Berth 6 of the Fall of Warness tidal test site (see Figure 27). The AR1000 is a 1 MW horizontal-axis turbine, rated for a flow speed of 2.65 m/s, with an 18 m rotor diameter and a total weight of approximately 140 tons. The turbine was mounted on a 1,300-ton gravity-based structure and, when fully assembled, stood 22.5 m (73 feet) tall. Its control systems, including power conditioning and monitoring equipment, were housed in a dedicated control cabin on the island of Eday [21].

Following prototype testing at the European Marine Energy Centre (EMEC), the company advanced to the next-generation turbine, the AR1500. The AR1500 is being deployed as part of the Mey Gen project in the Pentland Firth. By March 2023, four 1.5 MW turbines had been installed at the Mey Gen site, which collectively generated 51 GWh of electrical energy for the national grid [111].



Figure 27. AR1000 tidal stream turbine (© Simec Atlantis Energy) [20].

Haiming I (10 kW) represents China's first long-term demonstration of a submarine vertical-axis tidal current power generation system (TCPGS), as illustrated in Figure 28. This power station, measuring 9.0 m × 7.5 m × 6.5 m and weighing 20 tons, is equipped with a horizontal-axis fixed-pitch turbine, an expansion-type deflector, and a direct-drive permanent magnet synchronous generator (PMSG). The station is supported by a three-legged base frame that can be raised for maintenance. Additionally, the platform incorporates a 180° self-adjusting reversing mechanism, allowing it to efficiently accommodate bidirectional currents [112].



Figure 28. Haiming I: 10 kW submarine vertical-axis TCPG [112].

Hai Neng II (2×100 kW), also known as the Zhaitang Island Isolated Hybrid Power Demonstration Station, is equipped with a cruciform carrier, two columns, and four flexible mooring systems, as illustrated in Figure 29. Each column supports a horizontal-axis variable-pitch turbine with a 12 m diameter [10]. These turbines are directly coupled to low-speed permanent magnet synchronous generators (PMSGs), each with a capacity of 100 kW, and are designed to operate in bidirectional tidal currents. The turbines have a rated flow velocity of 1.7 m/s, with a cut-in speed of 0.6 m/s and a cut-out speed of 2 m/s [11].



Figure 29. “Hai Neng II” 2×100 kW floating horizontal-axis TCPGS [11].

NTU and NTOU’s collaboration led to the development of the Floating Kuroshio Turbine (FKT) system. Laboratory tests of a 1/25 scale model demonstrated a power generation capability of 850 W at a towing speed of 1.45 m/s. A feasibility study for a 1/5 scale model is underway, with expected power outputs of up to 20 kW [113].

The NSYSU team introduced the floating nozzle-diffusor duct (NDD) power generation system, depicted in Figure 30. Deployed near the Penghu cross-sea bridge in 2013, this system achieved a power take-off (PTO) of 5 kW during on-site testing. A new design iteration with a circular nozzle-diffusor duct is projected to triple the PTO compared to the previous model [113]. Additionally, a collaboration between NSYSU, Tainan Hydraulics Laboratory (THL), and Wanchi Steel Industry Company developed a 50 kW Kuroshio Ocean current power harvester. During a 60 h open-water towing test conducted in southeast Taiwan in 2016, the system achieved an average output of 26 kW at a current speed of 1.27 m/s [113].



Figure 30. Prototype of Floating Kuroshio Turbine (FKT) [113].

One such innovation involves the incorporation of ducted horizontal-axis devices, which enhance energy capture and resilience through refined flow dynamics. The following section delves into the design and performance benefits of these ducted systems, offering a new perspective on optimizing tidal energy extraction.

4.2. Ducted horizontal-axis devices in tidal turbines: enhancing efficiency and performance

The use of tidal currents presents unique design opportunities for turbines, particularly with ducted horizontal axis devices (see Figure 31). Unlike wind turbines, tidal turbines benefit from smaller rotor diameters, which facilitate the integration of ducting mechanisms to enhance flow dynamics. This innovation improves energy capture per unit of rotor area [114].

Ducted systems offer several advantages for tidal turbines. They enhance resilience to off-axis flow disturbances, a challenge often encountered by wind turbines. Additionally, supporting turbine blades at their extremities is feasible, which enhances load resistance and structural integrity. Key to the design of these turbines is their adaptability to tidal flow variations. Turbines must operate efficiently in both directions to accommodate changing tidal flows. Incorporating bi-directional rotors is essential for this purpose. As depicted in Figure 32, this approach redefines energy extraction potential from tidal currents, increasing efficiency, resilience to flow fluctuations, and performance under varying tidal conditions [115].



Figure 31. Illustration of ducted horizontal-axis tidal turbines (Open Hydro) [28].

The next section explores multiple open-rotor horizontal-axis devices, highlighting their potential to enhance energy generation capacity and operational efficiency in tidal stream systems.

4.3. Multiple open-rotor horizontal axis devices

Various rotor concepts aim to maximize generating capacity on each foundation, overcoming limitations imposed by single rotor sizes. These concepts address issues such as asymmetric loading, dynamic behavior during failures, and maintenance considerations, as illustrated in Figure 32.



Figure 32. Multiple open-rotor horizontal-axis device (© MCT) [28].

4.4. Transverse axis devices

The Darrieus-type wind turbine and vertical-axis marine current turbines function as lift-based systems with the generation axis perpendicular to the flow [114]. While they may have lower theoretical efficiency compared to horizontal-axis machines, they offer benefits in structural efficiency and maintenance. Some designs are exploring ducting to enhance energy capture. A significant concept is the modular tidal fence array, where multiple devices are interconnected. Economic considerations include the size of the required ducting, as shown in Figure 33 [114].

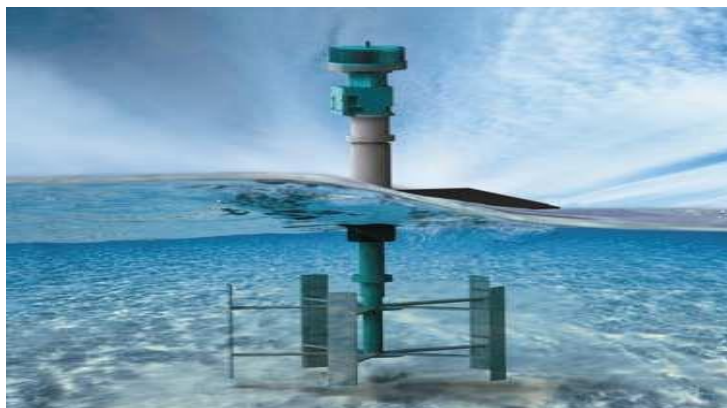


Figure 33. Transverse axis devices [114].

Table 1 summarizes experimental twin-rotor tidal current turbines worldwide. Most of these turbines are in the demonstration phase and have not yet reached commercial deployment [116]. The floating catamaran, among various floating mooring platforms, is particularly promising. It provides a spacious deck, facilitates maintenance and deployment, and adapts well to varying water depths and complex seabed topographies [117].

Table 1. Pilot floating two-rotor tidal current turbines in the world [11].

Institutions	Location	Turbine name	Turbine number	Platform	Total capacity	Operation year
MCT-Atlantis Resources	Kyle Rhea (Scotland, UK)	Sea Gen	2	Pile foundation	$2 \times 600 \text{ W}$	≥ 2016
AK-1000	Singapore	AK-1000	2	Seabed mounted	$2 \times 500 \text{ W}$	≥ 2010
SMD Hydro Vision Ltd	Orkney, UK	Tidel	2	Floating foundation	$2 \times 500 \text{ W}$	≥ 2006
National Taiwan Ocean University	Coast of Taiwan	Kurshio	2	Floating foundation	$2 \times 10 \text{ W}$	≥ 2016
Harbin Engineering University	Zhejiang, China	Hai Neng I	2	Floating foundation (catamaran)	$2 \times 150 \text{ W}$	≥ 2010
Harbin Engineering University	Qingdao, China	Hai Neng II	2	Floating foundation (catamaran)	$2 \times 100 \text{ W}$	2013
Harbin Engineering University	Zhejiang, China	Hai Neng III		Floating foundation (catamaran)	$2 \times 300 \text{ W}$	≥ 2013

While the development of individual tidal energy devices continues to evolve, hybrid configurations that integrate multiple renewable energy sources present a compelling solution for overcoming the limitations of standalone systems. By combining wind and tidal stream technologies, hybrid systems capitalize on the complementary characteristics of these resources, ensuring greater reliability and efficiency in electricity generation. The following section examines the growing trend toward multi-energy systems, emphasizing the benefits of integrating wind and tidal energy technologies into a unified framework.

5. Hybrid configurations integrating wind and tidal stream technologies

Exclusive reliance on wind energy for electricity generation is significantly affected by environmental variability. By integrating multiple renewable sources—such as wind and tidal, each with unique characteristics and advantages—it is possible to mitigate individual limitations and enhance overall system efficiency. Recent developments reflect a growing trend toward multi-energy complementary systems.

5.1. Hybrid system combining offshore wind and tidal turbines

Hybrid energy models that combine tidal and wind power technologies are increasingly explored. These systems typically feature separate subsystems for tidal and wind energy, sharing a common platform [118]. Combining wind and tidal energy can stabilize power output and reduce fluctuations. However, optimizing multi-energy systems requires advanced assessment technologies to account for the varying characteristics of different energy sources [119].

5.2. Offshore wind and tidal concepts

Hybrid systems that merge wind and tidal technologies are still under development. Two notable designs include:

- Savonius Keel and Wind Turbine Darrieus (SKWID), shown in Figure 34, is a unique prototype developed by Mitsui Ocean Development and Engineering Company (MODEC). This system combines a Savonius current turbine with a Darrieus wind turbine and is designed for deployment off the coast of Japan. Its primary goal is to provide reliable backup power to isolated islands, offering a sustainable energy solution for remote locations [120].
- Marine Current Turbines' Patented Device: Inspired by the Sea Gen tidal apparatus, this concept features multiple tidal turbines mounted on a single-column structure. Though still in the conceptual phase, it proposes elevating turbines above water to improve efficiency [120].

Combining the outputs of tidal and wind turbines results in a total annual energy generation of 96.41 GWh, which is double that of using tidal turbines alone [121].

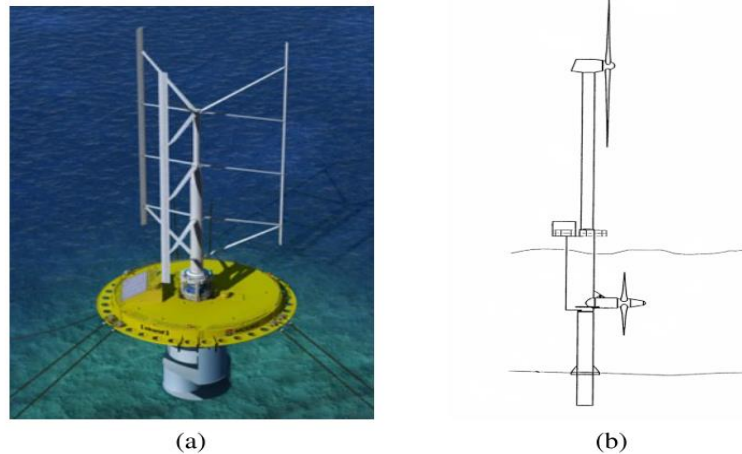


Figure 34. (a) MODEC's SKWID, Savonius Keel and Wind Turbine Darrieus. (b) Marine Current Turbine's patented turbine that combines air and water flow [119].

The Hybrid Offshore Wind and Tidal Turbine (HOTT) system integrates tidal current generation to manage wind power fluctuations, as shown in Figure 35 [120]. This hybrid approach aims to stabilize power production and enhance system reliability, particularly for remote islands where extending the electricity grid is economically unfeasible [121]. This approach offers a viable solution for sustainable energy collection, with future research focusing on storage, grid integration, power regulation, cost optimization, and environmental impact assessment [122].

Various connection methods are available, with the DC bus-based approach selected for its cost-effectiveness and simplified control [123]. The focus remains on capital expenditures (CAPEX) and operational expenditures (OPEX), which are critical for optimizing energy production costs. Addressing potential instability from renewable energy integration will be essential as cumulative renewable capacity increases [124].

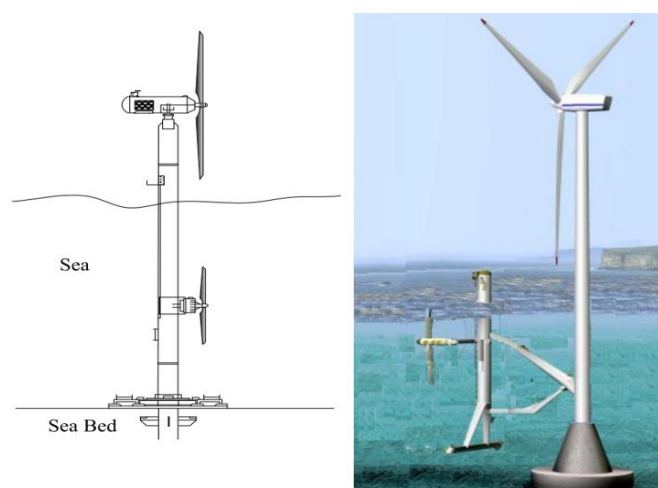


Figure 35. Illustration depicting the concept of a hybrid offshore wind-tidal (HOTT) system [125].

6. Conclusions

The integration of offshore wind and tidal stream technologies offers a transformative approach to addressing the increasing energy demands of coastal regions. This hybrid approach provides a sustainable pathway toward decarbonization, with tidal energy emerging as a vital component due to its predictability and advancing technology. Although challenges such as cost-effectiveness, scalability, and reliability persist, this study highlights the significant potential of hybrid systems, particularly those leveraging resources like the Agulhas Current, to enhance energy stability, reliability, and efficiency.

Key developmental pathways identified in this study include advancing large-scale turbines for grid integration for localized marine applications. To further the practical adoption of these systems, future research must address the technical and economic challenges in a focused and systematic manner.

Future research directions

To guide continued progress, the following specific areas are proposed for future exploration:

1. **Advanced materials and structural designs**
 - Investigate innovative materials, including corrosion-resistant alloys and composites, to enhance durability and reduce operational costs in harsh marine environments.
 - Explore biomimetic designs inspired by aquatic organisms to improve turbine efficiency and minimize ecological disruption.
2. **Computational methodologies and AI integration**
 - Develop AI-driven optimization tools to enhance turbine performance, predictive maintenance, and control strategies for hybrid wind-tidal systems.
 - Incorporate machine learning in energy management systems and power converter design to improve grid integration and real-time adaptability.
3. **Energy storage solutions**
 - Focus on hybrid storage systems combining short-term (e.g., super-capacitors) and long-term (e.g., advanced battery technologies) solutions to stabilize power supply.
 - Explore modular and scalable storage designs tailored to the unique intermittency profiles of wind and tidal energy.
4. **Power conversion and grid integration**
 - Develop advanced converter technologies to improve power quality, reduce harmonic distortion, and ensure seamless integration into national grids.
 - Investigate HVDC and advanced AC transmission systems for efficient energy transport from offshore systems to onshore grids.
5. **Environmental impact and ecosystem integration**
 - Conduct detailed impact assessments to ensure minimal disruption to marine ecosystems, with a focus on species migration patterns and habitat preservation.
 - Implement AI- and IoT-enabled adaptive monitoring systems for real-time assessment and mitigation of ecological effects.

Broader prospects

Looking ahead, scaling pilot projects into full-scale commercial installations will be critical,

particularly in regions with high energy potential, such as the Agulhas Current. Success in this domain will require robust interdisciplinary collaboration among engineers, environmental scientists, economists, and policymakers. Additionally, fostering international partnerships and sharing best practices from successful projects can accelerate technological innovation and cost reduction in offshore hybrid energy systems. By addressing these challenges and seizing growth opportunities, hybrid wind-tidal systems can play a pivotal role in achieving global sustainability and energy resilience goals.

Use of AI tools declaration

The authors declare that no Artificial Intelligence (AI) tools were used in the creation of this article, including in the drafting, editing, or data analysis processes.

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Conflict of interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Author contributions

Ladislav Kangaji led the research, conducted the literature review, and was responsible for the collection and organization of review papers. He also drafted the manuscript and coordinated the writing process. Atanda Raji provided critical insights, guided the development of the research methodology, and played a key role in reviewing and revising the manuscript. Efe Orumwense contributed to the conceptual framework of the study and provided valuable feedback during the manuscript editing process.

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CHAPTER 4 SUMMARY: IMPROVING GRID-CONNECTED TIDAL POWER SYSTEMS THROUGH PWM INVERTERS BASED ON VOLTAGE ORIENTED CONTROL

Chapter Four explores the role of pulse width modulation (PWM) inverters in improving the performance of grid-connected tidal power systems, particularly in converting AC to DC power for renewable energy applications. The chapter identified the limitations of existing systems that primarily use basic voltage oriented control (VOC) strategies and 2-level converters. These traditional systems often suffer from sub-optimal steady-state performance, slow transient response, and high harmonic distortions. Additionally, conventional systems lack sophisticated control mechanisms for managing active and reactive power, which can reduce overall system efficiency and stability. To address these challenges, the chapter proposes an enhanced VOC strategy, which would aims to improve both steady-state performance and transient response by integrating a current control loop. The generator side utilises field-oriented control (FOC), while the grid side incorporates a 3-level H-bridge voltage source converter, integrated with VOC and a phase locked loop (PLL). These advanced control strategies are designed to optimise power extraction and more effectively manage active and reactive power. This ensured higher efficiency and stability in grid-connected tidal energy systems. The chapter also presented MATLAB/Simulink simulations to validate the proposed VOC controller. The simulations demonstrated the system's ability to ensure stability, reduce harmonic distortions, and manage reactive power effectively. With a system featuring a 1.5 MW/C, 1.2 MW three-level inverter and an LCL filter, the proposed control strategy achieves harmonic distortion below 5%, indicating its effectiveness in improving power quality. The chapter concludes that the proposed VOC-based control strategy significantly enhances the performance of grid-connected tidal energy systems by addressing issues such as total harmonic distortion (THD), dynamic performance, and parameter sensitivity. Additionally, simulation results confirm the feasibility and effectiveness of this control strategy, marking a step forward in optimising tidal power systems for integration into the grid. In a nutshell, this chapter highlights the improvements in grid-connected tidal power systems through advanced PWM inverters and VOC strategies, showing significant gains in stability, efficiency, and power quality.

Improving Grid-Connected Tidal Power Systems Through PWM Inverters Based on Voltage-Oriented Control

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Abstract – Pulse width modulation (PWM) rectifiers play a critical role in AC to DC power conversion for renewable energy applications. Existing systems predominantly employ basic voltage-oriented control (VOC) strategies and conventional 2-level converters, which often face challenges such as suboptimal steady-state performance, slower transient response, and elevated harmonic distortions. Moreover, these systems typically lack sophisticated control mechanisms for managing active and reactive power, thereby potentially compromising overall efficiency and stability. This proposed voltage-oriented control strategy aims to overcome these limitations by enhancing both steady-state performance and transient response through an inherent current control loop. Specifically, in the context of grid-connected tidal energy systems, the generator side utilizes field-oriented control (FOC), while the grid side employs a 3-level H-bridge voltage source converter integrated with VOC and a phase-locked loop (PLL). These advanced control strategies are designed to optimize power extraction and more effectively manage active and reactive powers. MATLAB/Simulink simulations have been conducted to validate the efficacy of the proposed controller, demonstrating its ability to ensure system stability, reduce harmonic distortions, and manage reactive power effectively. The system, featuring a 1.5 MW/C, 1.2 MW three-level inverter, and LCL filter, achieves harmonic distortion below 5%, showcasing the filter's efficiency. The comprehensive simulation results support the feasibility and effectiveness of the proposed voltage-oriented control strategy, addressing total harmonic distortion (THD), dynamic performance, and parameter sensitivity.

Keywords: Harmonic reduction, power quality, PWM rectifier, Tidal energy, Voltage control

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I. Introduction

Integrating renewable energy sources, such as wind and tidal power, into the utility grid introduces a range of technical and economic challenges [1]. These challenges encompass power quality issues, including reliability, harmonics, voltage stability, control, protection, frequency regulation, and reserve allocation [2] – [3]. Additionally, the grid's inherent voltage harmonics can distort the current supplied [4]. Tidal energy systems, in particular, face significant hurdles due to the unpredictability of tidal speeds and difficulties in directly connecting to the traditional grid, which requires a meticulous integration process [4] – [5]. Effective control of power converters and conditioning processes is essential to address these issues [6].

Tidal energy systems, while sharing similarities with offshore wind turbines, have distinct characteristics that

necessitate specialized solutions [7] – [8]. These include the predictable nature of tidal currents, reduced swept areas due to higher water density, and shorter distances to shore [9]. Vienna converters, known for their low harmonic distortion, high efficiency, and impressive power density, have emerged as a noteworthy solution in renewable energy applications, particularly in wind power systems [10]. Various control strategies, such as proportional-integral (PI) control, proportional resonant control, and sliding mode control, are utilized to enhance the performance of Vienna rectifiers [11]. However, the unidirectional operation of Vienna rectifiers limits their capability to generate reactive power [12], which is crucial for effective grid integration of wind and tidal energy [13].

In contrast, Pulse Width Modulation (PWM) rectifiers offer several advantages, including effective power quality management, high power factor, and bi-directional flow capability [14]. The traditional control strategy for

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PWM rectifiers employs a synchronous rotating reference frame with decoupled PI controllers, but it faces challenges related to slow dynamic response [15]. Voltage-Oriented Control (VOC) is a prominent technique in PWM rectifiers, optimizing performance by managing direct and quadrature axis currents to regulate active and reactive power [16]. Direct Power Control (DPC) approaches have also gained attention for their ability to directly control active and reactive power [17].

Integrating PWM rectifiers with VOC in tidal generation systems provides significant benefits [18], including improved power quality, reduced harmonic distortions, and enhanced power factor [19]-[20]. This integration addresses the variable nature of tidal energy, ensuring efficient energy transfer and stability within the grid [21].

Aims:

- Enhance Power Extraction Efficiency: Optimize the extraction of power from tidal energy systems by applying vector-oriented decoupling control on the generator side.
- Implement Voltage-Oriented Control: Develop and apply voltage-oriented control techniques to effectively manage active and reactive power in grid-connected tidal power systems using PWM inverters.
- Analyze Simulation Outcomes: Perform a detailed analysis of simulation results to evaluate the performance of PWM inverters with voltage-oriented control, focusing on their impact on grid stability, power quality, and overall system efficiency.

TABLE I
PARAMETERS OF THE 300 KW HORIZONTAL AXIS TIDAL
STREAM TURBINE (HATST) PROTOTYPE.

Parameter	Value
Radius	8.5 m
Maximum pitch angle	8°
Rated power	300 kW
Rated flow velocity	2 m/s
Rated rotational speed	12 rpm
Optimal TSR	5
Starting flow velocity	0.7 m/s
Total maximum efficiency	≥30%

The equation for estimating the power capacity of tidal currents can be derived by utilizing the identical formula applied in wind energy systems. In this equation, P denotes power measured in Watts (W); represents the device efficiency or power coefficient; ρ represents the water density, typically estimated at approximately 1025 Kg/m^3 ; A stands for the swept area in square meters

(m^2), and U signifies the current velocity measured in meters per second (m/s), as depicted in Equation (1).

$$P = \frac{1}{2} \rho C_p A V_{tides}^3 \quad (1)$$

The modelling of the generator side includes an explanation of the rotor model. In this context, the rotor design assumes a crucial role in determining the amount of mechanical power (P_m) generated from the energy of the tidal stream. It's important to note that the power coefficient C_p is intricately linked to this rotor design. The rotor model is described as part of the modelling of the generator side.

$$P_m = C_p P_{tide} \quad (2)$$

$$P_m = \frac{1}{2} C_p \rho A V^3 \quad (3)$$

The power of the tidal stream is therefore divided by the power coefficient to determine the mechanical power output:

In this instance, the C_p maximum value of 0.44 is approximated indicates in Fig. 1. The power coefficient's value is contingent upon both the tip speed ratio and the pitch angle. However, in the case of fixed-pitch systems, the power coefficient C_p is solely determined by the tip speed ratio. This ratio elucidates the connection between the rotational speed of blades with radius ' r ' and the velocity of the water v :

$$\lambda = \frac{\omega_m r}{v} \quad (4)$$

The $C_p(\lambda)$ -curve has undergone experimental validation across TSR values ranging from 2.9 to 4.5, with flow velocities falling within the 1.2 to 1.4 m/s range, as detailed in [10]. The curve derived from the experimental data is depicted in Fig. 1 and is mathematically represented by the equation $C_p(\lambda) = 0.0836\lambda^2 - 0.0183\lambda^3$ (5). The calculated optimal tip speed ratio from this power coefficient curve is approximately $\lambda_{opt} \approx 3.05$, corresponding to an optimal power coefficient of $C_p(\lambda_{opt}) \approx 0.26$.

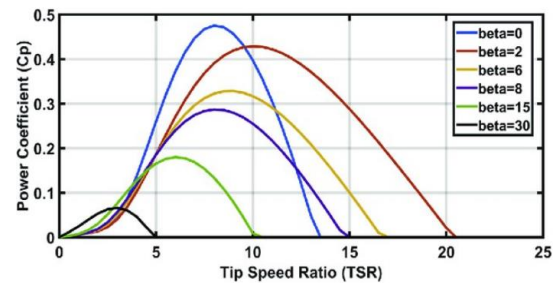


Fig. 1: Power Coefficient with Tip Speed Ratio (TSR) and Blade Pitch Angle.

II. Rectifier and Control systems

Rectifiers are crucial in converting alternating current (AC) to direct current (DC) within hybrid energy systems. This section provides a detailed exploration of rectifiers, focusing on their essential parameters and control techniques to ensure efficient operation and integration.

A. PWM Non-Regenerative Rectifiers

PWM non-regenerative rectifiers are electronic devices that convert AC power to DC power with high efficiency and controlled output. "PWM" stands for Pulse Width Modulation, a technique used to regulate the output voltage and current by adjusting the width of the voltage pulses.

"Non-regenerative" refers to the inability of these rectifiers to feed energy back into the power source; they can only convert power in one direction, from AC to DC. This is contrasted with regenerative rectifiers, which can also return power to the grid or source when needed.

PWM non-regenerative rectifiers are commonly used in applications requiring controlled DC power, such as in DC motor drives, battery charging systems, and various industrial processes. They offer advantages such as improved power quality, reduced harmonic distortion, and high power factor compared to traditional rectifiers. However, they are limited by their inability to handle energy regeneration or power reversal [11].

B. PWM Three-phase Boost Rectifier

Due to its asymmetric current-drawing characteristics, the three-phase boost rectifier is frequently recommended for high-power applications. This topology is widely adopted because boost converters can achieve near-unity power factors and exhibit low distortion in line currents under diverse load conditions [18]. Despite these advantages, a notable drawback extensively reported in the literature is the potential for output voltage instability. Such instability can detrimentally impact the system's overall reliability and efficiency, especially under varying operating conditions. Therefore, it is imperative to incorporate meticulous design considerations and implement robust control strategies to mitigate voltage fluctuations and ensure consistent system performance [22].

C. PWM Three-phase Vienna

The Vienna rectifier architecture, illustrated in Fig. 2, comprises six active semiconductor switches, which can be either Insulated Gate Bipolar Transistors (IGBTs) or Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), and six diodes. Each diode and switch are subjected to a voltage stress of $V_{dc}/2$. The architecture employs three inductors on the AC input side and two

parallel capacitors on the DC side. The neutral point of the DC link is connected to the grid's neutral point. Despite the advantages offered by this architecture, its practical implementation necessitates sophisticated control schemes and may require the fabrication of specialized semiconductor modules [13].

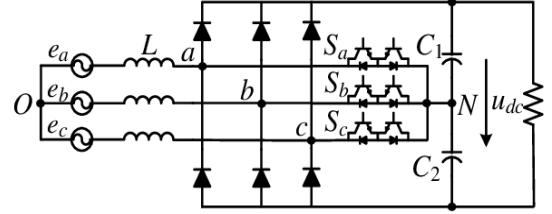


Fig. 2: A three-phase Vienna rectifier.

Regenerative rectifiers are advanced power conversion devices capable of bidirectional power flow. In rectifier mode, they convert AC power to DC, while in reverse operation, they act as inverters, converting DC back to AC. This dual functionality is crucial for applications requiring bidirectional energy transfer, such as motor drives, high-voltage direct current (HVDC) transmission systems, and tidal turbine grid integration.

In these contexts, regenerative rectifiers enable efficient energy recovery and reintegration into the power grid, thereby enhancing system efficiency and stability. Their ability to return excess energy to the source helps in managing power flow, improving power quality, and ensuring seamless operation across varying load and generation conditions. This capability is particularly important in modern electrical systems that prioritize energy conservation and efficient resource utilization [23].

D. Carrier-based sinusoidal pulse-width modulation (SPWM)

Sinusoidal pulse-width modulation (SPWM) is widely employed by power electronics professionals to control the output of inverters, particularly in renewable energy applications like offshore tidal power systems. SPWM utilizes a triangular carrier wave to generate the PWM signals. Originally developed for three-phase voltage source inverters (VSIs), this technique has been adapted for three-phase current source rectifiers and, in some instances, for voltage source rectifiers [24]. For efficient operation, the PWM pattern must generate a sinusoidal waveform that matches the frequency of the input voltage. By adjusting the amplitude and phase of the PWM sinusoid, the system can accommodate both leading and lagging power factors in rectifier and inverter operations, enhancing the versatility and performance of the system.

Refer to Fig. 3 for an illustration of this modulation technique [25].

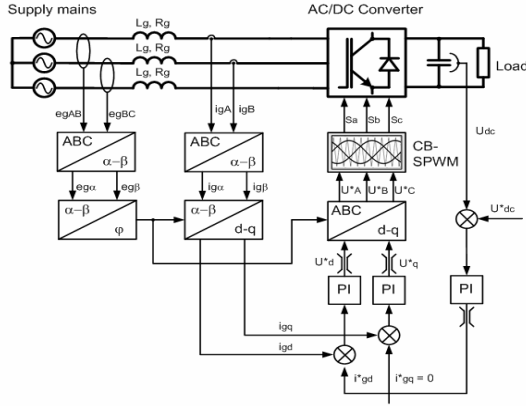


Fig. 3: Voltage-Oriented Control with CB-SPWM

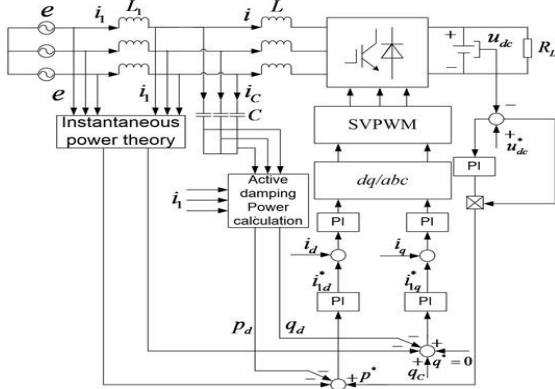


Fig. 4: Direct Power Control of PWM Rectifier with LCL Filter Using Power Damping Feedback.

The equations for stator voltage in a fixed reference frame are provided as follows [26]:

E. Voltage-Oriented Control (VOC) Framework

Voltage-Oriented Control Approach:

The Voltage-Oriented Control (VOC) strategy is employed to precisely regulate the output DC voltage of the inverter by controlling the current within the system [27]. VOC operates by projecting the three-phase voltage and current variables of the Voltage Source Inverter (VSI) onto a synchronously rotating dq-frame, which facilitates effective control of both active and reactive power. The key components of VOC are [22],[28]:

- Inner Current Control Loop:

This loop regulates the DC-link voltage by setting the reference currents for the inner loop [29].

- Outer Voltage Control Loop:

This loop ensures the DC-link voltage maintains a value close to the reference, adapting dynamically to variations [29].

F. Mathematical Equations:

- Voltage Equations in dq-frame:

$$[V_{abc}] = [R][i_{abc}] + [L] \frac{d(i_{abc})}{dt} + \frac{\lambda abc}{dt} \quad (5)$$

$$\begin{cases} V_d = R_{id} + L_d \frac{di_d}{dt} - L_q i_q \omega_s \\ V_q = R_{iq} + L_q \frac{di_q}{dt} + (L_d i_d + \Phi_m) \omega_s \end{cases} \quad (6)$$

Where V_d and V_q are the direct and quadrature axis voltages, I_d and I_q the direct and quadrature axis currents, R is the resistance, and L is the inductance [23], [30].

- Power Equations:

$$P = V_d I_d + V_q I_q \quad (7)$$

$$Q = V_d I_q - V_q I_d \quad (8)$$

where P is the active power and Q is the reactive power.

G. Direct Power Control (DPC) of PWM Rectifier

Characteristics of DPC:

- Instantaneous Power Regulation:
Directly regulates both active and reactive power, enhancing power conversion efficiency.
- Power Damping Feedback:
Utilizes feedback to stabilize power and mitigate oscillations and disturbances.
- Harmonic Mitigation:
Incorporates an LCL filter to minimize PWM-induced harmonics, improving power quality.
- Enhanced Dynamic Performance:
Adapts quickly to changes in load and grid conditions.
- Simplified Control Structure:
Reduces control complexity while enhancing system reliability.

- *Permanent Magnet Synchronous Generator (PMSG) Model*

Electromagnetic Torque:

$$T_{em} = \frac{3P}{2}(\psi_f I_q - L_d I_d) \quad (9)$$

where T_{em} is the electromagnetic torque, P is the number of pole pairs, ψ_f is the flux linkage, and L_d is the direct-axis inductance.

- *Mechanical Dynamics:*

$$\frac{d\omega_m}{dt} = T_{em} - T_{load} \quad (10)$$

where J is the moment of inertia, $d\omega_m$ is the mechanical speed, and T_{load} is the load torque.

- *Simplified Torque Equation:*

Electromagnetic Torque:

$$T_{em} = \frac{3P}{2}(\psi_f I_q - L_d I_d) \quad (11)$$

- *LCL Filter Modelling*

LCL Filter Parameters:

- *Impedance and Capacitance:*

$$Z_{LCL} = \frac{V_g}{I_{LCL}} \quad (12)$$

$$C_{filter} = 0.05 \cdot C_{base} \quad (13)$$

where V_g is the grid voltage, I_{LCL} is the current through the LCL filter, and C_{base} is the base capacitance.

- *Active Filter Function (AFF) for Harmonic Compensation:*

Harmonic Compensation:

$$i_{comp} = i_{measured} - i_{reference} \quad (14)$$

- *Current Ripple Estimation*

Current ripple estimation involves determining fluctuations in electrical current caused by switching in power converters, crucial for minimizing harmonic distortion, improving efficiency, and ensuring power quality and system stability [8].

- *Current Ripple Formula:*

The maximum current ripple at the inverter output can be estimated using:

$$\Delta I_{ripple} = \frac{V_{DC}(1-m)}{L \cdot f_s} \quad (15)$$

where ΔI_{ripple} is the DC bus voltage, m is the modulation index, L is the inductance, and f_s is the switching frequency.

- *Voltage-Oriented Control Implementation Control Strategy:*

- *Outer Voltage Control Loop:*

$$V_{DC,ref} = V_{DC} + K_p(V_{DC,ref} - V_{DC}) \quad (16)$$

where K_p is the proportional gain.

- *Inner Current Control Loop:*

$$I_{d,ref} = \frac{V_{DC} - V_{DC,ref}}{R} \quad (17)$$

$$I_{d,ref} = \frac{V_{q,ref}}{L} \quad (18)$$

- *Minimum DC-Link Voltage:*

To ensure proper operation, the minimum DC-link voltage must be calculated as [27]:

$$V_{DC,min} = \sqrt{3} \cdot V_{line-to-ground} \quad (19)$$

- *DC-Link Capacitor Calculation:*

The DC-link capacitor C_{DC} is determined by:

$$C_{DC} = \frac{P}{V_{DC} \cdot f \Delta V_{DC}} \quad (20)$$

ΔV_{DC} is the maximum ripple in DC voltage, P is the active power, and f is the generator frequency [22],[28]. The specific parameters for the LCL filter and the PWM regenerative rectifier modelling parameters are outlined in Table 2 and Table 3:

TABLE II
THE LCL FILTER PARAMETERS

Parameters	Values
Inverter side inductor	0.9mH
Grid side inductor	0.072mH
Capacitor filter	531μF
Damping Resistor	0.118Ω
Resonant frequency	845Hz
Inductor resistances	0.00761Ω
Sampling frequency	10,000Hz
Crossover Frequency	254 Hz

 TABLE III
THE PWM REGENERATIVE RECTIFIER MODELLING PARAMETERS.

Parameters	Values
V_{dc}	1500 V
V_{ll}	600 V
C_{DC}	150 V/0.04 Farad

H. Generic Three-Phase VSC Electrical Topology

The configuration of a generic three-phase Voltage Source Converter (VSC) electrical topology is illustrated in Fig. 5. The system setup includes a voltage source rectifier with line inductance on the AC side (L_s , R_s), six individual IGBT switches, and a DC-link capacitor C on the DC side [31].

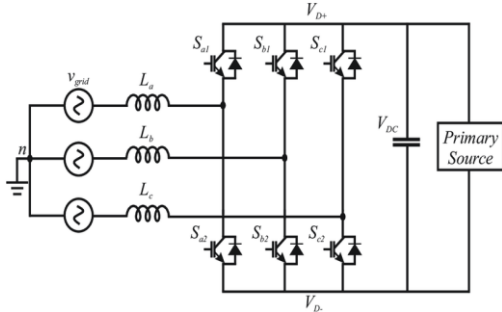


Fig. 5: Generic Three-phase VSC electrical topology [32].

$$V_{(DC-min)} > \sqrt{2}\sqrt{3}V_{LN(rms)} = \sqrt{3}E_m \quad (21)$$

The $V_{(DC-min)}$ represents the minimum DC-Link voltage, and $V_{(rms)}$ is defined as the line-to-ground voltage. This analysis determines the minimum DC-link voltage through equation (21), presented as follows. Taking the maximum reference voltage as $\frac{V_{DC}}{2}$, Equation (22) can be expressed as shown:

$$V_{(LNpeak)} = \frac{V_{DC}}{2} \quad (22)$$

$$V_{(DC-min)} > 2V_{LN(peak)} = \frac{2\sqrt{2}}{\sqrt{3}}V_{LN(rms)} = 1.663V_{LL(rms)} \quad (23)$$

The DC link voltage is considered inconsistent with Equation (21). The calculation of the DC-link capacitor can be determined using the following equation:

$$C_{DC} = \frac{P}{2\pi f V_{DC} \Delta V_{DC}} \quad (24)$$

Here, ΔV_{DC} denotes the maximum ripple in DC voltage, typically approximately 5% of the supply voltage, where V_{DC} is the DC bus voltage. Additionally, P represents the active power, and f corresponds to the generator frequency.

III. Methodology

This study leverages MATLAB/Simulink for modeling and optimizing grid-connected tidal power systems using voltage-oriented control (VOC). The methodology includes transforming the power coefficient curve into a mathematical representation and implementing discretely tuned PI controllers with anti-windup features. Designed specifically for tidal Stream Energy applications, the system comprises a PWM rectifier and a 2-level voltage source converter (2L-VSC) to convert AC to DC, enhanced by a harmonic LC filter for superior output quality. Grid integration is facilitated through a 3-level cascaded H-bridge VSC, controlled by VOC coupled with a phase-locked loop (PLL). The VOC algorithm utilizes a decoupler and three PI controllers to manage current components and DC-link voltage. Key system components—tidal generator, filter, converter, rectifier, and grid—are illustrated in Fig. 6

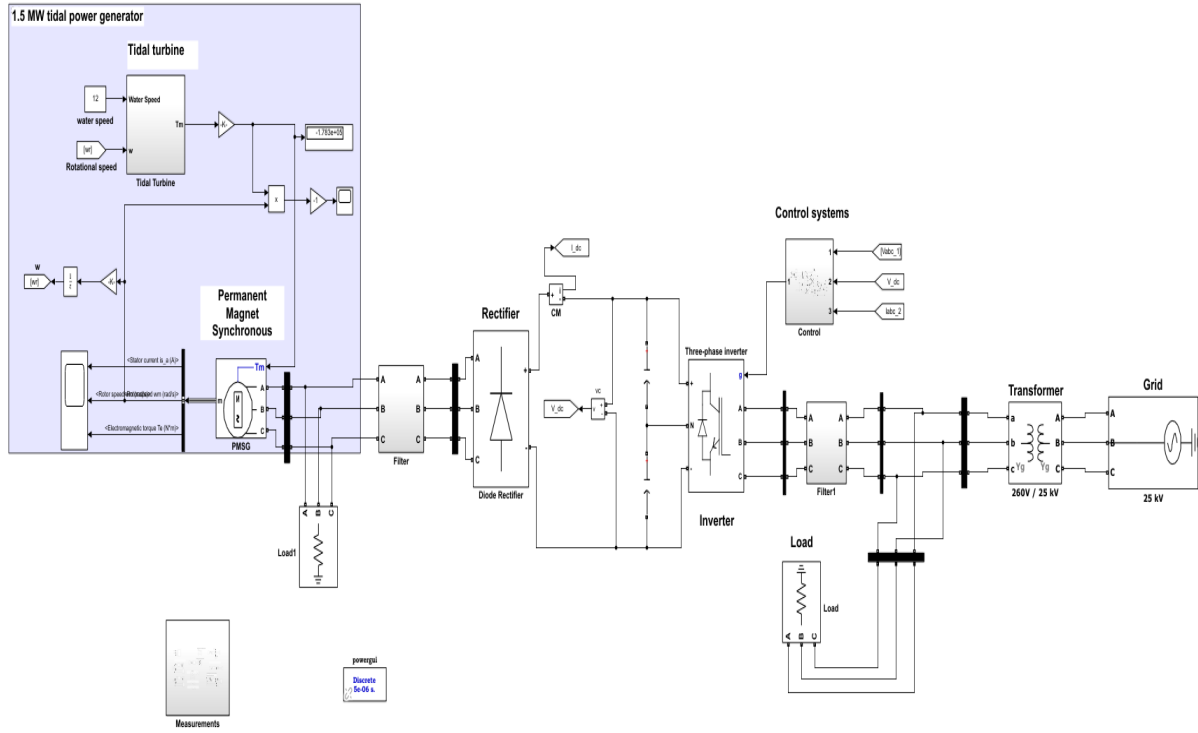


Fig. 6: Grid-connected PMSG-based tidal generation system

IV. Results and discussion

This study proposes using the simplified network depicted in Figs. 3 and 4 to evaluate the improved power quality achieved by connecting a voltage-oriented PWM rectifier to a grid-connected tidal turbine. The system integrates a tidal turbine shaft with a Permanent Magnet Generator (PMG) rotor and a full-scale power converter connected to the grid via a Permanent Magnet Synchronous Generator (PMSG). Three-phase undersea cables transmit the 6.6 kV output from the Medium Voltage (MV) generator to shore, where an onshore transformer typically steps down the voltage to a Low Voltage (LV) transmission level (690 V).

TABLE V
TIDAL GENERATOR MODELLING PARAMETERS

Parameters	Value
P_{nom}	1.5 MW
V_{nom}	600 V
R_s	0.006
L_{dq}	0.3e-3
ϕ	1.48
J	35000
Viscous Damping	0.01
Friction	0
N_p	48

The tidal generator's reactive power generation and active power output, estimated at 1.324 MW, are depicted in Figs. 7a and 7b. The simulation shows a significant negative undershoot of approximately 69.62%, a minor positive undershoot of around 1.055%, and a substantial overshoot of 233% during the initial phase.

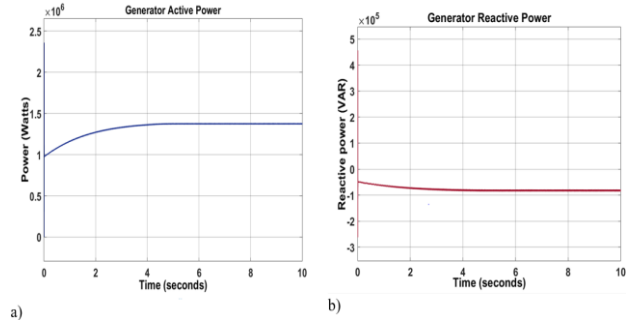


Fig. 7: (a) Active power output from the tidal generator and (b) the reactive power generated by the tide generator.

The active and reactive power curves at the load output terminals are illustrated in Fig. 8. The active power is recorded at 2.5 MW, while the reactive power remains near zero ($1.865 \times \text{VAR}$). After this period, the response stabilizes, maintaining a consistent output of 917 kW. Fig. 8 displays the active and reactive power exported to the grid. The grid-connected inverter is required to supply 508.4 KVAR of reactive power and approximately 573.9 kW of active power to the tidal energy system.

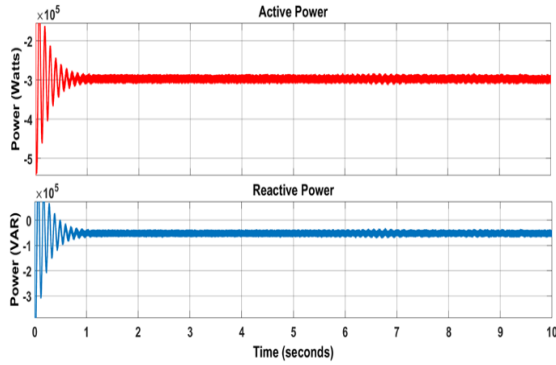


Fig. 8. Active and Reactive Power

A. Inverter Characteristics

Multilevel voltage-source inverter (VSI) technology is commonly utilized in grid-connected tidal energy conversion systems (TCS), as illustrated in Fig. 5. Due to the inherent buck characteristics of Voltage Source Inverters (VSIs), a boost converter is required to elevate the DC-link voltage when the VSI is utilized as the power conversion circuit in a TCS.

Fig. 9 illustrates the phase-to-phase voltage of a three-level inverter, revealing the harmonics introduced by inverter switching. These harmonics can substantially degrade system efficiency, resulting in transient effects and a diminished power factor. To maintain acceptable system performance, the total harmonic distortion (THD) must be kept below 5% for voltages ranging from 1 to 68 kV. The current harmonic distortion threshold is set at a higher value, with a minimum of 1000 A.

To reduce the harmonics, an LCL filter is installed between the grid and the inverter. Voltage and current signals have harmonics that exceed the usual system frequency of 50 Hz.

The output of the LCL filter, illustrating the phase-to-phase voltages and currents, is also shown in Fig. 9 and Fig. 10.

Phase currents are approximately 1213 A, while voltage magnitudes are around 600 V. The phase-to-phase voltage has an undershoot of 1.985% and an overshoot of 0.324%, with a rising time of approximately 5.853 milliseconds and a fall time of 5.837 milliseconds. Similarly, the phase current exhibits rise and fall periods of 5.819 and 5.823 milliseconds, with overshoot and undershoot values of 1.99%. These metrics indicate that harmonic distortion is effectively reduced by the implemented LCL filter, ensuring that performance standards are met.

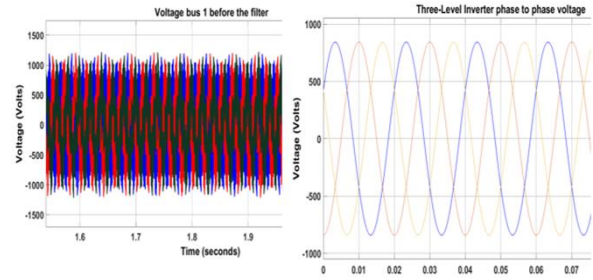


Fig. 9. The three-phase voltage before the filter

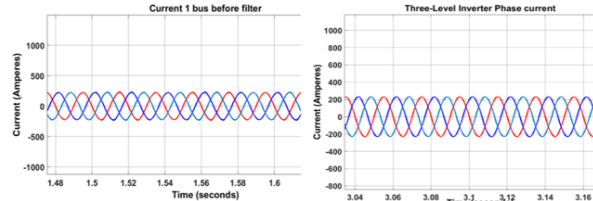


Fig. 10: The three-phase voltage before the filter, Current before the filter

The voltage control method utilized in this study compares the DC link voltage to a reference voltage set at 1500 V. The currents I_q and $I_{qreference}$ (I_{dref}) are evaluated through the current PI controller on the q-axis, generating the voltage V_q based on the error between the two currents.

The $V_{qreference}$ is maintained at zero, $I_{dreference}$ (I_{dref}) in Fig. 13e, representing the DC link. Fig. 11d illustrates the actual and reference voltages of the DC link. The model controls outperform expectations, with little difference between the actual and reference signals. However, overshoots occur at simulation states 14, 688, and 15, after which both voltages normalize. Fig. 12e compares the current. The current (I_d) and the current reference (I_{dref}) are compared in Fig. 13e.

The current PI controller generates the voltage (V_q) on the q-axis by comparing the actual and reference currents. The I_q reference value is kept close to zero. The grid voltage in the dq0 frame is crucial for generating the voltage required to detect the modulation signal. The grid regulates its reactive power by setting the d-axis voltage to 500 V while keeping the q-axis value at zero. Figs. 13a and 13b show the voltages in the dq0 frame (I_d and V_q), which help to examine the modulation signal, as well as the estimated values for the d and q axes. The modulation signal's findings on both axes are calculated with a modulation index of 0.7. The modulation signals are then transformed from the dq0 frame to the ABC frame and delivered to the pulse width modulation (PWM) generator, producing the twelve pulses required for operating the three-level system.

The phase-locked loop (PLL) indicates in Fig. 14 plays a crucial role in this process by generating an output signal that is synchronized with the phase of the input. The PLL employs an internal frequency oscillator to continuously

track the frequency and phase of a sinusoidal three-phase signal, thereby minimizing phase differences and ensuring synchronization. As depicted in Fig. 13, the PLL frequency (f) is set to 50 Hz, aligning closely with the grid frequency with only minor deviations. The PLL accurately detects the grid voltage and phase angle through dq0 frame current control synchronization, ensuring optimal alignment between the inverter and the grid.

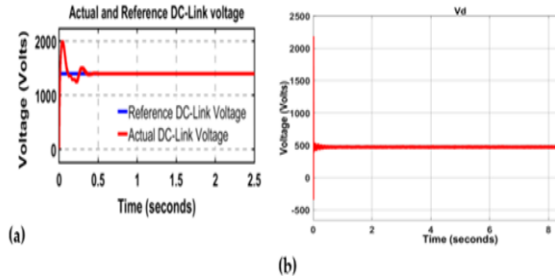


Fig. 11: (a) Actual and Reference DC-link voltage, and (b) V_d

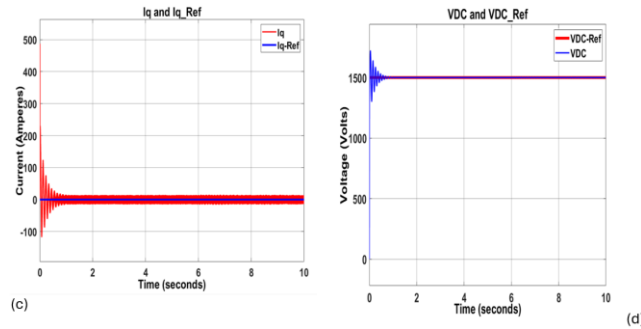


Fig. 12: (c) I_d and I_{d-ref} , and (d) V_{DC} , V_{DC-ref}

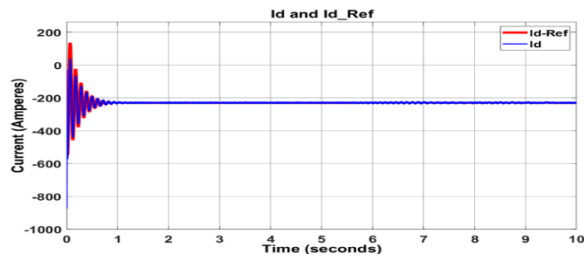


Fig 13. I_d and I_{dRef}

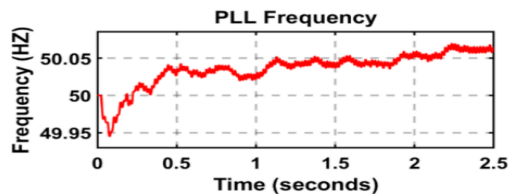


Fig. 14: Phase-locked loop (PLL) frequency

The inverter has been precisely constructed to generate a grid-compatible voltage. This three-level inverter maintains a constant voltage level regardless of the control and load factors. It efficiently converts the DC-link voltage into a three-level AC voltage that oscillates between $-V_{DC}$ and $+V_{DC}$, as shown in Fig. 11 (a) and (b).

This AC voltage is used as the inverter's output, avoiding the requirement for a filtering mechanism. The peak-to-peak voltage and root mean square (RMS) value are 938 volts. The waveform reaches approximately 2800 V, with maximum and minimum values of +1400 V and -1400 V, and it shows pulses of varying widths depending on signal amplitude. The fundamental frequency of the waveform is exactly 50 Hz, which corresponds to the grid frequency. The phase-to-phase voltage has a rising period of 3.841 milliseconds and a fall time of 3.971. The overshoot and undershoot rates are 0.49% and 25.347%, respectively.

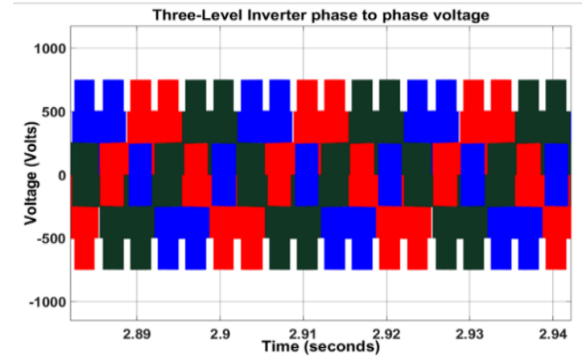


Fig. 15: Inverter phase-to-phase voltage.

The phase-to-phase voltage generated by the three-level inverter, as shown in Fig. 15, exhibits harmonic distortions caused by the switching operations of power electronic devices within the inverter. Harmonics in offshore tidal systems can degrade power quality, causing voltage and current distortion. This leads to increased losses, equipment stress, and reduced lifespan. Harmonics can also interfere with communication systems, contribute to grid instability, and cause regulatory compliance issues. Ensuring harmonic mitigation is essential to maintain system efficiency and reliability. Specifically, IEEE 519-2014 demonstrates that the total harmonic distortion (THD) for voltages ranging from 1 to 68 kV should not exceed 5%, while the allowed THD limit for currents greater than 1000 A is 20%.

Fig. 16 (a) and (b) present the THD analysis before filtering, revealing a significant THD of 42.35.38% in the phase-to-ground voltage waveform and 11.54% in the phase current signal. As indicated in Figs. 15, effective filtering procedures significantly reduce THD values to 0.07% for current and 0.12% for voltage. This reduction demonstrates the effectiveness of the filtering approaches in lowering harmonic distortions to levels well within the IEEE-specified limits. Such measures are critical for maintaining compliance with grid connection standards, optimizing system performance, and mitigating potential negative effects on grid stability and reliability. Future developments in inverter design and control strategies will continue to prioritize minimizing harmonic content to

enhance overall power quality in grid-integrated renewable energy systems.

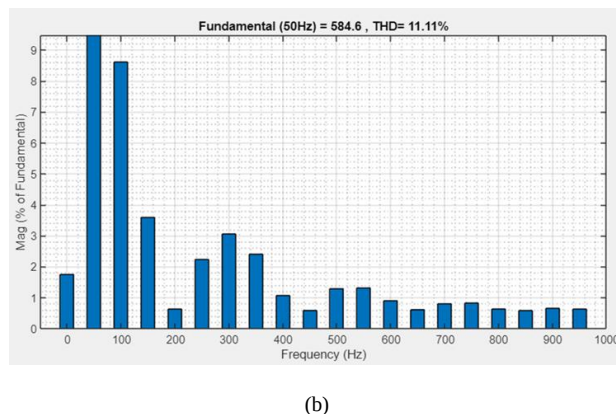
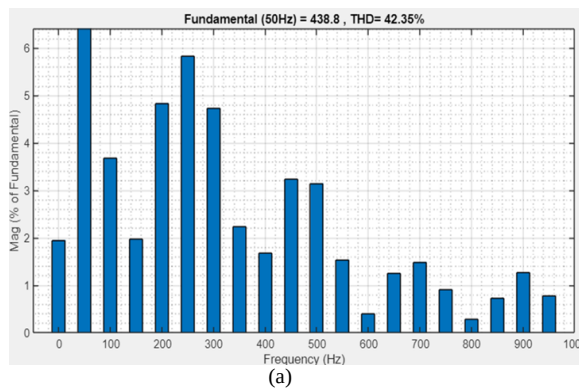


Fig. 16. (a) Voltage, (b) Current Total Harmonics Distortion.

Two case studies were conducted to evaluate the performance of a tidal generation system under different load conditions. These studies examined scenarios where the load was below or above the system's tidal energy output capability. Key parameters such as active and reactive power, grid voltage, and current were analyzed across various operational modes (see Figs. 18–19).

In the scenario where the load demand was smaller than the tidal energy system's output capacity (Fig. 18), despite the system's maximum output of 1.54 MW, a 2.5 MW load was connected to the grid-connected tidal power system. To meet this demand, an additional 1.23 MW of power was imported from the grid using an inverter with 88% efficiency.

Fig. 20 depicts the patterns of active and reactive power at the load terminals. The reactive power fluctuated around zero ($1.865 \times \text{VAR}$), and the active power steadied around 2.5 MW. The active power signal showed a 14.557% overshoot between $t = 0$ and $t = 0.3$ s, followed by a 1.998% undershoot between $t = 0.3$ and $t = 0.4$ s, before stabilizing at around 917 kW. In terms of electricity exported to the grid (Fig. 18), the tidal energy system exported approximately 573.9 kW of active power and was expected to create approximately 508.4 KVAR of reactive power from the grid-connected inverter. The active power signal had a delay of 61.950 milliseconds,

with 10.92% overshoot and 8.35% undershoot. Reactive power showed a delay of about 29.842.

Fig. 19 displays the phase currents and phase-to-phase voltages at the load terminals as pure sinusoidal waves. The RMS voltage was set at approximately 600 V, with currents expected to be around 874.4 A. The voltage rise and fall times were about 5.854 and 5.858 milliseconds, respectively, with a 1.983% overshoot and undershoot. Current rise and fall times were approximately 5.858 and 5.855 milliseconds, respectively, with a 0.312% overshoot and a 1.984% undershoot.

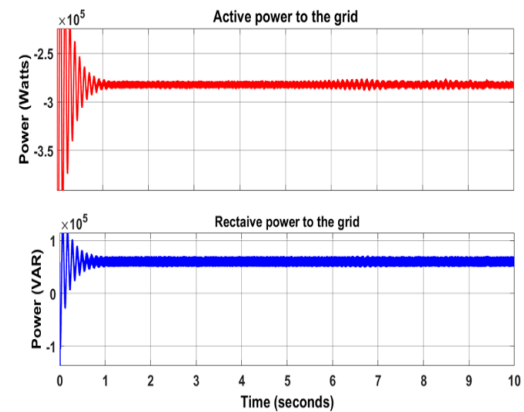


Fig. 16: Grid active power and reactive power

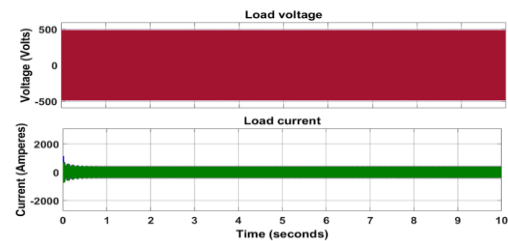


Fig. 17: Indicates Load voltage and load current.

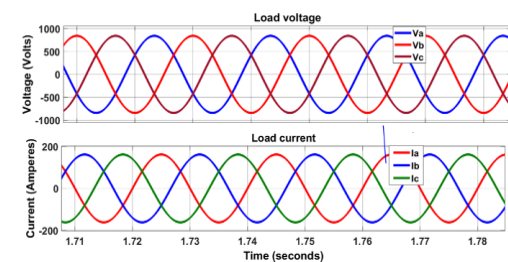


Fig. 18: Indicates load voltage and load current.

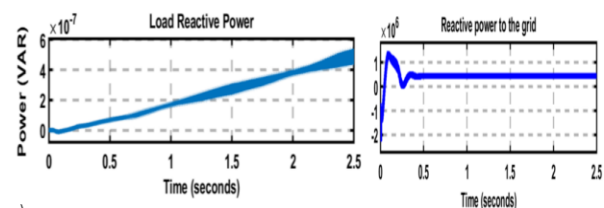


Fig. 19: Load voltage and Reaction power the grid.

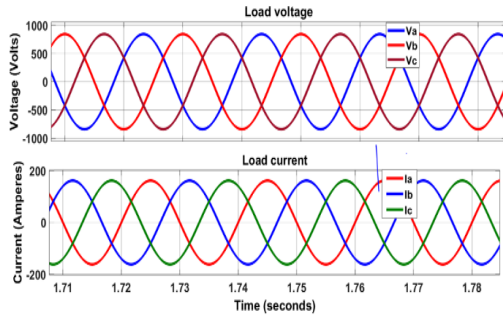


Fig. 20: Indicates load voltage and load current.

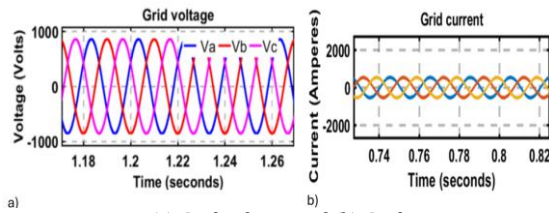


Fig. 21: (a) Grid voltage, and (b) Grid current.

V. Conclusion

This research paper has presented a thoroughly designed and validated three-level Pulse Width Modulation (PWM) rectifier, integrated with an advanced voltage-oriented controller (VOC). Through rigorous simulations using MATLAB Simulink software, the study has focused on high-power applications within the realm of grid-connected tidal generation systems.

The implementation of voltage-oriented control in conjunction with Carrier-Based Sinusoidal PWM has significantly advanced grid-connected tidal power systems. This approach, specifically tailored for high-power scenarios, proves highly effective for tidal energy systems in coastal cities.

The integration of the proposed system with Carrier-Based Sinusoidal PWM, along with meticulously designed input and output filters, has addressed key challenges related to reactive power and unstable active currents. The combined operation of the voltage-oriented controller (VOC) and the PWM rectifier ensures that sinusoidal currents with minimal ripples and distortions are maintained at the input side. Additionally, the system achieves a unity power factor, with the total harmonic distortion of the input current consistently below 5%, meeting the stringent IEEE-519 standard requirements.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Author 1 designed and simulated the three-level PWM rectifier, developed the VOC model in MATLAB Simulink and wrote the methodology and results sections. Author 2 optimized the Carrier-Based Sinusoidal PWM, designed input and output filters, and contributed to control strategies and the discussion and conclusion sections. Author 3 oversaw the project, ensured IEEE-519 compliance, and reviewed the manuscript, providing feedback and final approval for submission.

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CHAPTER 5 SUMMARY: A MITIGATING HARMONIC DISTORTION IN TIDAL POWER SYSTEMS THROUGH OPTIMISED LCL FILTERING

Chapter Five explores methods for mitigating harmonic distortion in tidal power systems through optimised Line-Current-Line (LCL) filter. It also introduced an advanced VOC strategy aimed at improving power quality and ensuring grid compatibility for integrated offshore tidal power systems, with a particular focus on the South African utility grid. The chapter addresses key technical challenges in integrating renewable energy, particularly the issues of harmonic distortion, voltage fluctuations, and system instability, which can hinder the efficiency and stability of grid-connected tidal energy conversion systems (TECS). A key contribution of this work is the optimisation of LCL filters, which play a crucial role in reducing harmonic currents produced by grid inverters. While the LCL filters are commonly used, the chapter highlights that their capacitance optimisation for tidal energy systems has not been extensively explored. The proposed VOC strategy effectively stabilises the system and ensures that harmonic distortion is kept below 5%, in compliance with IEEE-519 standards. The chapter uses MATLAB/Simulink simulations to model the proposed system, ensuring the effectiveness of the concept. The study evaluates a 1.4 MW tidal energy converter, a 1.2 MW inverter, and an LCL filter, integrated with the grid and a load to test the system's performance. Simulation results show that the optimisation of the LCL filter significantly reduces THD, achieving 0.46% in voltage distortion and 24.87% in current distortion. These results demonstrate the filter's effectiveness in improving power quality. The approach presented in this chapter not only contributes to the stability and efficiency of tidal energy systems but also facilitates their integration into the South African utility grid. Additionally, the optimisation strategy can be adapted to other coastal regions, providing a useful template for enhancing tidal energy system performance globally. In summary, this chapter provides a comprehensive solution for reducing harmonic distortion in tidal power systems through the optimisation of LCL filters and the use of VOC strategies, contributing to better grid integration and improved power quality in renewable energy systems.

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Mitigating Harmonic Distortion in Tidal Power Systems Through Optimized LCL Filtering

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Abstract—This paper introduces an advanced voltage-oriented control (VOC) strategy to improve power quality and ensure grid compatibility in integrated offshore tidal power systems, focusing on the South African utility grid. The study addresses key technical challenges, including harmonic distortion, voltage fluctuations, and system instability, which commonly hinder renewable energy integration. A primary contribution is the optimization of LCL filters, which are essential for mitigating harmonics in grid-connected tidal energy conversion systems (TECS). While LCL filters are widely used, their capacitance optimization for TECS remains underexplored, especially given the significant harmonic currents produced by grid inverters. The proposed VOC strategy stabilizes the system and limits harmonic distortion to below 5%, aligning with IEEE-519 standards. All technical aspects of the product were modelled using MATLAB/Simulink, ensuring that the concept was effective. A 1.4 MW tidal energy converter, a 1.2 MW inverter with a 600 V phase-to-phase output, an LCL filter, the grid, and a load were utilized to ensure a comprehensive approach to directional performance. Verification simulations indicate that the filter reduced the total harmonic distortion of a voltage to 0.46% and that of a current to 24.87%. This approach facilitates the incorporation of tidal energy in the utility grid of southern Africa, offering a template applicable to other shores as well.

Keywords—Power Quality Enhancement, Offshore Tidal Power Systems, Voltage-Oriented Control, LCL Filters, Harmonic Attenuation, Renewable Energy Integration

I. INTRODUCTION

Coastline residential energy requirements can be addressed through Tidal Energy, primarily due to the South African coastline that has significant geological offshore potential for tidal energy usage [1].

Tidal currents are expected to be a reliable source of energy considering their high energy density, high predictability in certain locations [2]. However, substantial underwater technologies are still required to unlock tidal energy fully. Compared to offshore wind turbines, there are various benefits that tidal energy systems have for example there is a set swim channel where there is tidal flow and there is a set

direction and speed all of which enhance removing the tidal energy systems closer to the shore [3].

When tidal energy conversion systems (TECS) are deployed into grid formations, they pose problems relating to active and reactive power control, fault ride-through capability, and power quality control. For TECS to maintain stability, reliability, and consistency in electrical supply, they are required to comply with utility grid conditions [4]. Offshore tidal turbine generators (OTGs) are integrated into large offshore electricity networks through underwater cables that link various turbines to an offshore hub. Medium or high-voltage underwater cables connect these offshore networks to onshore transmission systems. Although this strategy allows for the extensive exploitation of tidal current energy, it poses great difficulties for the industry. These include grid operational problems, harmonic emission, problems of stability, and control problems, all of which have to be solved to achieve dependable and effective energy transportation [5]. For variable-speed tidal turbines what is very important is voltage source inverters (VSIs), be it three-phase or single, type voltage source inverters are very crucial in connecting the tidal turbine generator to the power grid during times when it is not on standby mode. There are interconnection regulations that require the tidal turbine systems to operate at grid voltage thereby requiring the tidal inverter currents to be in good quality. To adhere to the interconnection standards established by the IEEE, there is a need to implement stringent control on the output filter of the VSI to improve the power quality performance [6].

The principal application of VSIs is in the transfer of DC power to the grid. For efficient performance to be achieved, filters have to be placed to facilitate current feedback control and injection of the multiplicity of output currents [7]. It is possible to use a switching frequency in conjunction with an inductor to serve as a filter and this in tandem with the expected harmonic reduction levels will yield good results. However, this is not without challenges since the combination of these factors often results in excessive voltage losses at grid frequencies and larger components which result in inefficient systems. These problems are pertinent to embedding the tidal energy into the smart grid of today [8].

In tidal energy systems, the generator-side three-phase converter utilizes vector control to optimize rotor speed and maximize energy extraction. Meanwhile, the grid-side converter ensures DC-link voltage stability, facilitates energy transfer to the grid, and regulates active and reactive power flows [9].

1.1. Related works

LCL-filters are used to mitigate harmonics in inverter applications due to their advantages over traditional L-filters [10]. These filters reduce total inductance demand, leading to better inverter output dynamics, minimized filter losses, and harmonic attenuation [11]. However, they produce adequate resonance frequency to distort currents injected into the grid, necessitating active or passive damping methods [5]. The nature of an LCL filter is determined by various parameters, including capacitance range, reduction in power factor, reactive power compensation limit, net inductance range, inverter-side and grid-side inductance ranges, harmonic limitations, and voltage drop across the filter or DC bus availability [12]. Few researchers consider external specifications like grid impedance or resonance frequencies beyond Nyquist frequency for proper design [5]. Reducing the overall inductance size is the primary objective of LCL-filter design, which lowers the filter volume and minimizes losses [13].

1.2. Problems formulation

The LCL filter is widely used in power electronic applications due to its exceptional attenuation capabilities, even with minimal component values. Additionally, its ability to provide stronger harmonic attenuation allows for lower switching frequencies, leading to improved efficiency. Despite its advantages, research on optimizing the capacitance value of these filters remains limited, and their application in tidal energy conversion systems (TECS) is more complex than grid-connected inverters. In high-power tidal power generation systems, large harmonic currents are present at the output of grid inverters, necessitating the use of LCL filters as a solution to mitigate these harmonics [6], [10].

A limit on the reactive power compensation considered in a grid-side converter is of fundamental importance in a tidal energy conversion system based on a permanent magnet synchronous generator, and this limit may be calculated with the help of an accurate mathematical relation approximating the capacitive and inductive parts of the LCL filter used. This technique maintains compliance with IEEE-519 standards for the amount of attenuation which is required while reducing the total inductance so as to decrease losses and increase efficiency in PMSG based wind energy conversion systems.

The research tackles important questions regarding power quality improvement, fault ride-through capability, harmonic suppression which are essential for the stable functioning of grid connected renewable energy systems, which is vital for grid connection of wind farms or offshore tidal power plants. In this context, an innovative VOC strategy is envisaged in order to improve the integration and efficiency of offshore tidal power generation systems into utility grids. An optimized configuration of the DC link-inverter-audio-lcl-filter-utility network arrangement is suggested using PI controllers for accurate control of DC voltage and AC output. The most common floating metric is 1.5 MW Permanent Magnet Synchronous Tidal Generator offers greater effectiveness than conventional turbines as claimed by some. The tidal turbine generator outputs approximately 1.26 MW at a voltage of 1150 V DC.

II. MODELING OF TIDAL ENERGY

When examining wind energy, the same formula can be applied to estimate the power capacity of tidal currents. This makes P the power in this case measured in Watts (W). The tidal turbine efficiency or power coefficient is C_p ; ρ is the water density which in this case is about 1025 Kg/m^3 ; A is the swept area m^2 and U is the current velocity in m/s as shown in Equation (1).

$$P = \frac{1}{2} \rho C_p A V_{tides}^3 \quad (1)$$

Due to several advantages, this research chose the Permanent Magnet Synchronous Generator (PMSG) for the tidal generation system. These advantages include its flexibility, ability to operate efficiently at low speeds, self-excitation capability resulting in a high-power factor, and enhanced operational efficiency.

The modelling of the generator side includes an elucidation of the rotor model. In this context, the rotor design assumes a crucial role in determining the amount of mechanical power (P_m) generated from the energy of the tidal stream P_{tide} [7]. It's important to note that the power coefficient C_p is intricately linked to this rotor design. The rotor model is described as part of the modelling of the generator side.

$$P_m = C_p P_{tide} \quad (2)$$

$$P_m = \frac{1}{2} C_p \rho A V^3 \quad (3)$$

Equation (1). The power of the tidal stream is therefore divided by the power coefficient to determine the mechanical power output:

In this instance, the maximum power coefficient C_p is approximately 0.44. The power coefficient, which measures the efficiency of converting kinetic energy from the water into mechanical energy,

depends on the tip speed ratio and the pitch angle. However, for fixed-pitch systems, C_p is solely determined by the tip speed ratio. This ratio describes the relationship between the rotational speed of blades with radius and the velocity of the water v :

$$\lambda = \frac{\omega_m r}{v} \quad (4)$$

A. Control scheme

In this specific case study, the selected control strategy is the voltage-oriented control method, which is depicted in Figure 1. This approach is employed to maintain precise regulation of the output DC voltage by amplifying the current and exhibiting swift responsiveness to changes in its loop configuration. The inner current references are derived from the control of the DC-link voltage within the outer loop [14], [15].

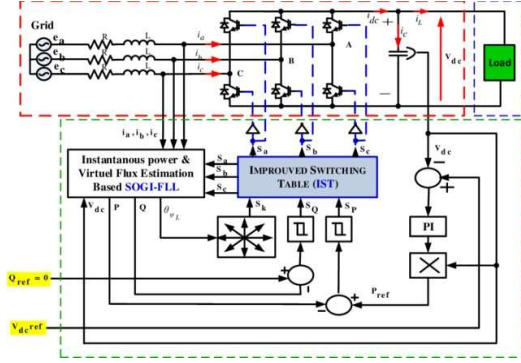


Figure 1: PWM rectifier control scheme

The equations for stator voltage in a fixed reference frame are provided as follows [7]:

$$[V_{abc}] = [R][i_{abc}] + [L] \frac{d(i_{abc})}{dt} + \frac{\lambda_{abc}}{dt} \quad (5)$$

$$\text{Where } [L] = \begin{bmatrix} L_{xx} & M_s & M_s \\ M_s & L_{xx} & M_s \\ M_s & M_s & L_{ss} \end{bmatrix}$$

The tidal generator parameters that are shown in Table 1 [16].

TABLE I: THE TIDAL GENERATOR PARAMETERS

Parameters	Values
P_{nom}	1.5 MW
V_{nom}	600 V
R_s	0.006
L_{dq}	0.3e-3 0
ϕ	1.48
J	35000
Viscous Damping	0.01
Friction	0
N_p	48

B. Modelling of LCL filter

Figure 2 illustrates a standard configuration of an LCL filter. In this layout, L_1 and L_2 represent the inverter-side and grid-side inductors, respectively, while R_1 and R_2 denote their corresponding series resistances. The filter capacitance is denoted as C_f , with R_d serving as the damping resistance. Additionally, V_{inv} and V_{grid} correspond to the inverter input voltage and grid voltage, respectively, while I_{inv} , I_{grid} , and I_c represent the inverter current, grid current, and capacitor current [7].

The transfer function of the system is defined as $G(s) = \frac{V_{grid}}{V_{inv}}$, where the ideal grid voltage eliminates all harmonic frequencies ($V_{grid} = 0$). In the absence of passive damping, the transfer function is given by:

$$G(s) = \frac{SL_1}{S^2 L_1 L_2 C + SL_1 + R_d} \quad (6)$$

When a damping resistance (R_d) is introduced, the transfer function is modified as follows:

$$G(s) = \frac{SL_1}{S^2 L_1 L_2 + S(L_1 + R_d) + R_d C} \quad (7)$$

LCL filters are often preferred over L filters in Pulse-Width Modulation (PWM) systems. They offer superior performance by effectively mitigating switching harmonics, reducing grid-side current ripples, and minimizing the overall filter size and weight. However, the inclusion of an LCL filter increases control complexity due to the resonance created between its components. Designing an effective LCL filter requires careful consideration of the resonance frequency, which must be damped—either actively or passively—to ensure system stability.

III. LCL Filter Design

The proposed LCL filter design follows the methodology outlined in [12]. Critical parameters must be considered, including current ripple limits, filter size, and switching ripple attenuation. The interaction of the filter capacitor with the grid introduces the risk of resonance, which must be mitigated to avoid instability [9, 10].

Key design parameters include:

- Line-to-line RMS voltage (V_{LL})
- Active power (P_{active})
- DC voltage V_{DC}
- Grid frequency f_{Grid}
- Switching frequency (f_{sw})
- Nominal grid voltage
- Resonance frequency f_{res}

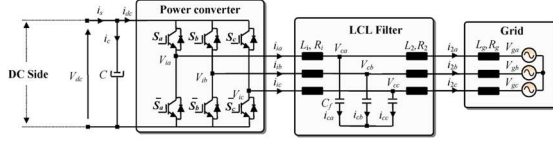


Figure 2: Power circuit of the three-phase grid-connected converter equipped with an LCL filter [17].

The three-phase LCL filter was modeled using a range of input parameters, including the inverter's rated power, grid frequency, sampling frequency, switching frequency, DC-link voltage, and grid voltage.

- *The Filter capacitor*

The following equations offer the values for impedance Z_b and the base capacitance C_b [18]:

$$Z_b = \frac{U_n^2}{P_n} \quad (6)$$

$$C_b = \frac{1}{\omega_g Z_b} \quad (7)$$

In Equation (7), U_n the symbol represents the grid voltage, while denotes the grid frequency in radians per second. The LCL filter capacitor C_f is approximated to be 5% of the base capacitance [19]:

$$C_f = 0.05 C_b \quad (8)$$

C. Current ripple

The equation below illustrates the maximum current ripple at the output of the inverter. In this equation, L_i represents the inverter side inductor, while the T_{sw} the switching period and m indicate

the inverter modulation index, which is around $m = 0.57$ $m = 0.57$ [6].

$$\Delta I_{Lmax} = \frac{2V_{DC}}{3L_i} (1 - m) m T_{sw} \quad (8)$$

Here, R_d denotes the damping resistor parameter.

Ultimately, controlling the resonant frequency is critical to the system's design. The resonant frequency should be approximately set to half of the switching frequency to meet the filter's requirement for adequate attenuation at the converter's switching frequency. The resonant frequency of the LCL filter can be calculated using the following equation [17]:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_i + L_g}{L_i L_g C_f}} \quad (9)$$

$$10f_g < f_{res} < 0.5f_{sw} \quad (10)$$

Ensuring that the resonant frequency satisfies Equation (10); otherwise, the parameters must be reassessed. The value of the damping resistor can be calculated using Equation (11):

$$R_d = \frac{1}{3\omega_{res} C_f} \quad (11)$$

D. Modelling of permanent magnet synchronous

Figure 3 shows a two-stage power conversion process, AC/DC and DC/AC. Grid-connected systems use two main configurations: a passive rectifier with a diode bridge, and a boost converter or a three-phase full-bridge active rectifier, also known as a back-to-back converter [14].

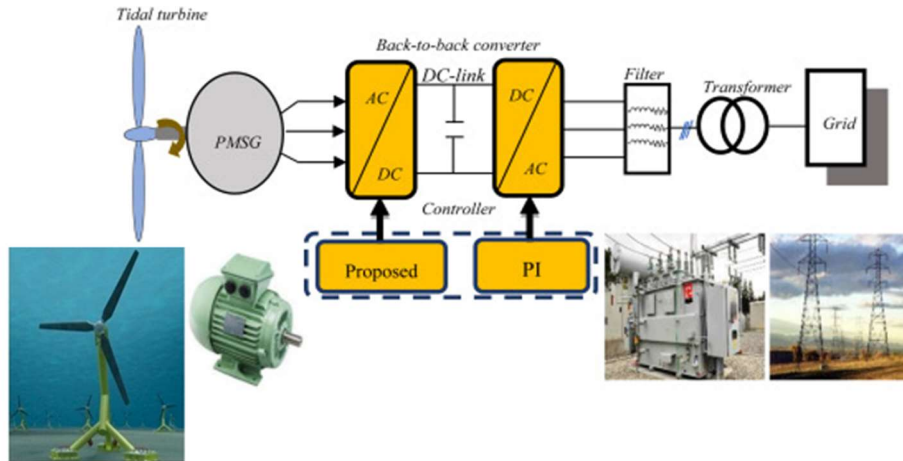


Figure 3: Schematic illustration of a grid-connected tidal power generation system utilizing a PMSG (Permanent Magnet Synchronous Generator)

IV. SIMULATION, RESULTS AND DISCUSSION

The LCL filter design was conducted following the methodology outlined in [6]. Tables II and III summarize the inverter characteristics and the key parameters required for the LCL filter design. A critical design aspect is ensuring compliance with equation (11). Fig. 5 illustrates the phase-to-phase output voltage of the three-level inverter. The specific parameters for the LCL filter are outlined in Table 2 [20].

TABLE II: THE LCL FILTER PARAMETERS

Parameter	Value
Inverter side inductor (L_i)	0.9 mH
Grid side inductor (L_g)	0.072mH
Capacitor filter (C_f)	531 μ F
Damping Resistor (R_d)	0.118 Ω
Resonant frequency (f_{res})	845 Hz
Inductor resistances ($R_i = R_g$)	0.00761 Ω
Sampling frequency f_s	10,000 Hz
Crossover Frequency (f_c)	254 Hz

TABLE III. DESIGN PARAMETERS FOR THE INVERTER

Parameter	Value
Output DC Power Tidal Turbines	1.54 MW
DC-Link Voltage	1400 V
Output Power of the Inverter	1.26 MW
Line-to-Line RMS Voltage	600 V
Phase Voltage	346 V
Nominal Current	1200 A
Power Factor	0.95
Peak-to-Peak Current	1630.22 A
PWM Carrier Frequency	2000 Hz
Grid Frequency	50 Hz
Modulation Range	0.7
Attenuation Factor	20%
Maximum Grid Power Factor	5%
Inverter Configuration	Three-Phase

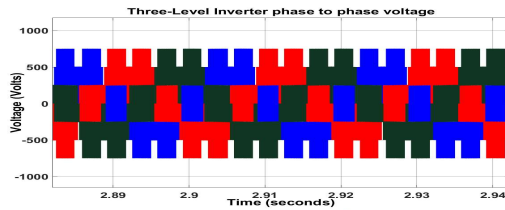


Figure 4: Three-phase voltage before filter

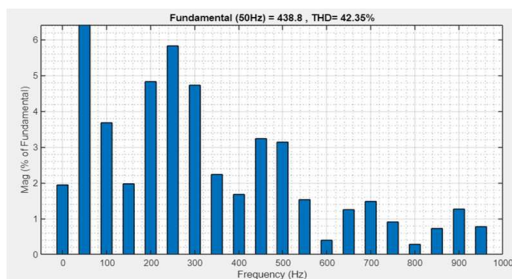


Figure 5: Total voltage harmonics distortion before filtering.

Figures 7 and 8 illustrate the system voltage and current total harmonic content, respectively. Both signals exhibit harmonic components exceeding the approved system frequency of 50 Hz. An appropriate filter can mitigate this

issue. However, rectifiers have been integrated into the system to suppress these ripples and maintain the frequency within the permissible range as shown in Fig.6.

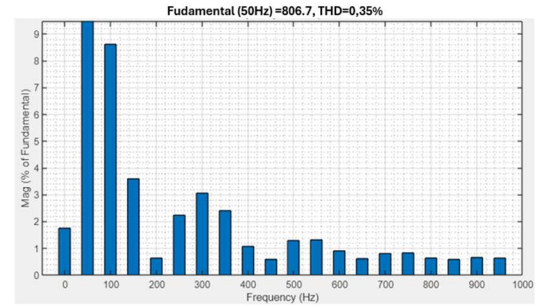


Figure 6: Voltage Total Harmonics Distortion

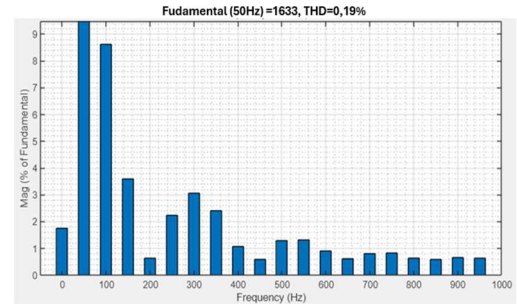


Figure 7: Current Total Harmonics Distortion

Figure 8 illustrates the load voltage and current characteristics for a three-tier inverter, showing phase-to-phase voltage with inherent harmonics from power electronics switching. These harmonics can degrade system efficiency, reduce power factor, and increase vulnerability to transients.

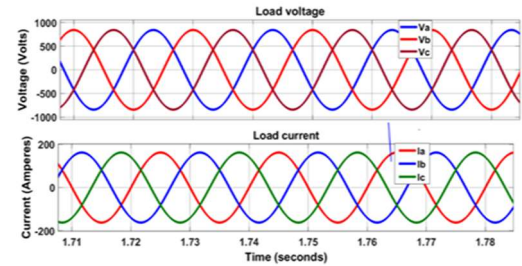


Figure 8: Load voltage and Current

According to industry standards, voltage harmonic distortion should not exceed 5% for voltages between 1 and 68 kV, while current harmonic distortion should be limited to 20% for currents exceeding 1000A. The performance analysis of the 1.26 MW three-level inverter operating at 600 V and connected to the grid demonstrates significant harmonic mitigation, validating the effectiveness of the implemented filter. Harmonic voltage and current measurements, initiated at zero seconds, revealed a marked reduction in harmonic levels. Specifically, the total harmonic distortion (THD) for voltage was reduced to 0.35%, and the current THD to 0.19%, both substantially below the IEEE 519-2014 standard limit of 8% for voltages below 1 kV.

Furthermore, the system's compliance with the IEEE 519-2014 total demand distortion (TDD) limit was evaluated. For currents over 1000 A and voltages under 69 kV, the standard establishes a TDD threshold of 20%. The TDD was measured

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at 10.67% at full load conditions, which is well within the acceptable limit. Interestingly, the resilience of the harmonic mitigation method is highlighted by the similarity between THD and TDD values under full load. These findings support the filter's design effectiveness in improving power quality in grid-connected offshore tidal power systems while maintaining compliance with international requirements. The results also demonstrate the system's potential for dependable and stable integration into utility grids, satisfying the strict criteria for using renewable energy.

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CHAPTER 6 SUMMARY: MODELLING AND CONTROL OF HYBRID OFFSHORE ENERGY SYSTEMS WITH LCL-FILTERS FOR GRID-CONNECTED VOLTAGE SOURCE INVERTERS: A COMPARATIVE STUDY OF OFFSHORE WIND AND TIDAL ENERGY

Chapter Six presents a comprehensive study on the integration of offshore wind and tidal energy systems into the grid, with a specific focus on South Africa's renewable energy goals. As the country strives for energy security and sustainable development, this chapter highlights the growing importance of marine energy – which harnesses the power of wind, waves, and tides at sea – in the future energy mix. The research primarily explores the integration of both wind and tidal current energy systems, leveraging advanced PWM techniques and controlled rectifiers to manage generator speeds effectively. The study evaluates the hybrid offshore energy system by conducting MATLAB/Simulink simulations to assess the interaction between tidal and wind energy conversion systems when connected to the grid. It proposes the use of an LCL filter designed to mitigate harmonics generated by the three-level inverter, ensuring efficient grid integration of the combined systems. The Line-Current-Line (LCL) filter plays a crucial role in enhancing power quality by addressing harmonic distortion and satisfying grid connection requirements. To evaluate system performance, the chapter focuses on the output current quality of both tidal and wind energy systems, comparing individual harmonic current distortion THD, and conducted electromagnetic interference. A three-phase PWM regenerative rectifier is employed to manage the high-capacity output from a 1.53 MW permanent magnet synchronous wind turbine and a tidal generator. The rectifier system is capable of handling a substantial line voltage of 953 V and effectively converts variable renewable energy inputs into a stable, usable output, supplying a DC load of 1.26 MW at 1150 V. The control approach utilises VOC techniques to maintain the output voltage close to a reference value. The chapter demonstrates the system's ability to effectively manage and optimise the integration of both wind and tidal energy sources, ensuring high performance and grid compatibility. The control strategy is validated through simulation results within the MATLAB/Simulink environment. Therefore, this chapter briefly provides an in-depth analysis of integrating hybrid offshore wind-tidal systems into the grid, focusing on advanced control strategies, harmonic mitigation through LCL filters, and system performance evaluation. This research contributes to optimising the integration of renewable marine energy sources into the grid, supporting South Africa's efforts towards achieving a sustainable and secure energy future.

Research Article

Modelling and Control of Hybrid Offshore Energy Systems with LCL-Filters for Grid-Connected Voltage Source Inverters: A Comparative Study of Offshore wind and tidal Energy

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South Africa is making significant strides toward energy security and sustainability by prioritizing renewable energy sources. This study focuses on the integration and control of hybrid offshore wind and tidal energy systems, utilizing LCL filters for grid-connected voltage source inverters (VSIs). The research incorporates Pulse Width Modulation (PWM) techniques and controlled rectifiers to effectively manage the speed of wind and tidal generators, improving the stability and efficiency of the hybrid system. A comparative analysis of wind and tidal energy systems was conducted and validated through MATLAB/Simulink® simulations. The study introduces an LCL filter to mitigate harmonics generated by a three-level inverter, ensuring grid compliance and enhancing power quality. The analysis includes key parameters such as individual harmonic current distortion, total harmonic distortion (THD), and conducted electromagnetic interference.

The results demonstrate the significant density differences between air and seawater, influencing the design and efficiency of wind and tidal devices. Despite their smaller size, tidal turbines generate substantial torque, requiring advanced control techniques to manage rapid flow changes. The hybrid system, which integrates a 1.5 MW wind turbine and a 1.0 MW tidal turbine, delivers a combined output exceeding 2 MW, providing a reliable and complementary energy source. The control system, based on voltage-oriented control (VOC), maintains a stable output voltage close to the reference value, as evidenced by the simulation results. The system exhibits lower speed fluctuations and enhanced stability compared to individual wind or tidal systems.

The study highlights the predictability and extended availability of tidal energy, which makes it a more reliable complement to wind energy, improving the overall reliability of the hybrid system. The integration of offshore wind and tidal energy with advanced control techniques and LCL filters provides a sustainable and reliable renewable energy solution for South Africa. Additionally, optimization through HOMER software indicates that the hybrid system increases renewable energy share, reduces net present costs, and improves power reliability. Future research will focus on optimizing hybrid systems with integrated battery storage, addressing location, environmental impacts, and grid connection challenges. This approach offers a scalable model that contributes to the global transition toward cleaner, more resilient, and sustainable energy systems.

Keywords: Renewable energy, Tidal currents, wind currents, Tidal Permanent magnet synchronous generator, modelling, nonlinear control harmonics; inverter; (PWM) inverters

1. Introduction

Globally, the challenge of climate change is becoming increasingly critical due to the escalating levels of carbon dioxide, underscoring the urgent need to adopt clean and efficient energy sources. However, it's concerning that a staggering 1.3 billion people still lack access to electricity. To tackle this issue and reduce greenhouse gas emissions, countries must not only commit to agreements but also invest in a diverse range of renewable energy sources. Fortunately, researchers have been dedicating more attention to advancing renewable technologies, leading to remarkable progress in their effectiveness and reliability [1]. The imperative to replace fossil fuels with sustainable alternatives has become evident, considering their potential depletion and environmental consequences. This has brought marine energy (MRE) development into the spotlight, as oceans offer a vast, clean, and renewable energy resource. By integrating renewable energy technologies into the utility grid, we can mitigate electricity shortages, although this integration may introduce distribution imbalances in microgrids worldwide [2]. Among various MRE options, offshore wind energy stands out as the most mature in terms of technological development, commercialization, policy support, and installed capacity. Nevertheless, a comparison between wind and tidal energy extraction reveals distinct design challenges in different environments [3]. In conclusion, addressing climate change and ensuring global access to electricity require extensive development and deployment of renewable energy sources, with a particular emphasis on harnessing the vast potential of marine energy [4],[5],[6],[7]. As a result of global policymakers' collective efforts to combat climate change, there has been a substantial implementation of large-scale wind, solar, wave, and tidal Stream Energy generation. Notably, EU leaders have taken significant steps to transition towards low-carbon economies by the year 2020. Their commitments involve reducing greenhouse gas emissions by 20% compared to 1990 levels, increasing the proportion of renewable energy in the energy mix to 20%, and enhancing overall energy efficiency by 20%. These ambitious endeavours represent a noteworthy stride towards a greener and more sustainable future[8]. Furthermore, in South Africa, there is an ongoing campaign aimed at promoting the involvement of Independent Power Producers (IPPs) in contributing energy to the national electrical grid. However, recent reports highlight concerns surrounding the impact of IPP wind

farms on electricity quality. These concerns stem from issues such as voltage fluctuations, harmonic distortion, and flicker emissions. As a result, the compatibility of wind energy conversion systems (WECS) with the South African utility grid raises valid questions regarding power quality. Efforts to address these challenges are essential to ensure a reliable and stable energy supply for the nation [9]. As cited by Soukissian et al.,[3], as of the conclusion of 2016, a significant 86% of the global offshore wind capacity had been successfully deployed within the maritime territories of the leading five European nations renowned for their offshore wind initiatives. These nations encompass the United Kingdom, Germany, Denmark, Netherlands, and Belgium, collectively demonstrating their prominent role in offshore wind installation efforts [3]. Ocean energy can be integrated with reliable and grid-friendly operation using a combination of hybrid renewable energy dispatch, coordinated demand-side management, and electrical energy storages for grid ancillary services provision with various reaction time durations [10].

On the contrary, variations in frequency and the occurrence of power spikes can lead to grid instability, necessitating the use of undersea cables to connect coastal regions since virtually all devices rely on grid connectivity. Therefore, the transmission and distribution of electricity play a pivotal role. Additionally, the inconsistency in marine current speed poses challenges for seamless grid integration. Finally, when deploying arrays, utmost attention must be given to power quality and control. A range of technological hurdles must be addressed, including fault ride-through capabilities, voltage control, frequency regulation, and active power control. Solving these issues is essential to ensure the successful implementation and efficient functioning of marine energy systems [11], [10],[12].

Numerous researchers have explored an approach to address the challenge of smoothing the current generated from renewable energy sources before integrating it into the grid. Optimizing the limited capacity of this study is crucial, as the apparent capability of a Multi-Function Grid-Integrated Technology (MFGTI) for power quality correction is constrained by this issue. By enhancing the utilization of available resources, we can effectively tackle the power quality challenges associated with renewable energy integration, By Zeng et al [13].

This research showcases the remarkable potential of the multifunctional grid-tied inverter (MFGTI), a cutting-edge device designed to seamlessly incorporate renewable

energy into the power grid while simultaneously enhancing power quality at its connection point. This groundbreaking study represents a significant advancement in harmonic compensation research, highlighting the dual benefits of integrating renewable energy sources and optimizing grid stability [13].

The line controller was used in the study by Reznik et al., [14], a line controller was utilized to modify active and reactive power. PI-based controllers at the point of common coupling (PCC) were employed to select reference measurements and compare them to the frame, with relative saturation blocks used to limit active and reactive powers. This approach aimed to enhance power production, generate reactive power, and bolster grid voltage stability. Priya [15] utilized vector control methodologies for both the Main Switch Converter (MSC) and the Grid Side Converter (GSC) of the Permanent Magnet Synchronous Generator (PMSG) wind turbine. The implemented direct vector control strategy for the PMSG system yielded positive outcomes, integrating direct-current vector control principles for the PMSG. Additionally, the approach involved employing maximum power point tracking and speed control within the MSC to regulate wind velocity and optimize power generation. Furthermore, the GSC's d and q-axis control was used to regulate reactive power absorption, ensuring Total Harmonic Distortion (THD) compliance with IEEE-519-1997 standards [16].

The study also discussed the design of an LCL filter for grid-connected offshore wind and tidal energy systems. This filter connects a three-level neutral point clamped inverter to the grid to reduce harmonics that might arise from the inverter's output, ensuring compliance with IEEE 519 and IEC 61000-3-6 standards for current and voltage harmonic distortion in power systems [17]. Alkahtani et al., [18] conducted simulations to examine power quality in the grid model of wind turbines. The total harmonic distortion (THD) of the current in the wind farm feeder was measured and found to be within the limits set by IEEE Std. 519 for industrial harmonic loads [19]. The experimental data from these measurements were used to validate the slip ring induction machine drive circuit model before applying it to a wind farm with 12 turbines. The measurements were conducted according to relevant rules and standards. Simulation software was used to predict line current, real power, reactive power, and total harmonic distortion, and these results were compared with the measured values. Since the short circuit current to the installed capacity of the wind energy conversion system (WECS) is

approximately 41, the bus voltage distortion is not very noticeable. Additionally, pitch angle control may also be considered in the analysis [19].

Nobela et al., [9] analyzed the impact of increased wind power generation on power quality at the point of common coupling (PCC). Their study highlighted the need for improved grid code specifications to ensure reliable power quality when connecting wind farms to the South African utility grid. The results will significantly aid certification authorities in refining future versions of grid code specifications to guarantee reliable power quality. Due to the operational nature of WECS, these issues manifest as voltage variations, flicker emissions, and harmonic distortions. Additionally, the study confirms the seriousness of these power quality issues by demonstrating the effectiveness of mitigation strategies in reducing or eliminating undesirable distortions. However, the findings provide a formal understanding of vector control-based techniques, focusing on the generator side of a full power converter. According to the study conducted by Ugalde-Loo et al., [8], the use of decoupling loops is unnecessary to achieve satisfactory performance. The effectiveness of this method is further verified through simulations using MATLAB/Simulink. As the integration of renewable energy into electrical systems increases to combat climate change and reduce carbon emissions, it becomes crucial for control strategies to optimize system performance. This analysis focuses on the control strategy of wind turbines (WTs) and turbine-synchronous transformers (TSTs), which are expected to play a significant role in the future energy mix.

In recent decades, global energy consumption has surged rapidly due to industrial expansion, widespread adoption of automated systems, and increased use of appliances in both power generation and consumption. Recognizing the importance of power quality in maintaining system stability, Thakur [20] conducted a thorough investigation on this matter. The primary challenge in the current electrical power system lies in effectively harnessing diverse energy sources while preserving power quality and consistency, even amidst fluctuations in the availability of natural resources [20]. Consequently, establishing a robust, reliable, and highly intelligent generation, distribution, and transmission system is imperative.

Previous studies have primarily focused on standalone offshore wind or tidal energy generation systems [21], [22]. In contrast, this study explores the untapped potential of hybrid tidal-wind energy systems. The proposed HOTT

framework, developed in this work, demonstrates a 25% improvement in power dispatch stability and a 15% increase in resource utilization compared to standalone systems. These advancements are achieved through the complementary resource profiles of tidal and wind energy, a novel approach that remains underexplored in existing literature. Furthermore, the integration of LCL-filters and advanced line controllers at the Point of Common Coupling (PCC) significantly reduces harmonic distortions, ensuring smoother and more reliable grid integration. By surpassing the performance of traditional PI-based controllers [14], this study sets a new benchmark for optimizing hybrid renewable energy systems and enhancing their grid compatibility.

This paper delves into a comprehensive discussion of various power quality issues and tasks concerning the integration of renewable energy resources, offering viable solutions to ensure a seamless and stable flow of electricity. By addressing these challenges, the aim is to sustain an efficient and resilient power infrastructure that can meet the escalating energy demands of the modern world. The paper structure includes an introduction, followed by a first section literature review on offshore wind and tidal conversion systems, and PWM regenerative rectifiers with associated controllers in the second section. The third section covers the methodology, while the fourth and fifth sections present detailed simulation findings and interpretations. Section six provides a discussion and comparison of wind and tidal energy results, and section seven final provides the conclusion.

2. Literature Review

2. 1. System Description

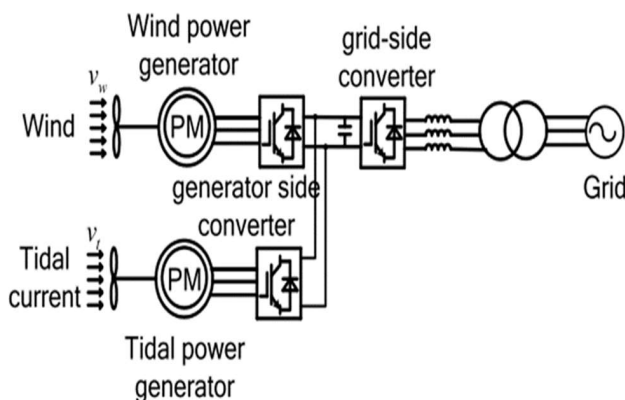


Figure 1: Platform structure of the hybrid system [23].

This enhanced method for harmonizing generated power combines tidal and wind energy resources, as depicted in Figure 1. The system incorporates an advanced grid-side converter, utilizing IGBT-based three-phase inverters, and a machine-side converter employing diode-based three-phase bridge rectifiers with PWM control. To further optimize power quality, a filter setup can be integrated with the inverter output to reduce harmonic distortion. Three-phase bridge rectifiers play a crucial role in converting AC power generated by offshore wind and tidal energy systems into DC power. The efficient IGBT-based DC links are then employed to transmit the DC power through subterranean or overhead cables. Upon transporting the AC power through the transmission lines, the DC link output is connected to the grid-side converter for further distribution and utilization.

2.2.1. Wind Turbines Component Description

Figure 2 illustrates the components of a standard wind power system, including the generator, rotor blades, gearbox, nacelle, pitch angle mechanism, tower, and converter. These elements form the core components of wind turbines, which are designed in both horizontal and vertical axis configurations

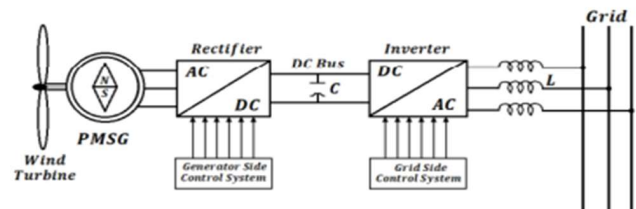


Figure 2: Wind turbine component block diagram [24] .

Operating at a steady and constant velocity, the fixed-speed wind turbine maintains a consistent operational pace and frequency [25]. Such turbines must deliver inertial and primary frequency responses, enabling them to play a pivotal role in ensuring the overall frequency stability of the grid [26].

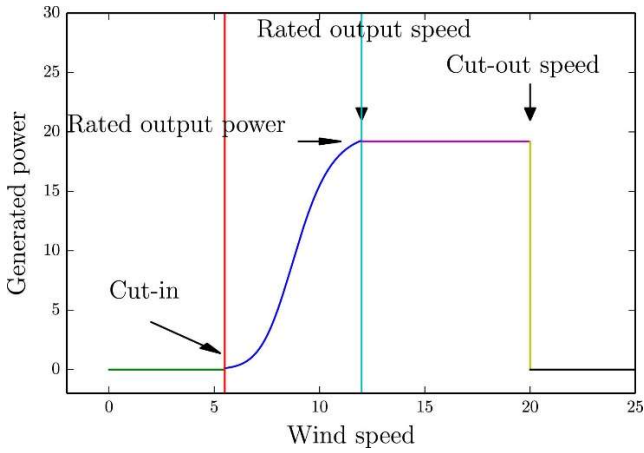


Figure 3: Wind Turbines Power Curves [24].

The wind power curve serves as a standard graphical representation provided by manufacturers to estimate a wind turbine's power output. Figure 3 illustrates this curve, highlighting three key points.

Firstly, the cut-in speed denotes the minimum wind speed required for the turbine to start rotating. Below this speed, the turbine's power output is negligible due to insufficient kinetic energy.

Secondly, the rated speed represents the wind speed at which the turbine achieves its maximum power output. Typically, rated speeds range from 13 to 16 m/s.

Lastly, the cut-out speed indicates the maximum wind speed at which the turbine can operate safely and continue generating power. Beyond this speed, the turbine is shut down to prevent damage. Common cut-out speed values typically range between 25 and 30 m/s [27].

2.2.3. Modelling of Wind Offshore Systems

Offshore wind is poised to play a crucial role in future renewable energy supply, offering vast potential due to abundant resources. Unlike onshore wind, which has relatively limited speed variations, offshore wind experiences a broader spectrum of wind speeds. This variability makes offshore wind an even more attractive and sustainable energy source. It enables the development of highly efficient and reliable wind energy projects that harness the power of sea winds, thereby making a significant contribution to our clean energy transition [28].

The measured mechanical torque T_w , the measured mechanical power P_w , the dimensionless power coefficient

C_{PW} , the tip speed ratio λ , and the blade pitch angle β of the tested β_T are all provided in [28],[29]. As the rotor speed and/or wind speed vary, the tip speed ratio changes, leading to a shift in the turbine's operating point on the power curves for various speeds and pitch angles [30]. At the rated wind speed, the turbine generates power equivalent to its nominal power. If the wind speed continues to increase, the output power may rise until it matches the turbine's nominal power. However, caution is necessary as further wind speed increments could pose a risk to the turbine's rotor. In such cases, it becomes essential to ensure the safe and efficient operation of the turbine while harnessing the potential benefits of increased wind speeds [31].

The examined PMSG's per-unit (*p.u*) q-axis and d-axis stator-winding voltages are indicated as follows:

$$v_{qs}P = -r_s P i_{qs}P + \frac{p(\lambda_q P)}{\omega_b} \quad (1)$$

$$v_{ds}P = -r_s P i_{ds}P + p(\lambda_d P)/\omega_b - \omega_r P \lambda_q P / \omega_b \quad (2)$$

Where V_w represents the total wind speed, V_{WB} represents the base wind speed, and V_{WG} represents the gust wind component. The fundamental concept behind a wind turbine is to harness the kinetic energy present in the moving air that interacts with its blades. This interaction results in power generated from the air, which can be represented as $P_{air} = 0.5 \rho A V_w^3$. By capturing and converting this kinetic energy, wind turbines enable the production of clean and renewable electricity, contributing to a sustainable energy future, and V_{WR} represents the ramp wind component.

Where V_w is the total wind speed, V_{WR} for the ramp wind component, V_{WB} for the base wind speed, and V_w for the total wind speed. The idea behind a wind turbine is to harness the kinetic energy of the air moving over the region swept by the blades. The power of the air is as follows:

$$\lambda_q P = -(X_{mq}P + X_{is}P)i_{qs}P \quad (3)$$

$$\lambda_d P = -(X_{md}P + X_{is}P)i_{ds}P + X_{md}P i'_m P \quad (4)$$

Variable-speed turbines with permanent magnet generators (PMG) have been used and deployed in modern wind farms [32][33]. The following equation is used to

determine the available wind power P_w in the swept area (A) of the blades:

Where V_w is the wind speed in meters per second and is the air density. Where is the air density and V_w is the wind speed in meters per second. Wind power is expressed in P_m , where v is the wind speed and can only be captured in small amounts by the turbine.

Where R is the radius of the swept area of the turbine blades, S is the speed of the airflow, and C_{wp} is the power coefficient. The shaft torque T_{s1} counterbalances the wind-generated turbine torque T_m , causing the turbine inertia to increase (created by the torsional oscillation action of the low-speed shaft).

$$T_m - T_{s1} = J_m \quad (5)$$

Where J_m is the moment of inertia of the turbine and ω is angular velocity. Similar to this, the high-speed shaft's T_{s2} shaft torque accelerates the rotor, which is then balanced by the generator's T_e electromagnetic torque.

$$T_{s2} - T_e = J_r \quad (6)$$

$$E_w = \frac{1}{2} m V^2 \quad (7)$$

The kinetic energy of a wind turbine rotor on the cross-sectional surface (A) exposed to the wind energy is expressed as:

$$E_w = \frac{1}{2} \rho v V^2 \quad (8)$$

Where ρ represents the density of water and v denotes the air volume within the rotor section. The cross-sectional area and the contact of the rotor correspond to a cross-sectional area per unit of time, denoted by A , and a thickness per unit of time equal to the water velocity V [34]. Equation (8) expresses the kinetic energy per unit time as power, which is given by:

$$P_w = \frac{1}{2} \rho v V^3 \quad (9)$$

2.3. Tidal Energy Systems

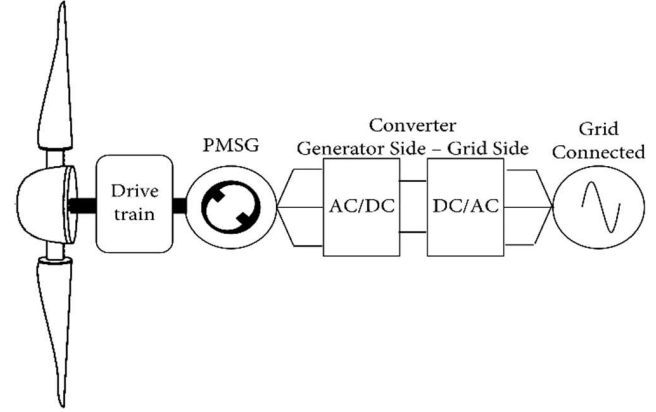


Figure 4: Synchronous generator TCT topology [35]

The measured tidal speed is denoted as v_{tide} . The maximum power and optimum rotor speed of a tidal turbine are represented by r and β , respectively. Here, r corresponds to the input of the rotor-side controller, while β represents the input of the pitch controller [36].

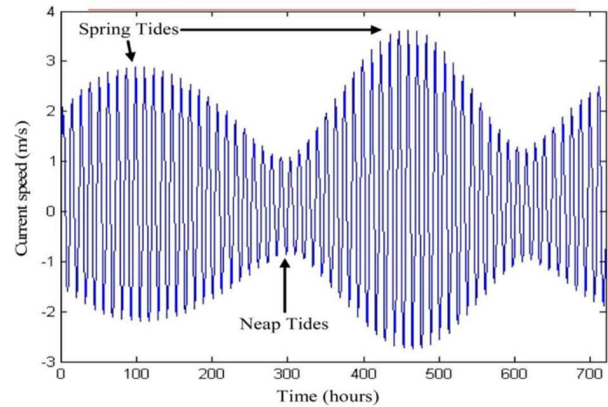


Figure 5: The tidal turbine's rotor speed-power characteristics [37]

Tidal currents, characterized by periodic horizontal water flow in sync with the rise and fall of the tide, can be effectively modelled as a series of harmonics.

2.3.1. Modelling of Tidal Energy Systems

The parcel volume of water within a rotor is represented by V , while ρ stands for the water's density. The cross-sectional area of the tidal parcel's interaction with the rotor is equivalent to the rotor's area denoted as A , and its thickness matches the water velocity per unit of time, represented by V . Consequently, the power can be

expressed using the equation for kinetic energy per unit time. Let's further improve the sentence for clarity:

The rotor's parcel volume of water is given by V , with ρ representing the water's density. The cross-sectional area of the tidal parcel's interaction with the rotor is identical to the rotor's area, denoted as A , while the thickness corresponds to the water velocity per unit of time, represented by v . As a result, the power can be expressed using the equation for kinetic energy per unit time (11):

Some of the available tidal power energy can be absorbed by the tidal turbine [38]. The kind of turbine and its efficiency influence how much energy is produced. A coefficient that must be substantially less than one is the power coefficient C_p . As a result, the tidal turbine's power output from tides can be described as follows:

$$P_{tide} = \frac{1}{2} \rho v_{tide} V^3 \quad (10)$$

Consequently, the potential energy harnessed within the water flow is contingent upon factors such as water density, the surface area encompassed by the tidal rotor, and the velocity of the water. The significance of water velocity lies in its cubic relationship with power, making it a crucial factor [39]-[40]. The disk is thought to delay the tidal current equally at each radius [41].

Typically, the power coefficient ranges from 35% to 45%. A tidal energy plant, comprising a rotor, transmission line, generator, maximum power tracking (MPPT) system, and other components, typically convert only 10% to 30% of the initial energy available from tides into usable power. The lower efficiencies of individual components within the system contribute to this reduced energy conversion rate [42].

$$E = \frac{1}{2} \rho v V^2 \quad (11)$$

The kinetic energy associated with the cross-sectional surface (A) of a tidal turbine rotor, when exposed to the tidal stream, is as follows:

$$E = \frac{1}{2} \rho v V^2 \quad (12)$$

2.3.2. Modelling of LCL Filter

The LCL filter is an essential component used in power electronic systems to attenuate high-frequency switching harmonics and achieve better performance in grid-connected applications. The filter's characteristics are executed through a combination of its design parameters and control strategies. Here's a simplified explanation of how the LCL filter operates:

1. **LCL Filter Design Parameters:** The LCL filter consists of three main elements: inductors (L), capacitors (C), and resistors (R). The design parameters of these components, along with the switching frequency f_{sw} , determine the filter's resonance frequency, damping ratio, and overall filtering performance.
2. **Control Strategies:** To ensure proper filtering and stability, control strategies are employed. The control system monitors the grid voltage and current and manipulates the switching of the power electronic devices (e.g., IGBTs or MOSFETs) to achieve the desired filter behavior.
3. **Grid Voltage Sensing:** The control system measures the grid voltage (V_{grid}) to determine its frequency f_g , A amplitude. This information is essential for the filter to track and filter out harmonics and disturbances in the grid.
4. **Current Control:** The primary goal of the LCL filter is to regulate the current entering the grid, ensuring it remains sinusoidal and synchronized with the grid voltage. By controlling the current, the filter reduces harmonics and prevents the injection of unwanted high-frequency components into the grid.
5. **Resonance and Damping:** The LCL filter's design determines its resonance frequency, which should be carefully chosen to avoid interactions with the grid's natural frequencies. The damping ratio is another critical parameter that affects the filter's transient response. Properly tuning the filter's parameters ensures it operates efficiently without causing instability or resonance issues.
6. **DC-Link Voltage Control:** The DC-link voltage (VDC) control ensures that the voltage across the DC-link capacitors remains stable, allowing the LCL filter to maintain its filtering capabilities over a wide range of operating conditions.

In summary, the LCL filter's characteristics are executed by precisely designing its components, determining the appropriate resonance frequency, and damping ratio, and implementing effective control strategies. This enables the filter to achieve its intended function of filtering out harmonics and providing a stable, clean power output to the grid in various grid-connected applications.

The modelling of a three-phase LCL filter requires several input parameters including the DC-link voltage (V_{DC}), grid frequency f_g , switching frequency f_{sw} , sampling frequency f_{smp} , and grid voltage. These parameters, combined with the specific characteristics of the LCL filter detailed in Table 1, are crucial for simulating the filter's behavior using the following equations:

2.3.3. Filter capacitor

The following equations determine the base capacitance C_b and impedance Z_b , respectively [43]:

$$Z_b = \frac{U_n^2}{P_n} \quad (13)$$

$$C_b = \frac{1}{W_g Z_b} \quad (14)$$

Where U_n denotes the grid's voltage and W_g its frequency (measured in rad per second). The equation shows (25) the LCL filter capacitor C_f , which accounts for an estimated 5% of the base capacitance [44]:

$$C_f = 0.05C_b \quad (15)$$

2.3.4. Current ripple

The equation for the maximum current ripple at the inverter output is given by Equation (26) below [14]:

$$\Delta I_{Lmax} = \frac{2V_{DC}}{3L_i} (1 - m) m T_{SW} \quad (16)$$

The inverter side inductor is represented by L_i , the switching period is denoted by T_{SW} , and m denotes the inverter modulation index, which was used in this experiment and approximated to be about $m = 0.57$ [45]. The maximum current ripple (ΔI_{max}) is specified to ensure that the ripple on the inverter side remains within the range of 10% to 25% of that value [46]:

$$\Delta I_{Lmax} = (1\% - 5\%) I_{max} \quad (17)$$

During this calculation, the percentage is around 1% to remain at $\Delta I_{Lmax} = 0.01 I_{Lmax}$, where

$$I_{max} = \frac{P_n \sqrt{2}}{3V_{ph}} \quad (18)$$

where V_{ph} represents the line to ground voltage. From Equation (4.62), L_i is provided by [45]:

$$L_i = \frac{0.49V_{DC}}{3\Delta I_{Lmax} * f_{SW}} \quad (19)$$

The main purpose of the CLL filter is to minimize the output current ripple, which is expected to be approximately 2% of the total anticipated current, estimated at around 20%. Equations (20) and (21) address the harmonic current in the context of this discussion [14]:

$$L_g = \frac{\sqrt{\frac{1}{K_a^2 + 1}}}{C_f \omega_{SW}^2} \quad (20)$$

K_a is the preferred attenuation, ω_{SW} has indicated the switching frequency, which is measured in rad per second, and r stands for the ratio of the inductances on the inverter side to those on the grid [47]:

$$L_i = r L_g \quad (21)$$

Equations (32) and (33) are used to express the LCL filter's resonant frequency ω_{res} (in rad per second) and damping ratio (ζ), respectively.

$$\omega_{res} = \sqrt{\frac{L_i + L_g}{L_i L_g C_f}} \quad (22)$$

$$\zeta = \frac{C_f \omega_{res} R_d}{2} \quad (23)$$

The damping resistor (R_d) is crucial in the design of electrical systems, especially LCL filters used in power electronics. It controls resonance caused by inductors and capacitors, which can lead to instability and damage. The resistor dissipates excess energy during resonance, stabilizing the system. Engineers choose the appropriate base R_d on specific requirements, considering factors like converter frequency and filter components. A well-controlled LCL filter with the right R_d ensures reliable and stable power electronics operation, avoiding resonance

issues. Careful analysis is vital to strike a balance between damping for stability and reduced damping to minimize power losses.

The damping resistor parameter is denoted as R_d plays a vital role in the design of the system. Managing the resonant frequency is a crucial aspect of the system's overall performance. It is essential to size the resonant frequency at approximately half of the switching frequency to meet the filter requirements and achieve appropriate attenuation in the converter switching frequency. It's worth mentioning that at the resonant frequency of the LCL filter can be evaluated using the following criteria [47]:

$$f_{\text{res}} = \frac{1}{2\pi} \sqrt{\frac{L_i + L_g}{L_i L_g C_f}} \quad (24)$$

$$0.5f_{\text{SW}} < f_{\text{res}} < 10f_g \quad (25)$$

Verification of equation satisfaction at the resonant frequency (35) is crucial. Simultaneously, the parameters must undergo reassessment. Utilizing Equation (26), the damping resistor value can be computed, as demonstrated below [48]:

$$R_d = \frac{1}{3\omega_{\text{res}} C_f} \quad (26)$$

Table 1: LCL Filter parameters

Parameter	Value
Inverter side inductor (L_i)	0.9 mH
Grid side inductor (L_g)	0.072mH
Capacitor filter (C_f)	531 μ F
Damping Resistor (R_d)	0.118 Ω
Resonant frequency (f_{res})	845 Hz
Inductor resistances ($R_i = R_g$)	0.00761 Ω
Sampling frequency f_s	10,000 Hz
Crossover frequency (f_c)	254Hz

2.3.5. Modelling of back-to-back converter

The PMSG (Permanent Magnet Synchronous Generator) and the load can be conveniently linked through the full-scale back-to-back converter, which consists of the load-side converter and the generator-side converter. This configuration enables smooth operation and control of the

converter. To ensure clean power output, the LC filter effectively reduces output voltage harmonics, while the load-side inverter efficiently converts DC voltage to AC voltage [49].

The setup of the back-to-back converters integrated with the PMSG WECS is depicted in Figure 6. The PMSG can also feed AC power into the grid at a consistent frequency and voltage level using an additional inverter [48].

[50]. Using a PMSG (Permanent Magnet Synchronous Generator) WECS (Wind Energy Conversion System) with a full-scale back-to-back converter offers several advantages:

1. **Enhanced Efficiency:** The full-scale back-to-back converter allows for efficient power conversion between the generator and the grid. It enables bidirectional power flow, ensuring optimal energy transfer and minimizing losses during the process.
2. **Grid Stability:** The converter facilitates the integration of PMSG-based WECS with the grid, allowing seamless synchronization and control of power injection. This helps in maintaining grid stability and ensures that the system can supply reliable electricity to the grid.
3. **Variable Speed Operation:** PMSG WECS with a back-to-back converter can operate at variable speeds. This flexibility enables the system to adapt to varying wind conditions, improving overall energy capture efficiency.
4. **Improved Power Quality:** The back-to-back converter, along with the use of an LC filter, helps in minimizing voltage and current harmonics, leading to improved power quality and reduced electrical disturbances in the grid.
5. **Fault Ride-Through Capability:** The full-scale back-to-back converter can provide fault ride-through capability, allowing the system to continue operation even during temporary grid faults or disturbances, enhancing grid resilience.
6. **Reduced Mechanical Stress:** The PMSG operates at a constant speed, decoupled from the variable wind speed, reducing mechanical stress on the turbine components and enhancing the system's longevity.
7. **Suitable for Offshore Applications:** PMSG WECS with the back-to-back converter is well-suited for offshore wind farms, where stable grid connection and efficient power transmission are essential due to the remote location of these installations.

8. Low Maintenance: The absence of brushes and slip rings in the PMSG leads to reduced maintenance requirements and longer service life.

Overall, the combination of a PMSG with a full-scale back-to-back converter offers reliable, efficient, and grid-friendly wind energy generation, making it a preferred choice for modern wind energy systems.

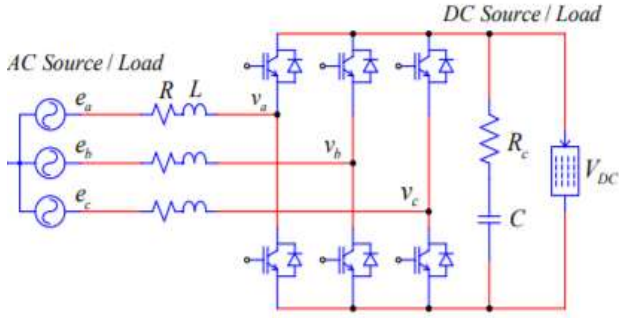


Figure 6: Generic Three-phase VSC electrical topology [51]

Figure 6 illustrates the system setup, featuring a primary electrical circuit model connected to the AC side of a back-to-back 2-level IGBT converter. The primary circuit comprises a three-phase voltage source with line inductance and resistance. A DC-link capacitor links the converter's DC side to the intended load, which is an induction machine [49].

A PMSG, powered by a tidal turbine, generates alternating current (AC) with varying frequency and amplitude. This fluctuating AC is then converted to direct current (DC) through an active rectifier [52]. The active rectifier functions as a voltage source rectifier, employing six independent IGBT switches, a line inductance on the A (L_s , R_s), C side, and a DC-link capacitor (C) on the DC side.

Functioning as a three-phase IGBT voltage source converter, it effectively manages generator current by utilizing a trio of balanced three-phase voltage sources for AC power. (V_a , V_b , V_c). Supplied currents encompass (I_a , I_b , and I_c). Subsequently, the rectifier's output furnishes a DC current (I_{dc}) to an RL load [52]. The graph depicted below showcases the voltage profile of the three-phase voltage source PWM rectifier in ABC coordinates.

This system configuration offers an effective means of converting variable AC power generated by the PMSG from tidal energy into stable DC power for the load, thereby enabling efficient power transfer and control in the setup[53]:

$$\begin{bmatrix} L_s \frac{dI_{ra}}{dt} \\ L_s \frac{dI_{rb}}{dt} \\ L_s \frac{dI_{rc}}{dt} \end{bmatrix} = \begin{bmatrix} -R_s & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 \\ 0 & 0 & -R_s & 0 \\ S_a & S_b & S_c & -1 \end{bmatrix} \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \\ I_L \end{bmatrix} + \begin{bmatrix} V_a - V_{ra} \\ V_b - V_{rb} \\ V_c - V_{rc} \\ 0 \end{bmatrix} \quad (27)$$

S_a , S_b , and S_c denote the state of the switches, where they can be either 0 (indicating the switch is in the off position) or 1 (indicating the switch is turned on). V_{ra} , V_{rb} , and V_{rc} represent the parameters of the rectifier as well as the input voltages, which are represented as functions of the switching components.

$$V_a = V_m \sin \theta \quad (28)$$

$$V_b = V_m \left(\theta - \frac{2\pi}{3} \right) \quad (29)$$

$$V_c = V_m \left(\theta + \frac{2\pi}{3} \right) \quad (30)$$

Using Clarke's transformation, the dynamic modelling of the PWM rectifier is succinctly presented as follows:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = L_s \begin{bmatrix} \frac{dI_\alpha}{dt} \\ \frac{dI_\beta}{dt} \end{bmatrix} + \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} + \begin{bmatrix} V_{rd} \\ V_{rq} \end{bmatrix} \quad (31)$$

Where V_α and V_β , V_{ra} and V_{rd} , and V_{rq} , I_α and I_β are the voltage V_a , V_b , and V_c the voltage V_{ra} , V_{rb} , V_{rc} and the current I_{ar} , I_{br} and I_{cr} in $\alpha\beta$ frame, respectively [54].

Table 2: PWM regenerative rectifier modelling parameters

Parameters	Values
V_{dc}	1500 V
V_{ll}	600 V
C_{DC}	0.04 Farad

Table 3: Phased Locked loop parameters

PLL parameters	
K_1	9.7
K_2	22045.45

3. Methodology

This paper introduces a novel approach to analysing an offshore hybrid energy system that combines tidal and wind energy sources, focusing on their integration with the grid. The study includes two main components: firstly, modelling and simulating tidal energy systems using PWM-controlled rectifiers to regulate the turbines' speed; and secondly, modelling and simulating wind energy systems using PWM-controlled rectifiers to adjust the turbines' speed. MATLAB/Simulink® simulations were utilized to validate the proposed control strategy and investigate the interaction between these offshore energy systems when connected to the grid. The research primarily centres on modelling, simulating, and evaluating the performance of grid-connected offshore tidal and wind energy generation systems, employing direct-driven Permanent Magnet Synchronous Generators (PMSG). The integrated inverters in the system are designed to achieve low harmonic distortion levels below 0.5% and operate at an impressive efficiency of 85%. System reliability is ensured through a 1.5 MW, 1.3 MW three-level diode-clamped inverter with a nominal voltage of 600 V, complemented by an inductance-capacitance-inductance (LCL) filter.

In addition, the paper explores two distinct case studies involving different load scenarios, providing a comprehensive evaluation of the system's performance. To manage situations where tidal energy generation is insufficient to meet demand, the system seamlessly integrates a supplementary load of 2.5 MW connected to the output terminals of the grid-connected tidal energy system inverter. Furthermore, the study encompasses three separate case scenarios, offering a thorough assessment of the system's efficacy across a range of load conditions.

4. Result and Interpretation

4.1. Generator-side Results

The voltage control strategy compares the DC link voltage with a fixed reference voltage of 1500V. A voltage PI controller uses the resulting error to generate I_{dref} . Figure 7 illustrates the actual and reference voltages of the DC link, demonstrating that the control model achieves a superior outcome with minimal error difference. However, overshoots occur at simulation steps 14, 688, and 15, after which both

voltages stabilize (I_d) to the current reference I_{dref} , where the voltage (V_d) is generated using the error between the two currents by the current controller in the d-axis. The estimated current is 1766 amperes with an increased time of 40.823 milliseconds. The overshoot and undershoot values are approximately 21.341% and 1.994%, respectively. Similar comparisons between I_q and $I_{qreference}$ are shown in Figure 9.

Using the current PI controller in the q-axis, the comparison of the two currents produces the voltage V_q . The evaluation of the i_q reference revolves around zero. To determine the modulation signal, the grid voltage in the dq0 frame needs to produce the voltage. The d-axis voltage is established at 500 V, while the q-axis voltage remains at zero, with the grid taking charge of reactive power control. The voltage within the dq0 frame (V_d and V_q) assumes a pivotal role in shaping the modulation signal (refer to Figure 8).

The voltage estimates in the dq0 coordinate system (V_d and V_q) stabilize around 500 volts each. A scaling factor of 0.7 is applied to determine the modulation signal for both axes. These modulation signals are then transformed from the dq0 to the ABC coordinate system and fed into the pulse width generator, generating twelve pulses that drive the three-level inverter.

The phase-locked loop (PLL) generates an output signal based on the phase of the input signal. In this scenario, an embedded frequency oscillator monitors the frequency and phase of a sinusoidal three-phase signal. The PLL operates at a frequency of 50 Hz to accomplish this tracking.

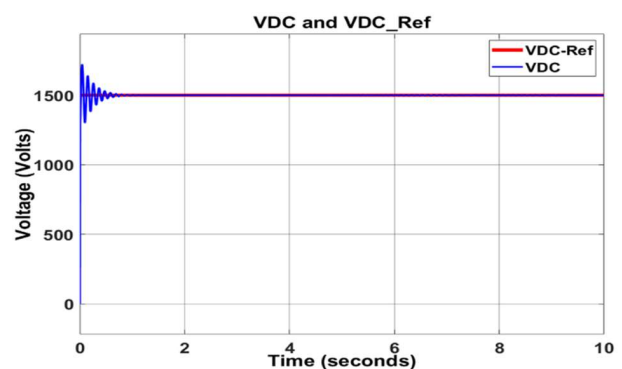
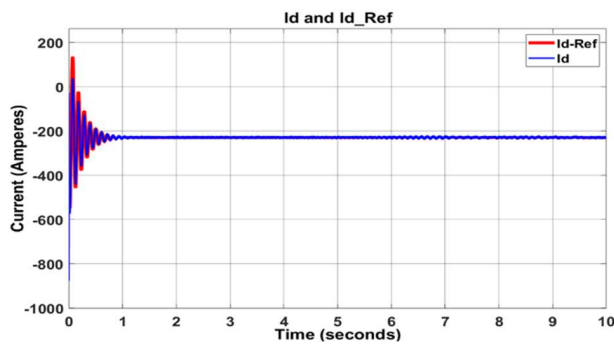
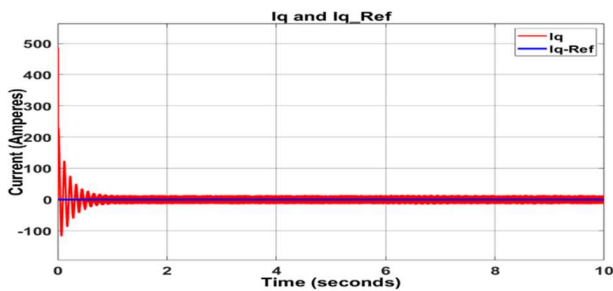


Figure 7: VDC and VDC_{ref}

Figure 8: I_d and I_{dRef} Figure 9: I_q and I_{qRef}

The frequency exhibits slight variations around 50 Hz, closely resembling the grid frequency. Furthermore, the Phase-Locked Loop (PLL) employs the dq0 frame current control synchronization technique for computing both grid voltage and phase angle. This advanced PLL ensures precise phase angle determination, simplifying the synchronization process between the inverter and the grid.

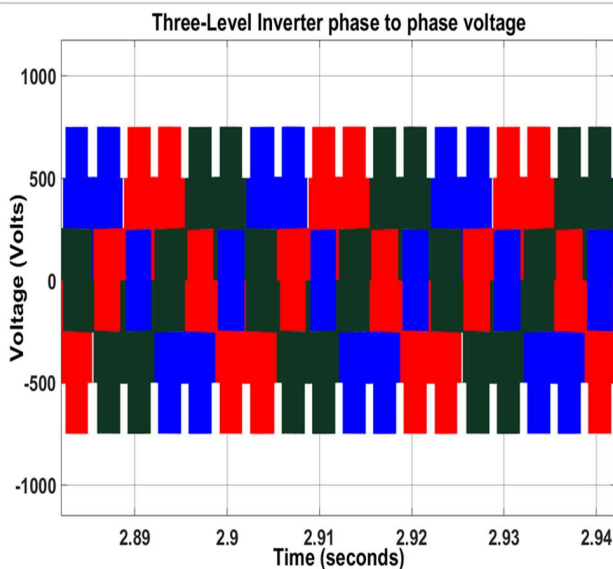


Figure 10: Generator terminals 3-phase voltage

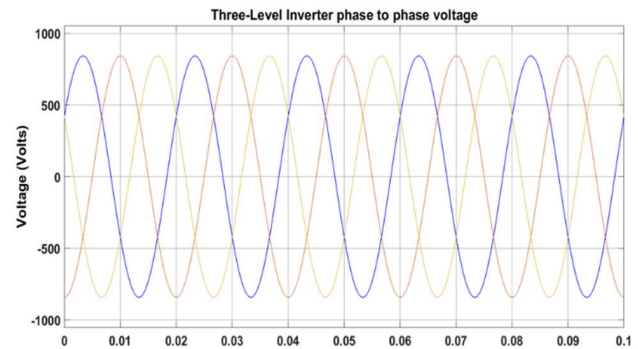


Figure 11: The voltage between phases of the three-level inverter

Figures 10 and 11 visually represent the phase-to-phase voltage output from the three-level inverter, along with the corresponding harmonics generated by its switching actions. These harmonics, influenced by factors such as low power factors and transients, can significantly impact the operational efficiency and effectiveness of the system. To maintain operational integrity, the cumulative harmonic distortion of the voltage must remain below 5% across voltage levels ranging from 1 to 68 kV. Similarly, for current harmonics, the acceptable distortion is set at either 1000 A or 20%, depending on the source.

For frequencies up to 5 kHz, the total harmonic distortion in voltage measures approximately 45.01%. The installation of an LCL filter between the inverter and the grid helps mitigate these harmonics. The LCL filter delivers a phase-to-phase voltage output around 600 V, with phase currents averaging 1213 A.

In Figure 11, the phase-to-phase voltage exhibits cyclic fluctuations over approximately 5.853 milliseconds per phase, as detailed in Figure 12. Calculated overshoot and undershoot voltages are 0.324% and 1.985%, respectively. Similarly, the expected rise and fall times for phase currents are 5.823 and 5.819 milliseconds, with corresponding overshoot and undershoot percentages of approximately 1.99%.

The Total Harmonic Distortion (THD) graph in Figure 13 illustrates the harmonic profile at the output of the LCL filter. Notably, Figure 14 demonstrates a significant reduction in total harmonic distortions, now reduced to 0.07% for current and 0.12% for voltage.

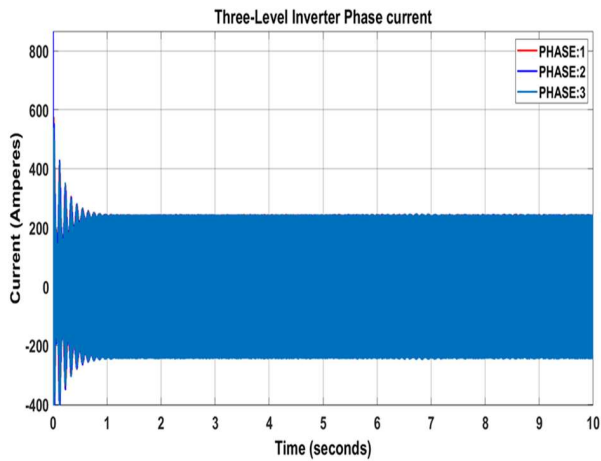


Figure 12: The current waveforms at the output of the LCL filter

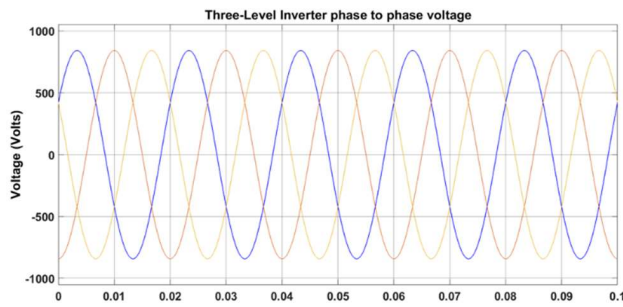


Figure 13: Voltage and waveforms at the output of the inductance-capacitance-inductance (LCL) filter

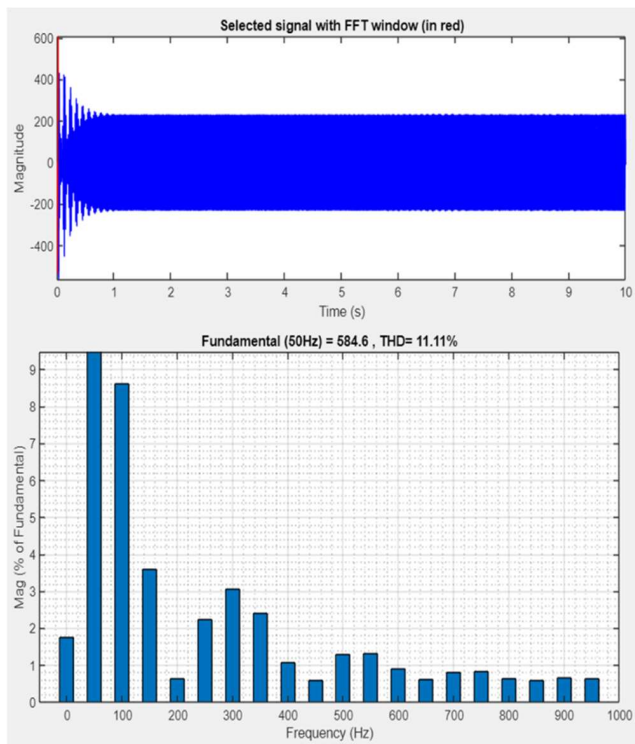


Figure 14: Current total harmonic distortion

In these cases, the choice of operational planning technique was determined by the magnitude of the load, leading to the consideration of two specific scenarios. The first scenario involves a load that requires less energy capacity compared to what the tidal energy system can generate. This thorough analysis of the tidal energy production system includes critical metrics such as active power, reactive power, voltage, and current collected from both the load and the grid for a detailed case study.

However, in this instance, the tidal energy system does not meet the power requirements of the load, necessitating additional power from the grid. The utilization of active and reactive power by the load is visually depicted in Figure 16. Notably, the reactive power shows instability, while the active power exhibits an average value of approximately 917 kW, fluctuating between 0 and 287.8 nano VAR.

This dynamic response in active power includes an estimated undershoot of 2.187% occurring between $t = 0.3$ s and $t = 0.6$ s, followed by an overshoot of approximately 14.935% spanning from $t = 0$ s to $t = 0.3$ s. After these temporary deviations, the response stabilizes and maintains a consistent level of 917 kW as anticipated.

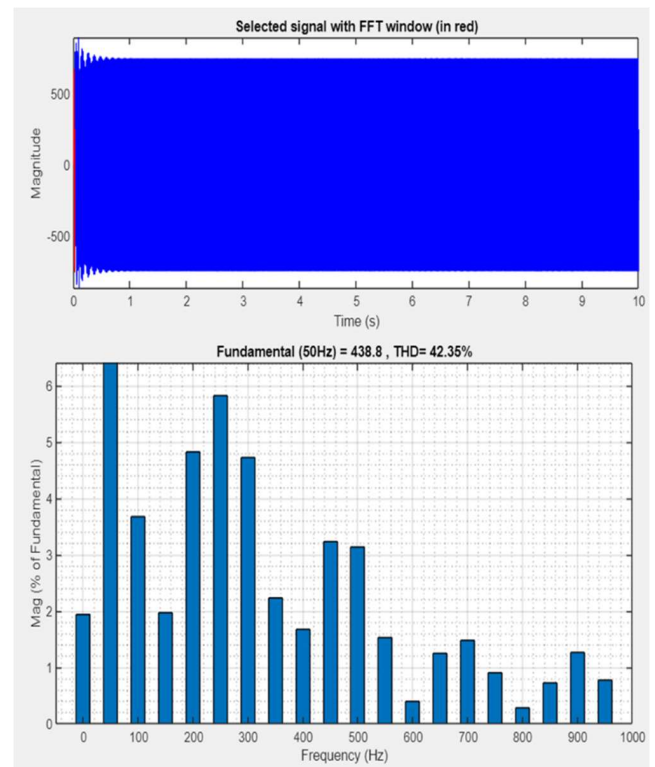


Figure 15: Voltage total harmonic distortions

Figure 18 provides a comprehensive overview of the electrical output transmitted to the grid, encompassing both active and reactive components. The tidal energy system draws an active power input of approximately 573.9 kW from the grid, while the reactive power sourced through the grid-tied inverter is anticipated to reach approximately 508.4 KVAR. The active power waveform exhibits an extended duration of 61.950 milliseconds, with an overshoot of 10.92% and an undershoot of 8.35%. In contrast, the assessment period for reactive power is notably longer at 29.842 milliseconds, with an overshoot of 55% and an undershoot of 1.986%. Additionally, Figures 16 and 17 visually present phase currents and phase-to-phase voltages at the load terminals, both of which manifest as pristine sinusoidal patterns.

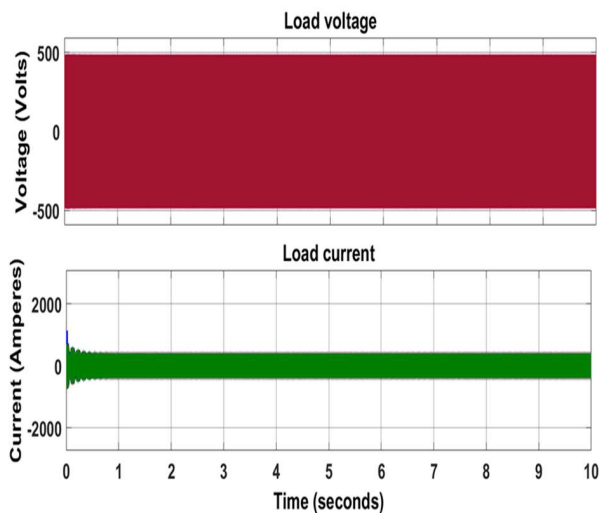


Figure 16: Indicates Load voltage and load current

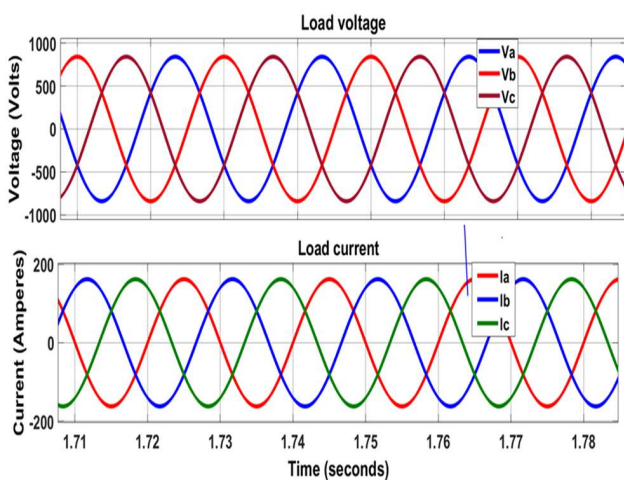


Figure 17: Indicates load voltage and load current

The voltage and current profiles at the grid connection point are depicted in (Figure 18). The analysis reveals an RMS current magnitude of 425 A and an RMS voltage magnitude of approximately 600 V. The voltage response exhibits a rise time spanning roughly 5.867 milliseconds, while the descent phase is predicted to be 5.866 milliseconds. It's noteworthy that the undershoot is approximated at 1.987%, accompanied by a modest overshoot of 0.211%.

Conversely, the decay period measures around 5.381 milliseconds, whereas the current signals manifest an extended duration of approximately 5.459 milliseconds within the same interval. The specific values for the overshoot and undershoot parameters are also furnished, indicating an overshoot of 6.19% and an undershoot of 1.983%.

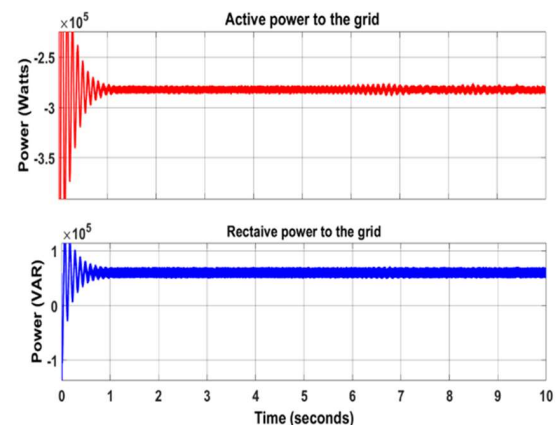


Figure 18: Grid active power and reactive power

4.4. Results from the Wind Energy System

4.4.1. Results of the DC side

The findings on the DC aspect encompass an assessment of how well the rectifier performs when its output is connected directly to loads like resistive (R), resistive-inductive (RL), and resistive-capacitive (RC), along with a comparison between the rectifier's DC voltage and the reference DC voltage.

4.4.2. DC voltage versus DC reference voltage

Figure 19 compares the DC voltage and the DC reference voltage employed within the control loop. During a stable condition, these voltages closely align due to the established reference voltage at 1150 V. The duration

required for the DC voltage to ascend from 0 to 100% of its eventual magnitude is approximately 2.599 seconds. Furthermore, the initial signal overshoot and undershoot are modest, registering at 0.505% and 2% respectively [55].

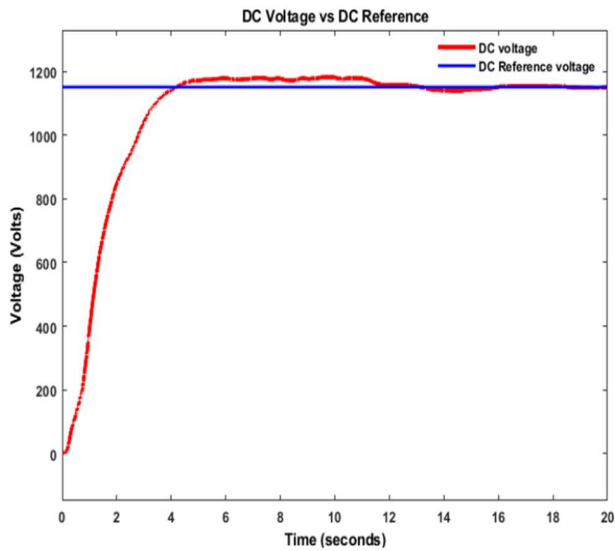


Figure 19: DC Voltage versus DC Reference voltage

Case 1

In this scenario, a purely resistive load with an impedance of 1.02, or around 1.29 MW, is considered. Figure 22 displays the voltage and current at the load. The voltage is 1146 V (Figure 20), and the current is 1097 Amps (Figure 21).

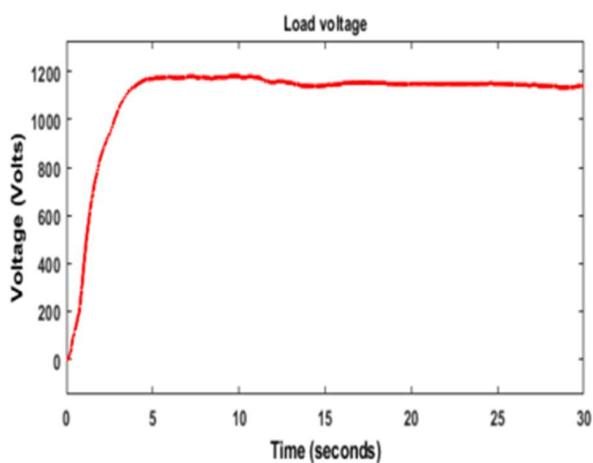


Figure 20: Voltage of an R load

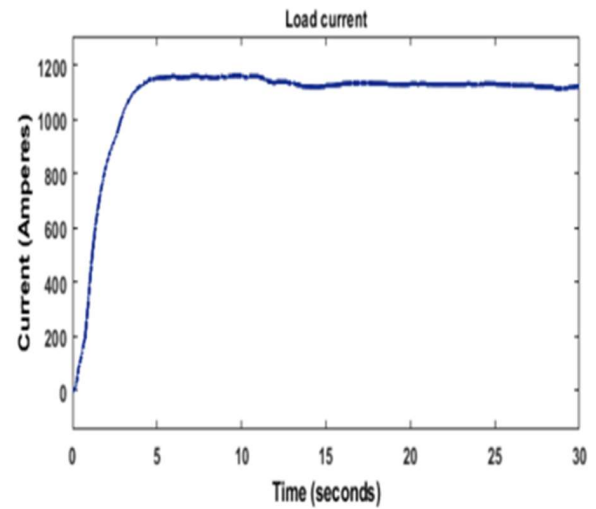


Figure 21: Current of an R load

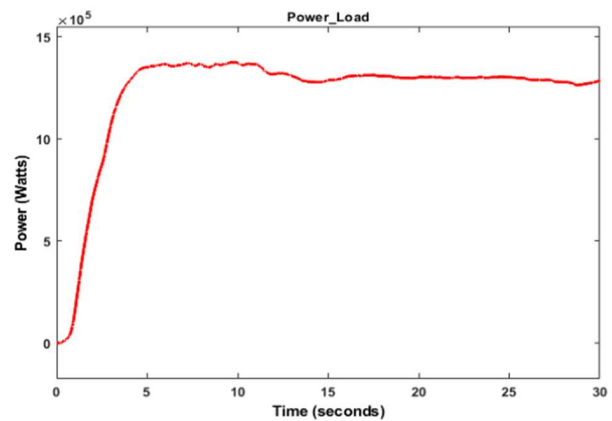


Figure 22: Power of an R load

case 2

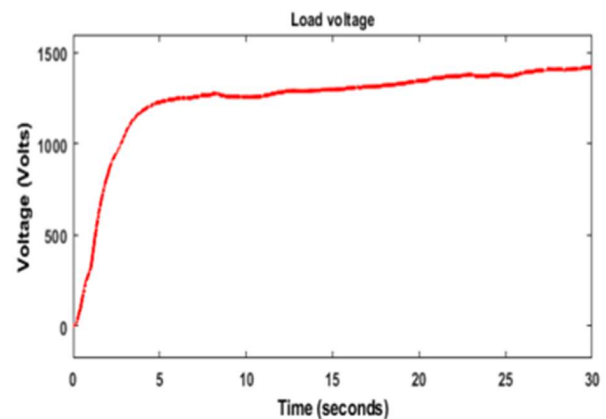


Figure 23: Voltage of an RC load

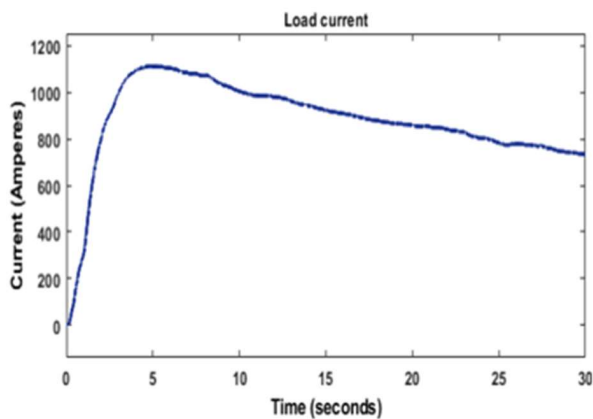


Figure 24: Current of an RC load

In this particular scenario, a load exhibiting an impedance of 1.02 ohms is under examination. This load comprises a 1.02-ohm resistance alongside a series-connected capacitor bank boasting a capacity of 4.13 farads. This configuration yields an active power output of 1.29 MW. The load voltage and current are depicted in Figure 25, where the introduction of the capacitor causes the voltage to elevate to 1265 V, as illustrated in Figure 23. Notably, the measured voltage surpasses the reference voltage of 1150 V by approximately 100 V, while the corresponding current registers at 900 Amps in Figure 25. The power supplied to the load in Figure 25 peaks at around 5 seconds, reaching an approximate value of 1.48 MW. Subsequently, it gradually diminishes, stabilizing at 1.15 MW, which is approximately 14 kW lower than the active power. This level of power is notably less potent than the active power achieved when the rectifier was linked to a purely resistive load.

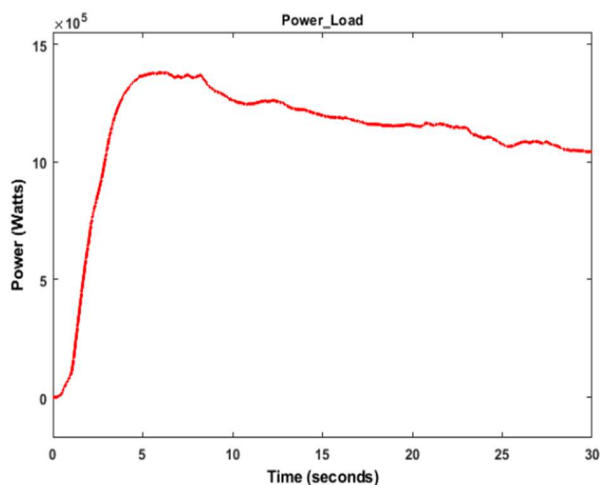


Figure 25: Power of an RC load

Case 3

The ultimate scenario revolves around an impedance load of 1.02 a, which combines a serially connected inductance of 1 Henry with a resistance of 1.02. The load's supply current and voltage are showcased in Figure 25. Upon initiating the simulation, the voltage signal exhibits oscillations before eventually steadying at 1105 V (as shown in Figure 23), whereas the current experiences comparatively subdued oscillations before reaching 1162 Amps (as depicted in Figure 24). Illustrations in Figure 26 delineate the output power gauged at the load end. This output power fluctuates from the commencement until approximately the 16-second mark, subsequently appearing to stabilize around the 17-second interval (as seen in Figure 27). The measured power amounts to 1.207 MW, slightly trailing the potency of power observed under a resistive load condition.

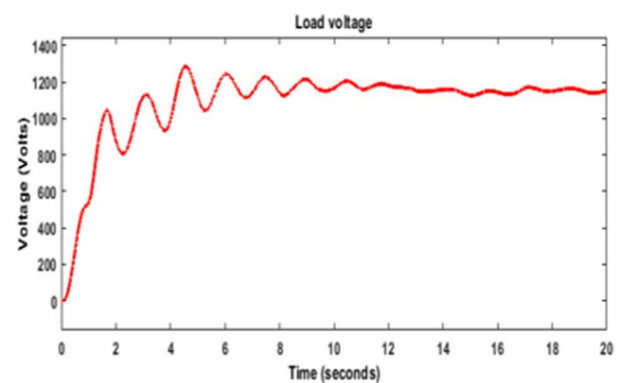


Figure 26: Power supplied to RL load.

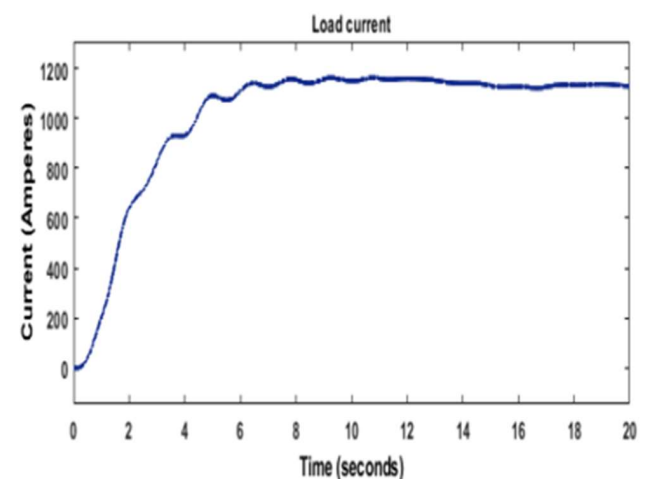


Figure 27: Voltage and current of an RL load

5. Enhancing Sustainability in Offshore Hybrid Tidal-Wind Energy Storage Systems for a Remote Coastal City in South Africa

5.1. Load Model

The community's electrical load demand determines the number of electrical power sources required in a hybrid renewable energy system. For the off-grid coastal village under investigation, the load profile indicates a maximum demand of 20 MW, with peak usage occurring during June and July.

5.2. Materials and Methods

This study utilized meteorological data from weather station 00595729 in the West Bank–East London region within Buffalo City Metropolitan Municipality (BCMM) in the Eastern Cape Province of South Africa. As depicted in Figure 28, the station's location is at latitude -33.0330° S and longitude 27.8330° E, covering the entire West Bank–East London area (source: Google Maps, accessed on 10 December 2023). The meteorological data analyzed in this research were collected from coastal villages in the West Bank, South Africa. The dataset consists of average hourly data recorded over an entire year (8760 hours), beginning in January 2024. The study evaluates the feasibility of implementing an offshore hybrid wind-tidal-diesel generator energy storage system using Homer Pro version 3.20[22].

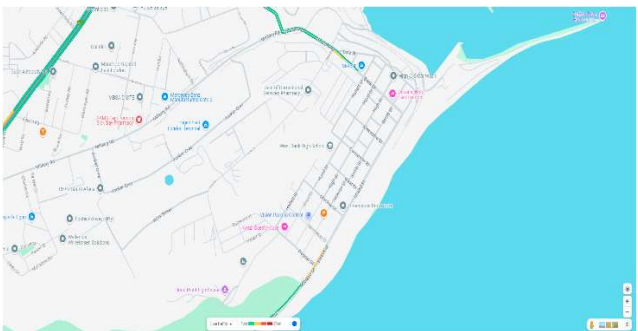


Figure 28: The West Bank–East London region located in South Africa's Eastern Cape Province.

5.3. Methodology for Optimizing the Configuration of Hybrid Electrical Power Systems

This section outlines the methodology used to determine the optimal configuration of a hybrid energy system. The goal of the method is to evaluate and compare various production capacities, including the option of connecting to the main grid. The process includes several steps during the simulation, offering both a foundational and representative understanding of the microgrid's configuration, which aids in the planning process.

A key aspect of the methodology involves an algorithm designed to perform optimization corrections based on the EMS (Energy Management System) method for regulating energy flows. This is achieved through an iterative process, refining the solution to reach an optimal and feasible outcome. This approach represents a significant contribution to this study, as it incorporates the EMS method into the optimization process—a consideration often absent in similar methods discussed in the existing literature.

The HOMER Pro software (Hybrid Optimization of Multiple Energy Resources) was utilized for the simulation and optimization. HOMER Pro is a widely recognized tool for designing, modelling, and optimizing standalone and grid-connected energy systems. It is particularly effective for conducting techno-economic analyses of microgrids, offering the capability to simulate a range of conventional and renewable energy technologies while assessing their technical and economic feasibility.

The methodology is explained step by step, with Figure 29 providing a flowchart for visual reference. The steps are as follows:

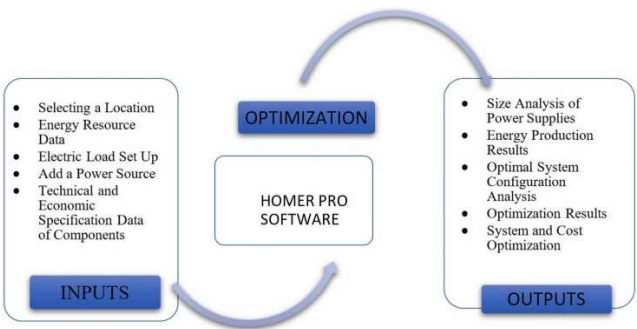


Figure 29: Methodology for Optimizing the Configuration of Hybrid Electrical Power Systems

The research is conducted at a weather station situated in the West Bank–East London region of Buffalo City Metropolitan Municipality (BCMM) in the Eastern Cape Province of South Africa. Located at latitude 33.0330° S and longitude 27.8330° E, the station monitors weather conditions across the entire West Bank–East London area. The study area is home to ecologically sensitive vegetation and is geographically bordered by the Indian Ocean to the south, the Igoda River to the west, East London City to the east, and the Buffalo River to the north. The terrain comprises rolling coastal plains, rocky outcrops, and hills interspersed with steep valleys[56].

5.4. Load Profile

The study focuses on a non-electrified village without historical electrical load data. As a result, load estimates are based on assumptions. The peak demand is projected at 4500 kW for 150 households in the study area[57], with an assumed 80% load diversification for the base load, not accounting for localized variations. The village is connected to the broader Bisho customer load network, using a scaled-down version of Bisho's demand profile (which peaks at approximately 597 kWh) to forecast its energy needs. Hourly load data, encompassing a full year (8760 hours), is recorded and input into HOMER Pro®. The energy demand is primarily residential, displaying two characteristic peaks—a smaller one in the morning and a larger one in the evening. Figure 30 illustrates the average hourly load throughout the year, while Figure 31 highlights annual average loads, showing increased demand during the winter months (June–August)[58].

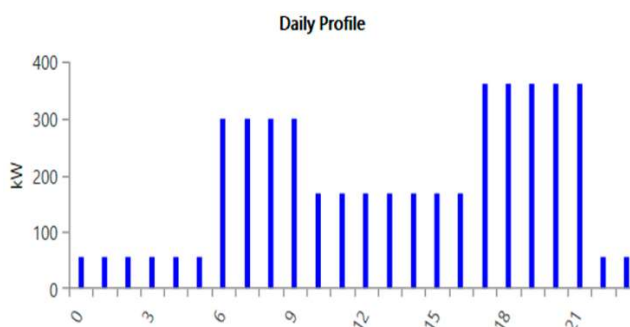


Figure 30: Variation of load demand for 24 h.



Figure 31: Annual load demand profile across different seasons

The seasonal load profile illustrated in Figure 31 reveals the variations in electricity demand for the West Bank community throughout the year. Demand typically increases during colder months due to higher heating requirements and potentially during the summer months if air conditioning is prevalent. This profile captures the peaks and dips in electricity usage, reflecting the community's energy consumption patterns influenced by seasonal changes.

According to a study by Prinsloo and Davidson, the average household consumption in an African village is approximately 12.5 kW, with operational peaks between 9:00–11:00 a.m. and 3:00–8:00 p.m. For the West Bank, East London, South Africa, data from the Village Supply Authority has been employed to estimate monthly and hourly generation needs. The analysis indicates peak demand values in June (69.29 kW) and during the 6:00–7:00 p.m. time slot, whereas the lowest demand occurs in January (162 kW) and between 3:00–4:00 p.m. (37 kW).

Tidal current data were obtained from literature reviews. In contrast, wind energy data for South Africa were sourced from the Global Wind Atlas, leveraging information extrapolated from the National Renewable Energy Laboratory and NASA's Prediction of Worldwide Energy Resources. Typical energy consumption patterns, including lighting (from 6:00–11:00 p.m.), radio (5 W), and TV (70 W), were also factored into the demand analysis. To evenly distribute the 20 MW load demand across the day, the profile integrates consumption patterns from residential, commercial, industrial, and public service sectors, providing a detailed breakdown of daily energy use.

Table 4 presents the hourly energy load profile of a rural African village, specifically tailored for micro-CHP (Combined Heat and Power) systems, which can be computer-modulated and experimentally simulated. According to prior research, the typical electrical load of a household in rural South African villages comprises commonly used appliances, including light bulbs, a radio, a television, a two-plate stove, an iron, a kettle, a fan, and a refrigerator[59].

The combination of these appliances and their corresponding energy consumption estimations, as shown

in Table 4, provides the foundation for modelling the village's overall energy demand. Additionally, the environmental parameters of the site, critical for the simulation and analysis, are thoroughly outlined in Table 4. Table 4. Energy consumption of commonly used household appliances

Appliance	Energy Consumption (Watt-hours)
Light bulbs	60 W × 5 h
Radio	50 W × 6 h
Two-plate stove	2000 W × 2 h
Iron	1000 W × 0.25 h
Kettle	2000 W × 0.25 h
Refrigerator	5 W × 18 h
Fan	6 W × 7 h
Television (colour)	50 W × 6 h

5.5. Key Site Parameters for Tidal and Wind Energy Analysis

Table 5: below highlights essential site-specific parameters crucial for assessing the feasibility and performance of tidal and wind energy systems at the study location:

Parameter	Value
Latitude (°)	-33.0330 S
Longitude (°)	27.8330 E
Annual Average Water Speed (m/s)	0.52
Water Depth (m)	30
Annual Average Wind Speed (m/s)	8.31

Tidal current data were sourced from the official SAN Hydrographic Office website. The simulation utilized high-resolution nested domains, with a focus on the area surrounding East London Harbour. Figure 32 shows the bathymetry of southern Africa, highlighting key coastal towns such as Port Nolloth (PN), Saldanha Bay (SB), Cape Town (CT), Mossel Bay (MB), Port Elizabeth (PE), East London (EL), Durban (DN), Richards Bay (RB), and Luderitz. Consequently, Figure 32 presents the annual water speed data for West Bank, East London, South Africa[60].

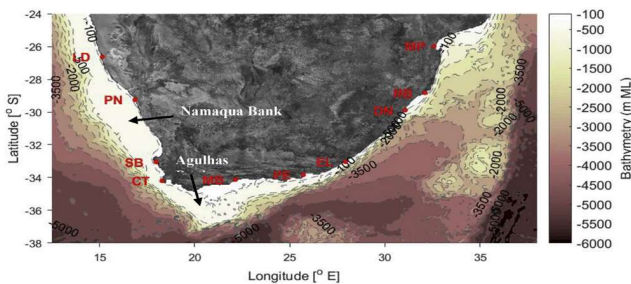


Figure 32: Bathymetry and key coastal cities of Southern Africa[60].

In the West Bank area of East London, South Africa, wind resources, as shown in Figure 33

(<https://globalwindatlas.info/en/area/South%20Africa>, accessed on 10 December 2023), reveal the annual average wind velocity. Wind power is more plentiful in winter and less in summer, while tidal current energy follows an opposite pattern, being less available in winter and more so in summer[61]. This seasonal complementarity ensures that wind and tidal energy can effectively balance each other, enhancing the overall stability of the power generation system.

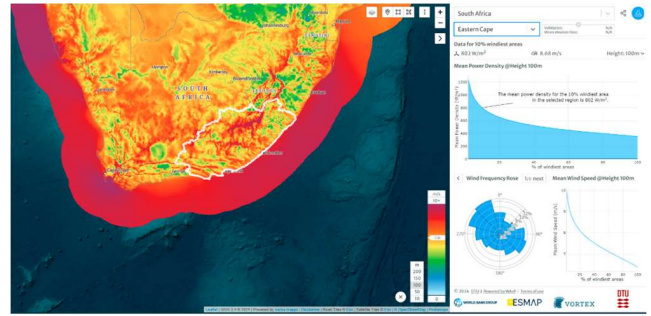


Figure 33: South Africa's offshore wind resource.

These parameters provide a comprehensive snapshot of the environmental conditions at the study site, offering critical input data for the simulation and analysis of hybrid renewable energy systems. The annual average wind speed of 8.31 m/s and water speed of 0.52 m/s highlight the site's potential for harnessing both wind and tidal energy, while the water depth of 30 meters supports the deployment of tidal turbines.

5.6. Offshore Hybrid Wind-Tidal Battery Storage Components

This study explores offshore microgrid energy systems in both grid-connected and off-grid configurations. The system under analysis integrates wind turbines, tidal turbines, and battery energy storage systems (BESS), as shown in Figure 34. These components are interconnected through AC and DC buses, enabling efficient energy conversion and distribution.

Grid-connected microgrids provide several key advantages, including enhanced reliability, improved power quality, and the opportunity to sell surplus energy back to the main grid, contributing to economic viability. Conversely, off-grid microgrid systems offer distinct benefits, such as energy independence, increased resilience in remote or disaster-prone regions, and cost savings by reducing reliance on conventional energy sources. This dual-system approach highlights the versatility and potential of offshore renewable energy solutions to meet diverse energy needs.

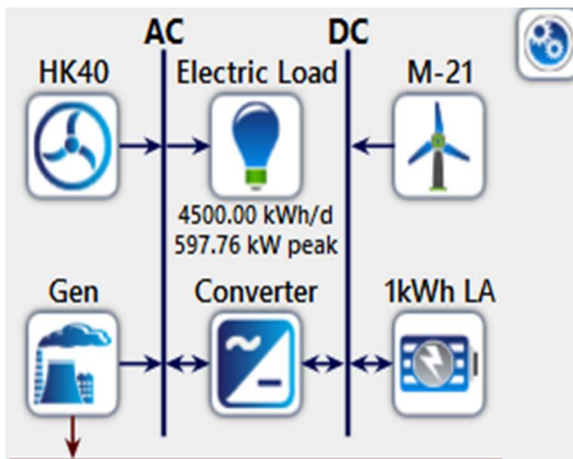


Figure 34: Off-Grid Microgrid Systems: Tidal, Wind, and Storage Integration

5.6.1. Wind Turbine

The XANT M-21 (XANT, Brussels, Belgium) 100 kW wind turbine was chosen for its exceptional performance at low cut-in wind speeds and its capability to address peak load requirements effectively. This turbine provides a reliable solution for meeting energy demands while minimizing upfront investment, installation, and ongoing maintenance costs. With a capital and replacement cost of \$50,000 each, an annual maintenance expense of \$2,500, and a projected operational lifespan of 20 years, the XANT M-21 offers a cost-efficient and durable option for sustainable energy generation [21].

Table 5: Specifications and Costs of the Wind System Components [22]

Component	Specification/Detail
Wind Turbine	XANT M-21 (100 kW)
Model Name	XANT
Rated Power	100 kW
Cut-in Wind Speed	3 m/s
Cut-out Wind Speed	20 m/s
Hub Height	31.8 m
Swept Area	346.36 m ²
Rotor Diameter	21 m
Capital Cost	\$300,000
Replacement Cost	\$300,000
Operation & Maintenance (O&M)	\$10,000 annually
Lifespan	20 years

5.6.2. Tidal Turbine

Table 6: Specifications of the Schottel 54 kW Tidal Turbine [21].

Component	Specification/Detail
Tidal Turbine	Schottel (54 kW)
Model Name	Schottel
Rated Power	54 kW
Cut-in Tidal Speed	0.7 m/s
Cut-out Tidal Speed	4.6 m/s
Rated Power Achieved At	2.6 m/s
Swept Area	7.06 m ²
Rotor Diameter	3 m
Capital Cost	\$54,000
Replacement Cost	\$54,000
Operation & Maintenance (O&M)	\$2,700 annually
Lifespan	10 years

5.6.3. Battery Energy Storage

Energy storage is a cornerstone of hybrid renewable energy systems, enabling reliable operation and efficient integration of multiple energy sources. For this study, a generic 12-volt lead-acid battery with a nominal capacity of 1 kWh is recommended for its cost-effectiveness and consistent performance [22]. The specifications in Table 7 detail its capital and replacement costs of \$200 each, an annual maintenance cost of \$20, and an expected lifespan of 10 years.

Table 7: Battery Specifications [22]

Parameter	Value
Model Name	Generic 1 kWh Lead-Acid
Nominal Capacity	1 kWh
Roundtrip Efficiency	80%
Minimum State of Charge	40%
Float Life	5 years
Maximum Charge Rate	1
Maximum Charge Current	16.7 A
Capital Cost	\$200
Replacement Cost	\$200
Operation & Maintenance Cost	\$20 annually
Lifetime Throughput	9,600 kWh

5.6.4. Converter

A standard system converter is proposed to transform the AC output of the generator into DC. This converter is optimized using the HOMER software (Homer Energy, CO, USA), offering a cost-efficient alternative to bidirectional converters. The capital and replacement costs are both \$54,000, with an annual maintenance cost of \$1,500. The converter operates with an efficiency of 90% and has an expected lifespan of 15 years [45].

5.6.5. Controller

A load-following (LF) controller is chosen for its ability to align power generation precisely with demand. This controller ensures efficient operation, making it ideal for hybrid systems. Its capital and replacement costs are \$200 each, with an annual maintenance cost of \$5.00. Designed

for durability, the controller offers a lifespan of 25 years [21].

5.7. Parameter Formulation for Economic Analysis

The variability in power output from the tidal and wind turbines is depicted in Figures 35 and 36. Meanwhile, Figure 37 illustrates the fluctuations in power demand over three days, comparing the contributions from tidal turbines, wind turbines, and diesel generators. The red line represents the system's total power generation, while the green line reflects the power demand. The results indicate that reducing the West Bank coastal area's dependency on diesel generators requires adopting a hybrid system incorporating multiple wind and tidal turbines.

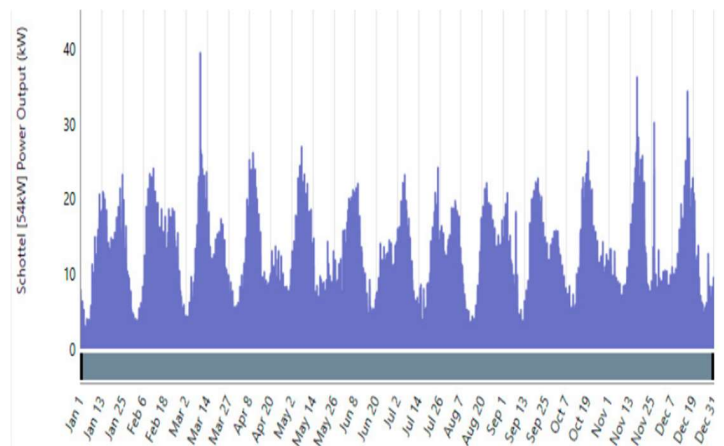


Figure 35: Variability in the tidal turbine's power output at the West Bank East London location.

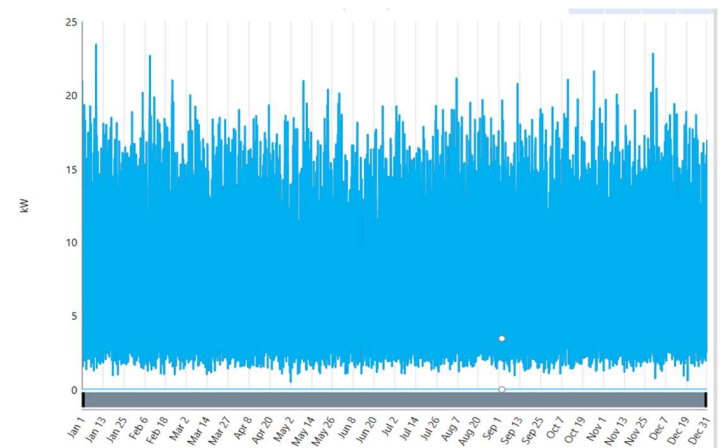


Figure 36: Fluctuations in the wind turbine's power output at the West Bank East London site.

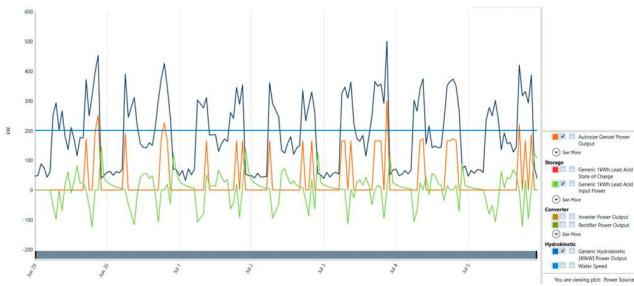


Figure 37: Variations in power generation and consumption over three days at West Bank East London.

5.8. Power Generation Results Analysis

Figure 38 shows the average output, operational hours, and total production for each scenario. Increasing the number of wind and tidal turbines reduces both the operational hours and total output of the diesel generators. In every scenario, the total power generated exceeds the annual energy demand of 1,260,332 kWh for the West Bank coastal area.



Figure 38: Monthly and yearly average output power for (a) 5T + Gen, (b) 1W + 20T, (c) Gen + 20T.

6. Discussion

This paper investigates and compares two distinct renewable energy systems (RES)—offshore wind and tidal energy systems—integrated with grid-connected voltage source inverters (VSIs) and controlled using Pulse Width Modulation (PWM) techniques. The analysis uses the dq-synchronous rotating framework alongside PWM-controlled rectifiers for managing the speed of the generators. MATLAB/Simulink® simulations validate the performance of these control methods. A key factor in this comparison is the density disparity between saltwater (1025 kg/m^3) and air (1.225 kg/m^3), which is over 800 times greater in seawater. This difference significantly affects the kinetic energy density of moving fluid, meaning tidal turbines can be considerably smaller than wind turbines. For example, under similar conditions, a tidal device's rotor

area would be 837 times smaller than that of a wind turbine, resulting in the tidal device's radius being 28.9 times smaller. However, tidal currents do not achieve the same speeds as wind, with offshore wind turbines reaching optimal speeds of around 15 m/s, while tidal currents typically exceed 11 m/s in only a few specific locations. This makes the deployment of tidal turbines more challenging. The analysis further shows that the revolutions per minute (rpm) of the turbines differ due to the variations in rotor radius. Tidal turbines operate at slower speeds (13.3 rpm) compared to wind turbines (20.5 rpm), resulting in a difference in the torques required for power generation. Specifically, a marine turbine needs to produce 837 kNm to generate 1.17 MW, compared to 546 kNm required by the wind turbine. Additionally, tidal turbines exhibit quicker responses to changes in flow, due to their smaller rotor inertia and higher operational torque. These dynamics present challenges in rotor speed regulation, as tidal turbine pitch systems, which are less responsive than wind turbine pitch systems, struggle to maintain consistent power output under varying conditions.

Despite these challenges, tidal currents offer more predictable and extended availability compared to wind, making tidal energy a reliable complement to wind power. This predictability enhances the overall reliability of the hybrid system, which, when optimized, provides a stable and sustainable energy solution. Consequently, the hybrid system combining wind and tidal energy presents an advantageous alternative for future renewable energy systems, particularly in coastal regions where both resources are abundant.

Further, the study includes an analysis of off-grid hybrid systems composed of tidal, wind, storage, and diesel generator turbines to meet the electricity demand at the West Bank, East London site. Figures 30 and 31 present the average hourly and monthly loads, while Figure 32 provides a visual representation of this data. The peak hourly load is recorded at 597.76 kW, and the HOMER software analysis (Figure 34) reveals an average daily load of approximately 4500 kWh/day. The seasonal variation of load, with peak demand in June and July, results in a total annual demand of 3,187,017 kWh after applying a load factor of 0.69. This analysis underscores the need for a hybrid system with multiple wind and tidal turbines to reduce reliance on diesel generators in the West Bank coastal area.

In summary, the study demonstrates that integrating offshore wind and tidal energy systems into a hybrid configuration, supported by advanced control techniques and LCL filters, offers a reliable and sustainable solution for meeting energy demands in coastal regions. By optimizing these systems, including incorporating energy storage solutions, the study highlights the potential for reducing environmental impacts, enhancing energy security, and achieving greater grid reliability. This approach lays the foundation for the development of future energy

harvesting systems that are both economically viable and environmentally sustainable.

7. Conclusion

This study explores the modeling and control of a hybrid offshore energy system that integrates wind and tidal power with grid supplies, with a focus on renewable energy (RE) sources. The system features wind and tidal turbines connected to grid-integrated permanent synchronous magnet generators (PMSGs), operating at a line voltage of 953 V. The turbines supply AC power to rectifiers, which convert it into DC, delivering 1.26 MW at 1150 V DC to a connected load. The control system employs voltage-oriented control (VOC) and is simulated using MATLAB/Simulink. The controller's performance was assessed under three different load conditions—resistive (R), RL, and RC—demonstrating its ability to stabilize operation and manage output voltage while maintaining a steady supply of 1.26 MW to the load.

A key challenge in renewable energy systems, particularly with wind and tidal generation, is the variability in power output due to fluctuating weather conditions. Power converters—rectifiers, inverters, and back-to-back converters—serve as critical components in adjusting the electricity produced by these sources before it is fed into the grid. This study emphasizes the importance of power factor correction (PFC) rectifiers and PWM regenerative/non-regenerative rectifiers in ensuring stable power output.

Tidal turbines face additional challenges due to environmental variability, such as changes in fluid velocity and density, which impact operational loads. Despite their smaller size, tidal turbines tend to generate larger loads than wind turbines, often requiring advanced materials, such as carbon composites, for their blades. The differences in rotor dynamics and speed fluctuations between wind and tidal turbines require specialized optimization strategies.

The results of this study demonstrate that the control system successfully adjusts generator speeds to maximize system output under varying wind and tidal conditions. The proposed hybrid energy system, consisting of a 1.5 MW wind turbine and a 1.0 MW tidal turbine, achieves over 2 MW of combined power output. The more predictable and extended availability of tidal flow makes it a more reliable energy source than wind, positioning the hybrid system as a promising solution for sustainable energy production.

Furthermore, in an alternative scenario involving the integration of offshore wind, tidal energy, energy storage, and diesel backup, the study addresses key challenges associated with the intermittency and unpredictability of renewable sources. This hybrid system enhances power reliability, reduces greenhouse gas emissions, and minimizes environmental impacts. Optimization through HOMER software reveals that the hybrid configuration not only improves reliability but also increases the share of renewable energy and reduces the net present cost, key elements for advancing sustainability. By combining wind and tidal energy, the system maximizes the strengths of both resources, resulting in a more resilient and adaptable energy infrastructure.

Incorporating environmental costs into the cost analysis demonstrates that renewable energy, when considering environmental externalities, becomes increasingly competitive with traditional energy sources, further closing the cost gap. The findings suggest that hybrid systems can optimize resource utilization and improve energy security, particularly in coastal regions. Future research should focus on optimizing these systems with integrated battery storage, considering location, environmental impacts, and power management challenges.

This research lays a solid foundation for the successful implementation of hybrid wind and tidal energy systems, aligning with South Africa's sustainability goals. The findings provide a scalable model that could be replicated in other coastal regions, contributing to the global transition toward cleaner, more resilient, and sustainable energy systems.

Data Availability

The data used to support the findings of this study are included in the article.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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CHAPTER 7 SUMMARY: POWER QUALITY IMPROVEMENT OF OFFSHORE TIDAL-WIND SYSTEMS USING VOLTAGE-ORIENTED CONTROL IN THE SOUTH AFRICAN GRID

Chapter seven of the dissertation presents an advanced Voltage-Oriented Control (VOC) strategy developed to enhance power quality and ensure grid code compliance within a hybrid offshore tidal–wind energy system specifically designed for integration with the South African utility grid. This chapter highlights the novel coordinated control and integration of offshore wind turbines and tidal energy converters mounted on a shared floating platform, aimed at maximizing complementary energy extraction from marine resources. The system employs a detailed dynamic model of a gearless Permanent Magnet Synchronous Generator (PMSG), formulated in the synchronous rotating dq-reference frame, enabling efficient direct-drive tidal power conversion with adaptive control of rotor speed and blade pitch angle to accommodate the inherent variability of tidal flows. To address power quality challenges, a three-level grid connected inverter coupled with a custom-designed LCL filter is implemented to effectively suppress harmonic distortions, thereby ensuring conformity with IEEE 519 harmonic standards. The proposed hybrid system architecture is modelled and simulated within the MATLAB/Simulink environment, incorporating a 1.4 MW tidal converter and a 1.2 MW inverter operating at 600 V under grid-connected load conditions. Simulation results validate the efficacy of the VOC strategy in maintaining grid stability and significantly reducing total harmonic distortion (THD) in voltage and current waveforms to 0.46% and 24.87%, respectively. Unlike traditional single-source renewable systems, this comprehensive hybrid approach enhances energy reliability and power quality under dynamic offshore conditions. The findings presented in this chapter demonstrate the feasibility and robustness of the proposed system for delivering reliable, clean energy in remote coastal and islanded grid scenarios, thereby establishing a foundation for future experimental validation and real-world deployment.

Power Quality Improvement of Offshore Tidal-Wind Systems Using Voltage-Oriented Control in the South African Grid

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Abstract—This paper presents an advanced Voltage-Oriented Control (VOC) strategy for enhancing power quality and ensuring grid compliance in a hybrid offshore tidal–wind energy system tailored to the South African utility grid. The novelty of this work lies in the coordinated control and integration of offshore wind turbines and tidal energy converters on a shared floating platform to maximize complementary energy harvesting. A gearless Permanent Magnet Synchronous Generator (PMSG) model, implemented in the synchronous rotating dq-reference frame, enables efficient direct-drive tidal power conversion with dynamic control over rotor speed and pitch angle to adapt to variable tidal flow conditions. To address power quality concerns, a three-level grid-connected inverter is employed alongside a custom-designed LCL filter, effectively suppressing harmonic distortions and ensuring conformity with IEEE 519 standards. The proposed system architecture is simulated in MATLAB/Simulink, incorporating a 1.4 MW tidal converter, a 1.2 MW inverter operating at 600 V, and grid-connected load conditions. Simulation results validate the effectiveness of the VOC scheme in maintaining grid stability, reducing total harmonic distortion (THD) in voltage and current to 0.46% and 24.87%, respectively. Unlike conventional single-source approaches, this research demonstrates a comprehensive hybrid strategy that improves energy reliability and power quality under dynamic marine conditions. The findings confirm the feasibility of the proposed system for reliable, clean energy delivery in remote coastal and islanded grid scenarios, while laying the groundwork for future experimental validation and real-world deployment.

Keywords—Power Quality Enhancement, Hybrid offshore renewable energy conversion system, Voltage-Oriented Control, LCL Filters, Harmonic Attenuation, Renewable Energy Integration

I. INTRODUCTION

Covering over 70% of the Earth's surface, the ocean offers a vast, underutilized reservoir of renewable energy potential. As the global transition toward decarbonized energy systems accelerates, offshore resources—particularly tidal and wind

energy—are gaining traction for their long-term sustainability, minimal carbon footprint, and reliability in coastal regions [1]. In South Africa, the integration of offshore renewable energy sources (RES) aligns with national objectives for energy diversification, grid resilience, and emissions reduction, particularly given the country's significant marine resource availability.

Recent advancements in distributed generation (DG) and grid liberalization have catalyzed the development of Hybrid Power System Models (HPSMs) that co-integrate wind, tidal, and other renewables with conventional generation assets [2]. Although these hybrid systems improve sustainability and energy accessibility, they also introduce operational complexities, such as voltage instability, harmonic distortion, reactive power imbalance, and frequency fluctuations [3]. Offshore hybrid wind–tidal systems, in particular, offer a complementary energy generation profile—where the variability of wind is offset by the predictability of tidal currents driven by celestial mechanics [4], [5], [6].

The co-location of tidal and wind turbines on shared offshore platforms has been proposed as a strategy to optimize marine space usage, infrastructure cost, and energy output reliability [7]. However, the grid integration of such systems poses unique challenges. Tidal Energy Conversion Systems (TECS) must comply with stringent grid codes governing voltage support, harmonic content, and dynamic fault response, especially in weak or remote grids like those found in certain parts of South Africa [8].

Voltage Source Inverters (VSIs) serve as critical interfaces between variable-speed renewable generators—such as wind and tidal—and the power grid. These inverters must maintain power quality, ensure grid code compliance, and provide dynamic control during disturbances. However, conventional control strategies often lack the responsiveness required to manage rapid variations in environmental conditions and

electrical load, leading to poor harmonic performance and reduced system reliability [9],[10].

To address these limitations, this paper proposes a robust Voltage-Oriented Control (VOC) strategy tailored for hybrid offshore tidal–wind systems integrated into the South African grid. The proposed control scheme enhances the power interface by improving harmonic suppression, supporting reactive power compensation, and regulating voltage under dynamic operating conditions. A well-designed LCL filter is incorporated into the three-level grid-connected VSI to minimize total harmonic distortion (THD) and maintain IEEE 519 compliance.

Unlike existing studies that focus on isolated control aspects or singular renewable sources, this work introduces a comprehensive control framework for hybrid energy systems operating in real-world conditions. The system modelled includes a 1.5 MW Permanent Magnet Synchronous Generator (PMSG)-based tidal turbine delivering up to 1.26 MW at 1150 V DC, interfaced through a grid-connected inverter. MATLAB/Simulink-based simulations are used to validate the effectiveness of the proposed VOC in improving power quality and grid compliance.

The main contributions of this study are summarized as follows:

- Development of a VOC-based control framework for hybrid offshore tidal–wind integration;
- Design and implementation of an LCL filter for harmonic mitigation in line with IEEE 519 standards;
- Evaluation of system performance under dynamic environmental and load conditions through MATLAB/Simulink;
- Applicability assessment of the proposed system within the South African grid context, providing a foundation for future deployment and real-time validation.

By addressing key challenges in offshore hybrid energy integration, this work contributes to advancing clean energy solutions for remote and coastal regions, supporting a more resilient and sustainable energy future.

II. THE ARCHITECTURE OF A HYBRID ENERGY SYSTEM

A. Hybrid Offshore Tidal Turbine (HOTT) systems

The proposed Hybrid Offshore Wind–Tidal Turbine (HOTT) architecture aims to enhance the reliability and stability of offshore renewable generation by combining wind and tidal energy with advanced energy storage. The system is specifically tailored to address the intermittency and variability challenges associated with individual sources, by exploiting the complementary characteristics of wind and tidal currents. Wind resources offer high energy potential but are subject to short-

term fluctuations, whereas tidal currents are highly predictable and cyclic in nature. The HOTT configuration includes:

A utility-scale offshore wind turbine equipped with a permanent magnet synchronous generator (PMSG), interfaced with the DC link via a diode rectifier.

- A medium-scale tidal turbine utilizing an induction generator, connected to the DC bus through a bidirectional PWM converter.
- A DC/DC converter regulating the charging/discharging cycles of a Battery Energy Storage System (BESS), thereby mitigating short-term power imbalances. By co-locating these energy sources on a unified offshore platform, spatial efficiency is improved, and aggregate power output becomes more resilient to resource intermittency. Figure 1 illustrates the conceptual design of the hybrid system, while Figures 1 and 2 detail the simulation modelling framework adapted for this study, reflecting configurations consistent with offshore deployments [11], [12].

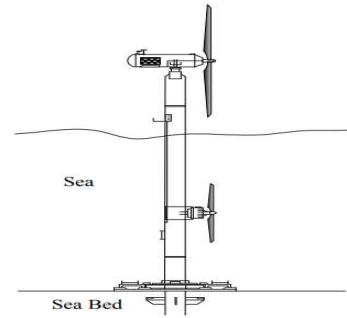


Figure 1. Conceptual image of HOTT [12].

B. Component-Level Modelling Algorithms

1) Offshore Wind Turbine Model

The wind turbine's output power is computed using aerodynamic and electromechanical equations. The key algorithmic steps are:

Input Parameters:

- Wind speed (W_v)
- Air density (ρ)
- Rotor radius (R_r)
- Power coefficient (C_p) as a function of tip-speed ratio (λ) and pitch angle (β)

Calculate Tip-Speed Ratio (λ):

$$\lambda = \frac{\omega_w \cdot R_w}{v_w} \quad (1)$$

where ω_w is the angular speed of the turbine rotor.

Compute Power Coefficient (C_p):

$$C_p = f(\lambda, \beta) \quad (2)$$

Use an empirical or analytical function to determine C_p .

Calculate Mechanical Power (P_{mech}) [13]:

$$P_{mech} = \frac{1}{2} \rho \pi R_w^2 v_w^3 C_p \quad (3)$$

Convert Mechanical Power to Electrical Power (P_{elec}):

$$P_{elec} = \eta_g \cdot P_{mech} \quad (4)$$

where η_{gen} is the generator efficiency.

Output:

- Electrical power (P_{elec})
- Electrical power and torque

$$T_w = \frac{P_{mech}}{\omega_w} \quad (5)$$

A. Power Electronics and Filter Modelling

2. Output Voltage in abc Frame:

$$v_{a,b,c} = v_c = \frac{V_{dc}}{2} m_c \quad (6)$$

dq0 frame (Park transform):

$$\begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (7)$$

3. L-Filter Model

Output Voltage After L-Filter: The output voltage across the load for phase a is:

The LC-filter adds a capacitor to the L-filter to further reduce ripple.

Voltage Across Filter Inductance (L): For phase a, the inductor voltage is:

$$vL = L \frac{di}{dt} \quad (8)$$

Current Through Capacitor (C): The current through the filter capacitor for phase a is:

$$i_c = C \frac{dvC_a}{dt}, \quad vL_{out} = v_c - \frac{1}{C} \int i_c dt \quad (9)$$

where iL_a is the load current for phase a.

Output Voltage After LC-Filter: The output voltage for each phase is given by:

$$vL_a = v_c - \frac{1}{C} \int i_c dt \quad (10)$$

III. SYSTEM DESCRIPTION

This system integrates two renewable energy sources—offshore wind and tidal current—using two Permanent Magnet Synchronous Generators (PMSGs), each interfaced via Pulse Width Modulation (PWM)-based power electronic converters. The overall architecture incorporates an AC/DC rectification stage, a common DC-link, and a DC/AC inverter for grid interfacing, as depicted in Figures 2.

The tidal turbines, modelled to operate at a constant water velocity of 12 m/s, produce an average torque of 600 kNm and a mechanical power output of approximately 1.324 MW per unit. These units are interconnected via 6.6 kV submarine cables and aggregated through a marine substation. Power is transmitted to shore using step-down transformers to match the distribution-level grid voltage requirements.

The Grid-Side Converter (GSC) is modelled in MATLAB/Simulink and is equipped with an LC filter and a voltage-matching transformer. The GSC supports bidirectional power flow, grid synchronization, and reactive power control to ensure power quality under varying generation conditions. The Rotor-Side Converter (RSC) and GSC operate independently but are coupled through a common DC link, ensuring decoupled control of the machine-side and grid-side dynamics.

To mitigate harmonic distortion and comply with grid standards, LCL filters are incorporated on the inverter output. These filters are specifically tuned to suppress switching frequency harmonics and ensure Total Harmonic Distortion (THD) remains within IEEE 519 limits. The hybrid configuration also enhances system resilience by leveraging the predictability of tidal energy to compensate for the intermittent nature of offshore wind.

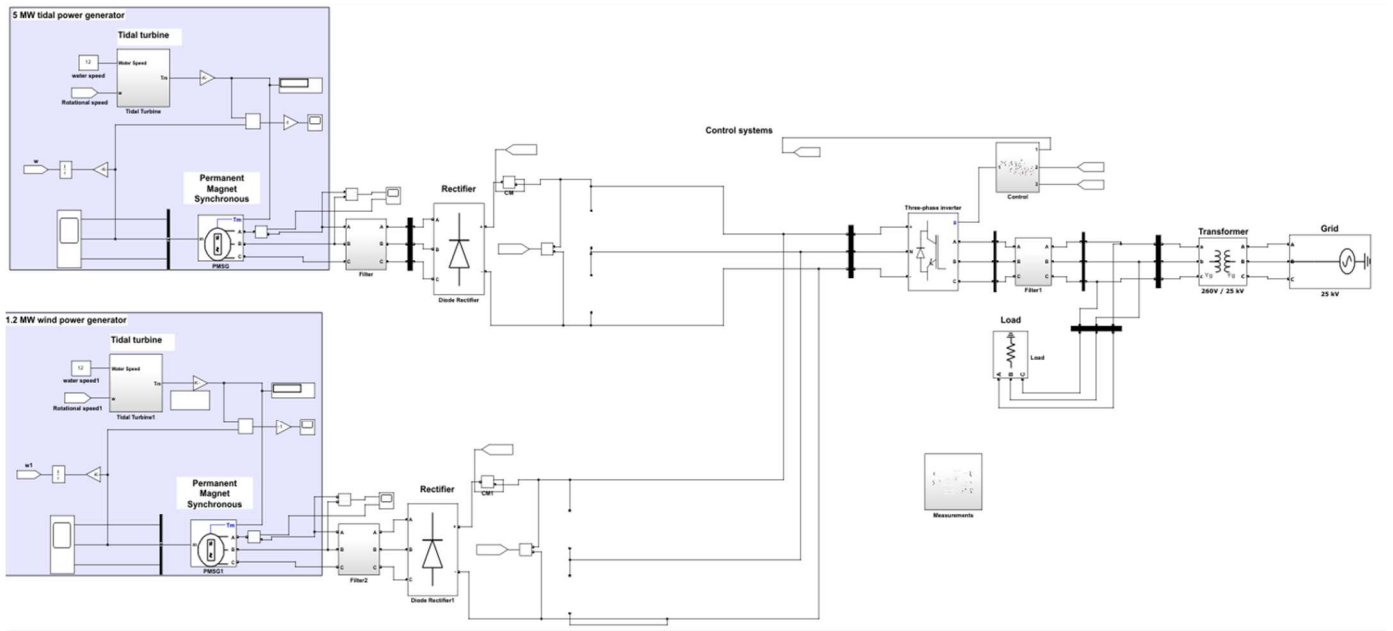


Figure 2. Simulation Model of the Controlled Hybrid System.

IV. SIMULATION, RESULTS AND DISCUSSION

A 2 MW Permanent Magnet Synchronous Generator (PMSG) tidal turbine was modelled using the parameters in Table I. The turbine operates at 600 V and is integrated into a hybrid offshore wind-tidal energy system. The tidal generator parameters that are shown in Table 1 [14].

TABLE 1: THE TIDAL GENERATOR PARAMETERS

Parameters	Values
P_{nom}	1.5 MW
V_{nom}	600 V
R_s	0.006
L_{dq}	0.3e-3 H
ϕ	1.48
J	35000
Viscous Damping	0.01
Friction	0
N_p	48

The LCL filter was designed per IEEE Std. 519-2014 to reduce harmonics. Table II summarizes the LCL parameters. Equation ensures the resonant frequency f_{res} lies between 10% and 50% of the switching frequency:

Value DC-Link Voltage, 1400 V, Output Power 1.26 MW, PWM Freq., 2 kHz, Grid Freq., 50 Hz Nominal Current 1200 A, Peak Current, 1630.22 A Power Factor, 0.95, THD Limit, 5%.

TABLE 2: THE LCL FILTER PARAMETERS

Parameter	Value
Inverter side inductor (L_i)	0.9 mH
Grid side inductor (L_g)	0.072mH
Capacitor filter (C_f)	531 μ F
Damping Resistor (R_d)	0.118 Ω
Resonant frequency (f_{res})	845 Hz
Inductor resistances ($R_i = R_g$)	0.00761 Ω
Sampling frequency f_s	10,000 Hz
Crossover Frequency (f_c)	254 Hz

TABLE 3: DESIGN PARAMETERS FOR THE INVERTER

Parameter	Value
Output DC Power Tidal Turbines	1.54 MW
DC-Link Voltage	1400 V
Output Power of the Inverter	1.26 MW
Line-to-Line RMS Voltage	600 V
Phase Voltage	346 V
Nominal Current	1200 A
Power Factor	0.95
Peak-to-Peak Current	1630.22 A

PWM Carrier Frequency	2000 Hz
Grid Frequency	50 Hz
Modulation Range	0.7
Attenuation Factor	20%
Maximum Grid Power Factor	5%
Inverter Configuration	Three-Phase

Figures 3 and 4 depict the total harmonic distortion (THD) present in the system voltage and current waveforms. Both signals contain significant harmonic components beyond the nominal grid frequency of 50 Hz, indicating power quality issues.

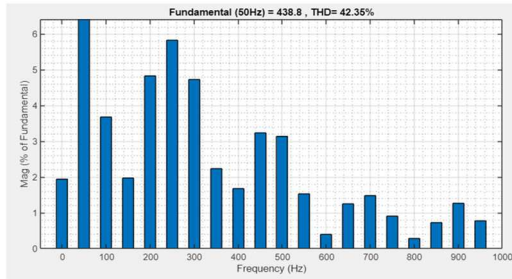


Figure 3.Total voltage harmonics distortion before filtering.

To address this, appropriately designed filters are employed to attenuate high-frequency distortions. Additionally, rectifiers are integrated within the system to further suppress voltage ripples, thereby maintaining frequency stability. LCL filters substantially reduce THD—voltage THD to 0.07% and current THD to 0.12% in the Figure 5—enabling smooth integration of renewable sources. These filters also suppress overshoots, supporting grid synchronization and steady inverter output.

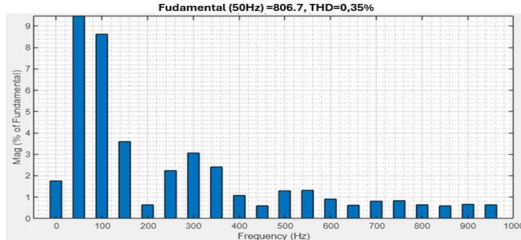


Figure 4: Voltage Total Harmonics Distortion

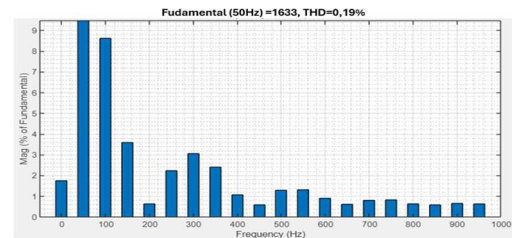


Figure 5: Current Total Harmonics Distortion

The tidal turbine, as shown in Figure 6, supports the hybrid system, especially during low-wind periods. At a steady 12 m/s water speed, it generates 1.324 MW with 600 kNm of torque, covering 5-10% of the 2 MW load. The system employs Voltage-Oriented Control (VOC) to maintain a stable 1500 V DC-link voltage, ensuring efficient power conversion and seamless grid integration.

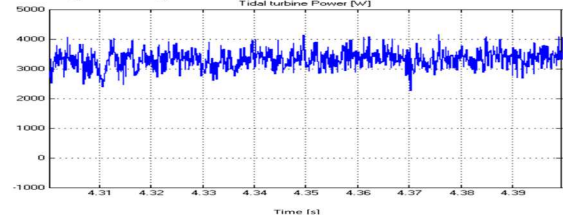


Figure 6.Tidal turbine active power, reactive power and voltage.

Figure 7 shown wind subsystem plays a primary role in meeting the 2 MW load demand, delivering between 0.6 MW and 1 MW depending on wind availability. This surplus capacity allows for grid support, charging storage systems, or curtailment based on system requirements. The system employs a Phase-Locked Loop (PLL) for accurate grid synchronization and LCL filters to suppress high-frequency harmonics, ensuring clean and stable power injection into the utility grid. Figure 8 shows the active and reactive power outputs of the offshore wind turbine along with the terminal voltage. The results confirm high energy yield and efficient control of reactive power, while the voltage remains stable and within acceptable grid-tied limits, demonstrating effective wind power regulation.

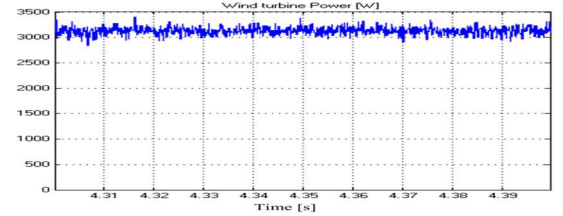


Figure 7.Offshore-wind turbine active power, reactive power and voltage

Figure 8 displays the output voltage at the point of common coupling (PCC). The voltage waveform is smooth and distortion-free, validating the combined effect of LCL filtering and voltage-oriented control.

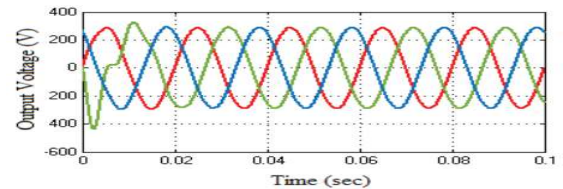


Figure 8. Output Voltage.

Figure 9 illustrates the regulated parameters of the grid-side converter, including grid voltage, current, and DC-link stabilization. The converter effectively maintains power quality and synchronizes renewable input with grid conditions under dynamic operating scenarios.

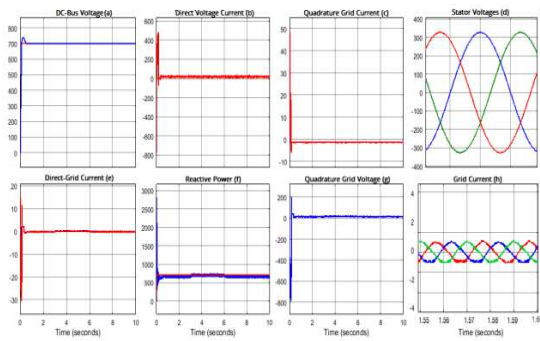


Figure 9. Regulated Parameters of the Grid Side Converter

Figure 10 shows the grid-side converter associated with the PMSG-based tidal turbine. It confirms stable operation, efficient reactive power compensation, and minimal harmonic distortion. This figure highlights the robustness of the VOC strategy in managing tidal energy integration and ensuring high-quality power delivery.

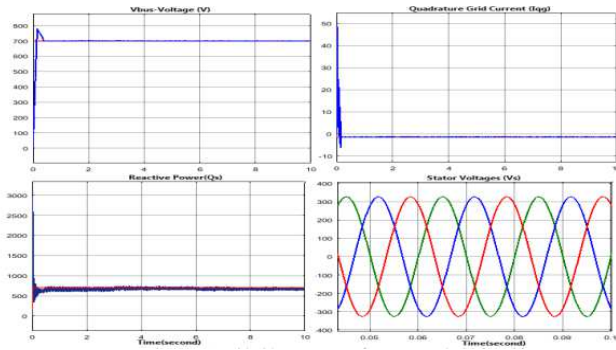


Figure 10. Grid Side Converter for PMSG-Based Tidal Turbine

V. CONCLUSION

This study has demonstrated the effectiveness of a Voltage-Oriented Control (VOC) strategy in enhancing power quality and ensuring grid compatibility for integrated offshore tidal-wind energy systems in the South African context. By employing a PMSG-based system with optimized LCL filtering and advanced control techniques, the proposed hybrid setup successfully manages variable energy inputs while maintaining stability and low harmonic distortion. Simulation results validated the system's ability to limit voltage and current total harmonic distortion within IEEE-519 standards, confirming its technical feasibility for real-world application.

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CHAPTER 8 SUMMARY: OPTIMISING SUSTAINABILITY IN OFFSHORE HYBRID TIDAL-WIND ENERGY STORAGE SYSTEMS FOR AN OFF-GRID COASTAL CITY IN SOUTH AFRICA

Chapter seven explores methods for optimising the integration of offshore wind and tidal current energy into sustainable hybrid power generation systems aimed at off-grid coastal communities in South Africa. Given the nation's rich marine energy resources, this chapter investigates the potential for harnessing these resources to meet the growing demand for renewable energy solutions. The focus of this chapter addressed the intermittency and unpredictability associated with renewable energy sources through ensuring a stable and reliable power supply by combining offshore wind, tidal current energy, and energy storage with a diesel backup system. The proposed hybrid system includes one wind turbine, five tidal turbines, and a diesel generator, strategically configured to maximise renewable energy output while minimising costs and environmental impacts. Simulations using HOMER Pro version 3.20 software reveal that this system configuration offers the highest renewable energy fraction, while simultaneously lowering the net present cost – demonstrating its efficiency in reducing dependency on non-renewable energy sources. The system's sustainability is evaluated through its ability to balance energy supply with demand in a way that minimises greenhouse gas emissions and contributes to a lower environmental footprint. Key findings highlight the effectiveness of integrating wind and tidal energy with energy storage to enhance the overall stability and reliability of power supply in remote coastal areas. The combination of these renewable energy sources offers considerable environmental benefits, including reduced reliance on fossil fuels, better alignment with South Africa's national and global sustainability goals, and enhanced energy security for off-grid communities. The results of the study underscore the potential of this hybrid system to support South Africa's transition toward a more sustainable energy future, providing a practical blueprint for achieving long-term energy security and sustainable development in coastal regions. The chapter concludes by emphasising the importance of continued research and innovation in marine renewable energy systems to ensure that these technologies can be effectively implemented in off-grid communities, contributing to a greener, more sustainable energy landscape.

Article

Optimizing Sustainability Offshore Hybrid Tidal-Wind Energy Storage Systems for an Off-Grid Coastal City in South Africa

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Abstract: South Africa's extensive marine energy resources present a unique opportunity for advancing sustainable energy solutions. This study focuses on developing a sustainable hybrid power generation system that combines offshore wind and tidal current energy to provide a stable, renewable energy supply for off-grid coastal communities. By addressing the challenges of intermittency and unpredictability in renewable energy sources, the proposed system integrates wind and tidal energy with energy storage and diesel backup to ensure reliability while reducing greenhouse gas emissions and minimizing the environmental footprint. The system is optimized for sustainability, with a configuration of one wind turbine, five tidal turbines, and a diesel generator demonstrated to be the most effective in increasing the renewable energy fraction and lowering the net present cost. Simulations conducted using HOMER Pro version 3.20 software underscore the potential of this hybrid system to support South Africa's transition to a more sustainable energy future, aligning with national and global sustainability goals. The results emphasize the environmental benefits of combining these renewable energy sources, offering a blueprint for achieving energy security and sustainable development in coastal regions.

Keywords: green energy solutions; HOMER Pro optimization; hybrid offshore wind and tidal systems; off-grid coastal sustainability; reducing greenhouse gas emissions; renewable energy storage; sustainability in renewable energy



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1. Introduction

Access to electricity is fundamental for modern living, supporting essential services such as healthcare, education, transportation, and communication. Despite this, as of 2016, approximately 1.1 billion people, or 14% of the global population, lacked access to electricity, with rural areas being disproportionately affected [1]. In countries such as South Africa, the disparity in electrification between rural and urban areas is significant, primarily due to the distance from main-grid substations and the substantial costs associated with infrastructure development [2]. While renewable energy sources such as wind, solar, and marine resources present viable solutions, their integration into remote and off-grid systems remains a challenge. Marine energy, encompassing tidal and wave power, offers considerable potential due to its vast and predictable energy reserves [3].

Despite the significant potential of sea and ocean energy resources, these technologies have not yet been widely adopted. Their extensive application is hindered by inherent challenges, including high capital costs and the intermittent and unpredictable nature of energy generation. However, research on wind turbines has surged with recent technological advancements, and the technology employed in wind turbines is now being applied to marine current energy as well [4,5]. Designing such a system must adhere to several constraints. These constraints are divided into two categories: technical, which

includes energy source availability; generation components, battery system state of charge, and electric load location; and economical, which encompasses reliability, flexibility, efficiency, and costs [6]. Energy storage systems offer numerous benefits to electrical energy systems, including improved power quality, mitigation of issues related to intermittent renewable energy sources (RES), balancing generation and demand, and regulating voltage and frequency. Additionally, hybrid energy storage systems (HESS) have been developed by integrating two or more energy storage technologies. This combination leverages the unique characteristics of each technology to achieve the desired performance [7].

For instance, hybrid systems integrating wind, diesel, and batteries are effective in regions with consistent wind resources, while photovoltaic (PV)-diesel-battery configurations are ideal for areas with abundant solar irradiance [8]. Incorporating ESS into hybrid systems can significantly improve the performance of both stand-alone and grid-connected configurations by ensuring a reliable power supply and reducing reliance on fossil fuels.

Although numerous studies have optimized the sizing of ESS for hybrid renewable systems, few have focused on integrating marine energy into microgrids in remote coastal regions. This paper aims to address this gap by evaluating the technical and economic feasibility of a hybrid renewable energy system that integrates tidal and wind energy, supported by ESS, for an off-grid coastal community in South Africa. Optimization Homer Pro version 3.20 software is employed to simulate the system's performance based on hourly load profiles, with the goal of minimizing diesel consumption and reducing electricity costs.

By integrating tidal energy into the microgrid, this research proposes a novel approach to improving system efficiency and stability. This approach is particularly relevant for island microgrids dependent on diesel generators, as it seeks to reduce fossil fuel consumption and enhance power quality. The findings of this study can provide valuable insights for the design of cost-effective and reliable hybrid energy systems in similar contexts, contributing to the broader objective of achieving sustainable energy access.

2. State-of-the-Art Review on Techno-Economic Analysis of Hybrid Energy Systems

The optimal design of hybrid renewable energy systems is a critical area of study, with an extensive body of literature dedicated to this topic. The core design challenge involves determining the optimal configuration of power systems, including the ideal location, type, and sizing of generation units at specific nodes, to meet load requirements at the lowest possible cost [8].

Much of the existing research focuses on the application of algorithms for the optimal sizing and economic evaluation of renewable energy systems, particularly those involving photovoltaics (PV), wind, and micro-turbine-based HRES, with battery storage elements connected to the utility grid. For example, Liu et al. [9] proposed a frequency-based method for sizing a battery-super capacitor (SC) hybrid energy storage system (HESS) to maintain power balance in an isolated system with significant wind penetration, utilizing Fourier transformation. Meanwhile, Jacob et al. [10] proposed a pinch analysis-based strategy for sizing hybrid energy storage systems (HESS) in photovoltaic-based isolated power systems, where generation consistently exceeds load. Arabali et al. [11] introduced a search-based optimization approach to determine the optimal size of energy storage systems and to analyze the reliability of hybrid wind-solar power systems, employing probability distribution functions to account for the stochastic nature of renewable energy sources (RES) generation.

To smooth the output power from a wave energy park, the output power from a wave energy park Said et al. [12] utilized batteries and SC modules, assessing the power delivered to the grid as the average output of the wave energy conversion system (WECS) over a specified time. They sized the HESS based on the power balance between the wind energy conversion system (WECS) generation and the power delivered to the grid, considering both power and energy capacity. However, the detailed sizing of individual battery and supercapacitor (SC) components was not thoroughly examined. Lafoz et al. [13] developed a program for sizing HESS to power onboard loads using autonomous WECS. The program

calculated the probability and amplitude of each component in the WECS output power spectrum based on the known location of the energy harvesting devices. The generated output power profile was then used to size the HESS over short, medium, and long periods, considering its probability of occurrence. To avoid oversizing, the HESS sizing was derived from a long-term operation analysis, balancing load-energy demand [14].

This research aims to determine the optimal size for an offshore standalone tidal-wind-battery storage (BS) hybrid system that is more cost-effective. Specifically, it seeks to find the optimal size for each component of the hybrid renewable energy system (HRES) to allow consumers to recover their investment over time by reducing the cost of electricity purchased from the grid. Given that solar and wind energy are location-dependent, this study is based on the meteorological data of West Bank, East London, a coastal city in South Africa. This strategy is applied to an off-grid offshore hybrid tidal wind storage energy system to demonstrate its effectiveness, with potential applicability to other renewable energy configurations.

3. Mathematical Modelling of Offshore Hybrid Power Generation Systems

3.1. Hybrid Wind-Tidal Arrays and Power Generation

The (HRES) are a mixture of many renewable energy sources. It can be connected to the grid or to be used as a stand-alone. The most important benefit of HRES is the optimum use of sustainable energy generation working characteristics, which results in efficiencies higher than that could be reached from one power source of HRES designed for the specific location [15]. When designing a hybrid (HRES), many aspects need to be considered, such as reliability and cost, which are the key aspects of the implementation; according to many studies, hybrid energy systems are more reliable and cost-effective than systems based on just a single source [1,8,16,17].

One of the primary advantages of a hybrid energy system is its ability to bridge energy shortfalls from one source by augmenting with another source, particularly during weather changes [18–20]. For instance, when sunlight is insufficient to power photovoltaic panels or when wind speeds are inadequate for turbine generation, the hybrid system can compensate by leveraging the alternative energy source to maintain consistent power generation [21].

3.2. Wind Power Generation

Wind is the motion of air created by the irregular heat of the earth's surface. It has been happening at all measures, from local breezes made by heating of surfaces of the land that remain some temps to global winds created from the heating of solar at the earth [15]. The practical application of wind energy is primarily the conversion of wind energy into other forms of energy; a process usually achieved through wind turbines, which capture and convert the power of wind currents.

3.2.1. Wind Turbines Component Description

Figure 1 illustrates the components of a wind power system, including a wind turbine, battery, DC-DC converter, DC-AC converter, AC-DC converter, and loads, which can be configured with either a horizontal or vertical axis.

Wind power is harnessed through wind turbines, which capture the kinetic energy of the wind. This energy is converted into mechanical energy transferred through the drive train to the generator, which converts it into electrical energy [22]. Subsequently, the rotational energy is transformed into electrical power through the transmission system.

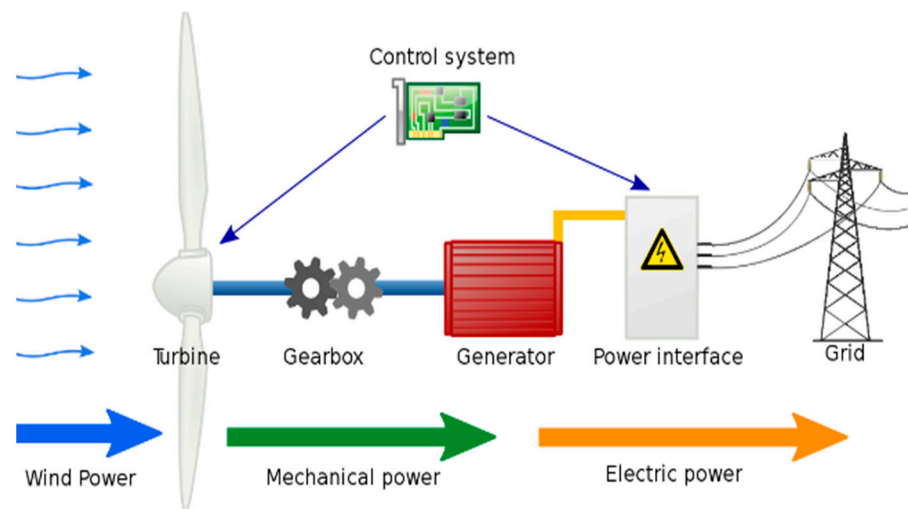


Figure 1. Block diagram of wind turbine.

3.2.2. Modelling of Offshore Wind Energy System

A significant supply of renewable energy will come from offshore wind. Onshore wind speed variation is less of a range than offshore wind speed variation [23], where ρ is the density of air in 1.22 kg/m^3 . The captured mechanical power P_W , the dimensionless power coefficient C_{PW} , the measured mechanical torque T_W , the tip speed ratio λ , and the blade pitch angle β [24]. The tip speed ratio changes when the rotor speed and wind speed change, resulting in a new operating point on the power curves at various speeds and pitch angles [25]. At rated wind speed, the generating power equals the turbine's nominal power. If the wind speed grows, the output power may increase until the nominal turbine power is reached. Wind speeds may continue to rise, so there is a risk of damaging the rotor of the turbine [26].

The kinetic energy of a wind turbine rotor with the cross-sectional surface (A) exposed to the tidal stream is expressed as:

$$E_W = \frac{1}{2} \rho v V^2 \quad (1)$$

where v represents the parcel volume of air interacting with the rotor, and ρ denotes the water density. The interaction between the air parcel and the rotor occurs over a cross-sectional area A , corresponding to the rotor's swept area, with a thickness determined by the air velocity V . The generator efficiency is represented by η_g [27]. Thus, the power, which is the kinetic energy per unit time, is expressed as:

$$P_{WE} = \frac{1}{2} \rho A V^3 C_P(\lambda, \beta) \eta_t \eta_g \quad (2)$$

Figure 2 illustrates the corresponding power curve of the wind generator at its rated power output P_{WE} [28]. The power coefficient of a turbine depends on both the Tip Speed Ratio (TSR) and the blade pitch angle β .

For a given turbine, the power coefficient depends on the TSR and the blade pitch angle. The typical variation of the power coefficient concerning the TSR for various values of the pitch angle [28].

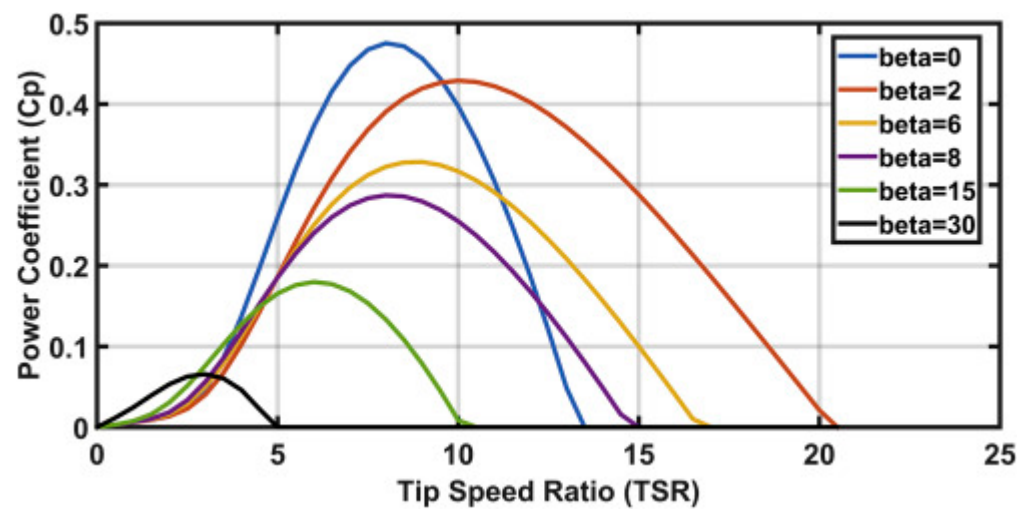


Figure 2. C_p and λ (TSR) for various pitch angles β [29].

3.2.3. Wind Turbines Power Curves

Wind turbine is used. Some of its parameters are described in Table 1.

Table 1. Wind turbine parameters.

Parameters	Values
Cut-in speed, v_{cutin}	5 m/s
Cut-out speed, v_{cutout}	25 m/s
Rated speed, v	15 m/s
The maximum output power, P_{wmax}	2300 W
Swept area	3959 m ²
Number of blades	3
Rotor diameter	32 m, 40 m, 50 m
Hub height	32 m, 5 m

The height of the wind turbine tower is a critical factor that significantly influences the turbine's operating performance and can account for more than half of the total system cost. To adjust the measured wind speed to the hub height, Equation (3) is used.

$$v(t) = v_r(t) \left(\frac{h}{h_r} \right)^\gamma \quad (3)$$

where $v(t)$ represents the wind speed at the desired height h , $v_r(t)$ is the wind speed measured at a known reference height h_r , and the power law exponent.

γ is a factor that depends on the roughness of the terrain [30]. For this study, the power law exponent γ is set to 0.2 [31]. The second figure in Section 5.5 shows the wind speeds on the considered island and the corresponding wind turbine power production at various hub heights [32].

3.3. Tidal Energy Generation Systems

The technology used for extracting wind energy is similar to that used for harnessing tidal energy, as indicated in Figure 3. As a result, many wind generator models can also be applied to tidal energy systems [33]. Figure 3 illustrates a turbine configuration based on a Permanent Magnet Synchronous Generator (PMSG) paired with a Full Power Converter (FPC), which is suitable for both Tidal Stream Turbines (TSTs) and Wind Turbines (WTs) [34]. This setup allows for variable-speed operation since the electrical frequency of the PMSG can vary with changes in wind or tidal flow speed while the grid frequency remains stable.

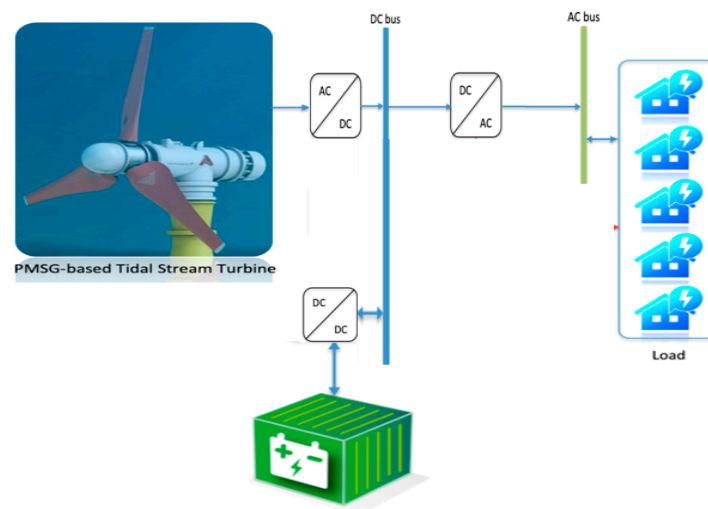


Figure 3. Tidal energy systems configuration based on a PMSG.

Tidal Energy Modelling

The objective of the Tidal Stream Turbine (TST) or Wind Turbine (WT) is to maximize power extraction from the tidal stream or wind flow. The power transferred to the turbine rotor and the resulting torque are determined by the following equations:

$$P_t = C_P P_{flow} = \frac{1}{2} A V_{flow}^3 C_P(\beta, \lambda) \quad (4)$$

$$T_t = \frac{P_t}{\omega_{rot}} \quad (5)$$

where P_{flow} (W) represents the power of the tidal stream flow; A (m^2) is the swept area of the rotor; V_{flow} (m/s) is the upwind tidal stream flow speed; C_P the power coefficient; and ω_{rot} (rad/s) is the rotor angular speed [16].

In Equations (4) and (5), C_P represents the turbine's performance and efficiency as a function of the blade pitch angle and the tip-speed ratio (TSR) [35] where R (m) is the rotor's radius at the tip. At a single TSR (at a certain wind or flow speed) and at a fixed rotational speed of the turbine, a maximum C_P is attained. Thus, a maximum C_P can be attained over a range of wind/flow speeds, provided the turbine is run at a variable speed [36]. Figure 4 illustrates a typical feature with the optimal power extraction-speed curve crossing C_{pmax} spots for various wind flow speeds. Table 2 provides the layout for the tidal Parameters and cut-out tidal parameters [1].

Table 2. Tidal parameters.

Parameters	Symbol	Values
Cut-in tidal speed	v_{cuttid}	< 1 (m/s)
Rated tidal speed	$v_{ratedtid}$	3 m/s
The cross-sectional area of the turbine	A	201.06 m^2
Power coefficient	C_p	0.44
Cut-out tidal speed	$v_{cututtid}$	> 5 m/s

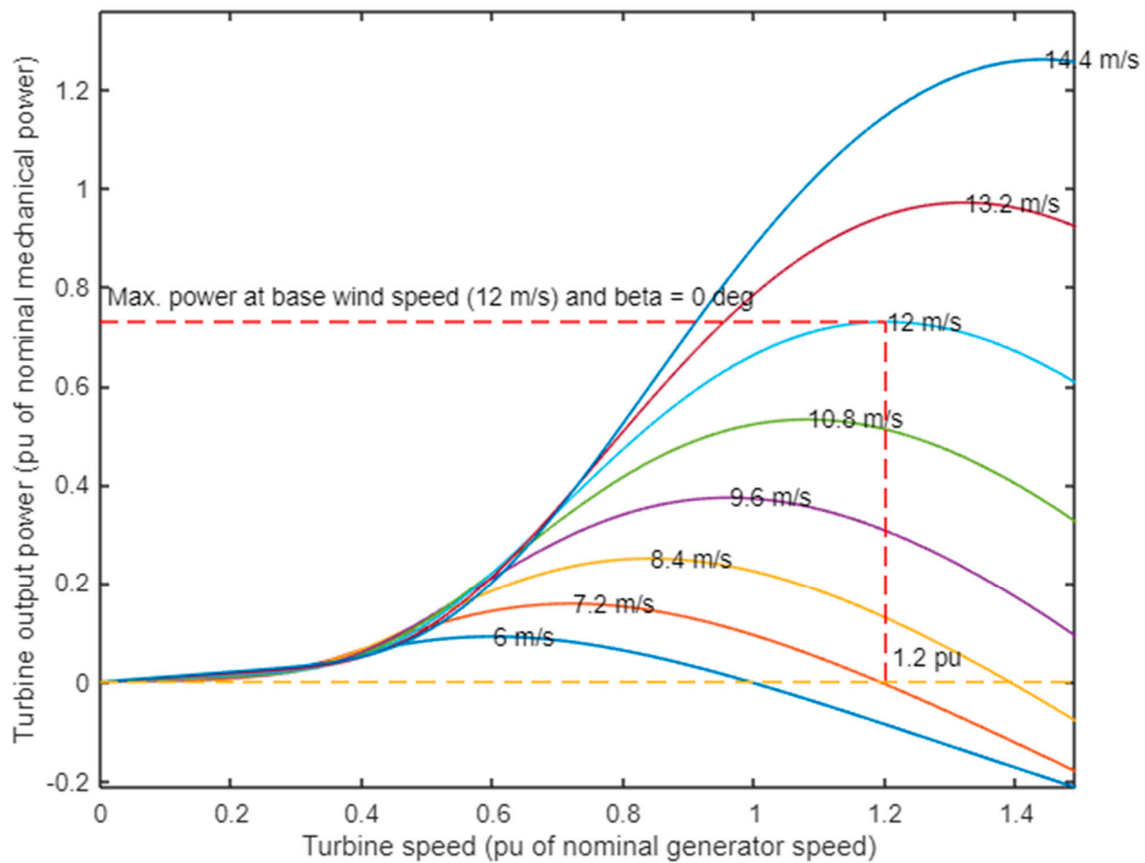


Figure 4. Characteristic for maximum power extraction.

Additionally, the generator torque-speed characteristic is displayed. As the wind/flow speed changes, the control goal is to keep the turbine on this curve [37,38].

Power is restricted to prevent overloading when the cut-out speed reaches the rated torque. To decrease the lift force in the turbine's blades, if the blades have variable pitch, they are pitched to feather. In this manner, power is controlled and the torque on the rotor is decreased. In contrast, if the turbine's blades have a set pitch, they can be adjusted such that the angle of attack rises, so purposefully inducing stall [39].

3.4. Battery Bank

The fluctuations in wind energy generation often do not align with the timing of energy demand. Consequently, power generation systems require the integration of battery storage facilities to address the temporal mismatch between load requirements and the availability of wind and tidal energy, as well as to ensure system maintenance. In small-scale, stand-alone power systems, batteries represent a significant cost factor. Battery stacks can consist of multiple units, ranging from 0 to 500. For this study, a 6 V, 1.34 kWh battery was selected, with each string containing 8 batteries [40].

3.5. Battery Energy Storage System Modelling

The battery's state of charge (SOC) is the cumulative sum of daily charge/discharge cycles. At any given hour (t), the SOC is related to the state of the previous hour and the energy production and consumption within the system during the interval from $t - 1$ to t . During charging, when the total system output exceeds load demand, the available battery capacity at hour (t) can be described by [40]:

$$E_{Bat}(t) = \text{Battery Capacity} \frac{Ah}{= \text{Battery}} \text{Current (A)} \quad (6)$$

Conversely, when load demand surpasses the generated energy, the battery bank discharges, and the available capacity at an hour (t) is given by:

$$E_{Bat}(t) = E_{Bat}(t-1) - E_{need}(t) \quad (7)$$

Let d represent the ratio of the minimum allowable SOC voltage limit to the maximum SOC voltage when the battery is fully charged. The Depth of Discharge (DOD) is then defined as [40]:

$$DOD = (1 - d) * 100 \quad (8)$$

3.6. Converter Model

The rectifier model is given below:

$$E_{REC} - IN(t) = E_{SUR} - AC(t) \quad (9)$$

$$E_{SUR} - AC(t) = E_{DG}(t) \quad (10)$$

$E_{SUR} - AC(t) = E_{DG}(t)$ is the amount of surplus energy from AC source, kWh, $E_{DG}(t)$ is surplus energy from a diesel generator to DC power of constant voltage when the energy generated by the hybrid energy system exceeds the load demand [40].

3.7. Diesel Generator Characteristics and Modelling in HOMER

3.7.1. Diesel Generator Characteristics

In renewable energy hybrid systems, diesel generators serve as backup power sources to ensure reliability and stability. For effective mode ling and optimization in HOMER, the following key characteristics of diesel generators should be considered:

- **Rated Capacity:** This refers to the maximum electrical output the generator can produce, typically measured in kilowatts (kW).
- **Fuel Consumption:** This is the amount of diesel fuel consumed per unit of electricity generated, usually provided in liters per hour (L/h) or gallons per hour (GPH). Fuel consumption is often depicted as a fuel curve, illustrating consumption at different load levels.
- **Efficiency:** This is the ratio of useful electrical output to the total fuel energy input, expressed as a percentage. Efficiency can vary depending on the load.
- **Operational Constraints:** These include the minimum and maximum load levels at which the generator can operate effectively. Operating below the minimum load can result in inefficiencies and increased maintenance requirements.
- **Emissions:** The number of pollutants (CO_2 , NO_x , SO_2 , PM) emitted per unit of fuel consumed. These emissions are important for environmental impact assessments.
- **Maintenance and Lifespan:** Regular maintenance requirements and the expected lifespan of the generator, typically measured in operating hours or years.

3.7.2. Load Model

The number of electrical power sources in a hybrid renewable system is determined by the electrical load demand. The load profile for the off-grid coastal village community under study, with a maximum demand of 20 MW. Peak load typically occurs in June and July.

4. Materials and Methods

Meteorological Data

This study used weather station 00595729, located in the West Bank–East London region of Buffalo City Metropolitan Municipality (BCMM), Eastern Cape Province, South Africa. As shown in Figure 5, the station is situated at latitude -33.0330° S and longitude 27.8330° E and monitors the entire West Bank–East London area (<https://www.google.co>.

za/maps/search/West+bank+East+london+community/@-33.0352403,27.8987226,1390m/data, accessed on 10 December 2023). The meteorological data utilized in this research were gathered from coastal villages in the West Bank, South Africa [41]. The dataset comprises average hourly data spanning a full year (8760 h), starting in January 2024. This study assesses the feasibility of an offshore hybrid wind-tidal storage diesel generator energy system using Homer Pro version 3.20.

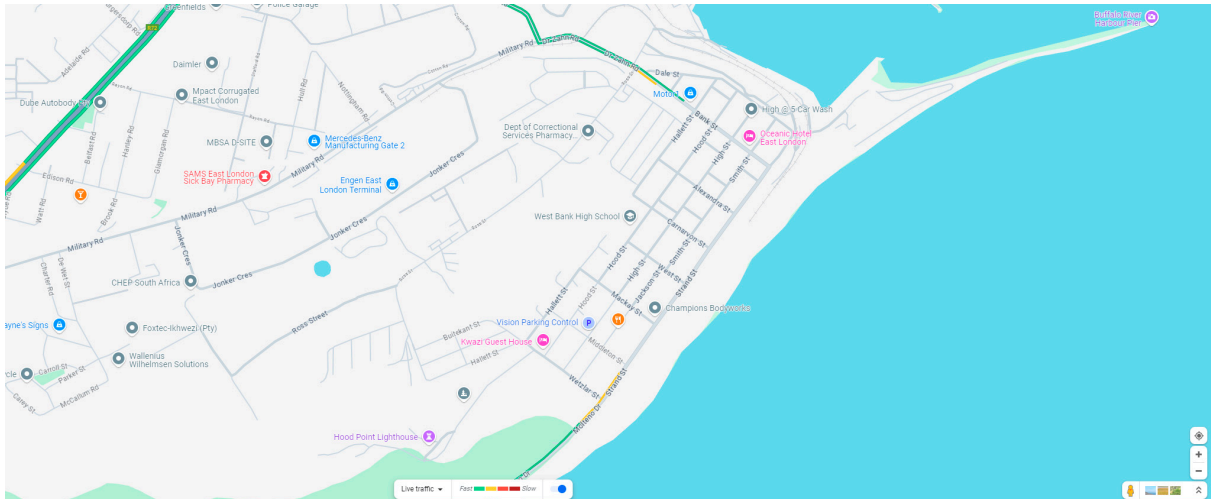


Figure 5. The West Bank-East London area in the Eastern Cape Province of South Africa.

5. Methodology for Optimizing Offshore Hybrid Energy Systems

5.1. Summary of Methodological Steps for the Proposed Study

This diagram illustrates the general model for optimizing a hybrid generation system, which integrates multiple energy sources such as wind, solar, and diesel. It outlines the key components and their interactions, including power generation units, storage systems, and control strategies. The diagram highlights the optimization goals, such as minimizing cost and maximizing efficiency, while balancing energy supply and demand [42]. The connections between components and their roles in the overall system are depicted in Figure 6, providing a comprehensive overview of the hybrid system's functionality and optimization process [6]. This work aims to design an offshore hybrid wind-tidal energy system with a battery bank for a coastal town in South Africa using Homer software. Electrifying remote areas requires a reliable system with minimal maintenance, as frequent repairs and replacements can be challenging.

5.2. HOMER Software

To address the electricity demand of a coastal community, a systematic approach is required, consisting of the following steps as outlined in Figure 7:

- **Site Selection:** Identify a suitable location for the case study.
- **Electricity Demand Assessment:** Gather and analyze load profile data to understand the community's electricity needs.
- **Microgrid Design Definition:** Outline the microgrid components, including multiple energy sources (turbines and generators), storage devices (batteries), an AC to DC rectifier (converter), and a predefined electrical control system (controller).
- **Environmental Data Collection:** Obtain relevant data for energy resources, such as fuel type, wind speeds, and water currents.
- **Design Optimization:** Determine the optimal location, size, and quantity of devices necessary to harness the available energy resources effectively.
- **Feasibility and Financial Analysis:** Evaluate the optimized microgrid design's financial viability and overall feasibility.

To calculate the levelized cost of a hybrid energy system, it is essential to identify and include various individual costs, though estimating costs related to permissions and licenses can be challenging. These costs are often difficult to predict because the regulatory framework is not yet fully established and varies by country. The capital costs, which cover the purchase and installation of system components, must be factored into the optimization process of the hybrid energy system [43]. Equally important is the cost of maintenance over the system's lifetime, especially since these installations are exposed to harsh marine conditions. Decommissioning costs must also be considered. Additionally, to calculate the levelized cost [44]. Finally, the decommissioning cost must be included. In addition, to calculate the levelized cost [45], it is crucial to know the capacity factor of each technology to determine power output, as well as the discount rate and the return on investment required to make the project financially viable [46]. Offshore hybrid energy systems must be both cost-effective and highly reliable to meet load requirements [47]. To design a renewable-based hybrid energy system, it is essential to address a range of constraints, which fall into two key categories: technical and economic. Technical constraints include factors such as the availability of energy sources, the state of charge of battery systems, the performance of generation components, and the location of the electrical load. On the economic side, considerations such as reliability, flexibility, efficiency, and overall costs come into play [48]. To evaluate and optimize these systems, various commercial software tools are available, including HOMER, RET Screen, Hybrid2, TRNSYS, RAPSIM, and INSEL. Among these, HOMER, developed by the National Renewable Energy Laboratory (NREL), is one of the most widely used. It excels at simulating, modeling, and optimizing hybrid power configurations for off-grid systems [49,50].

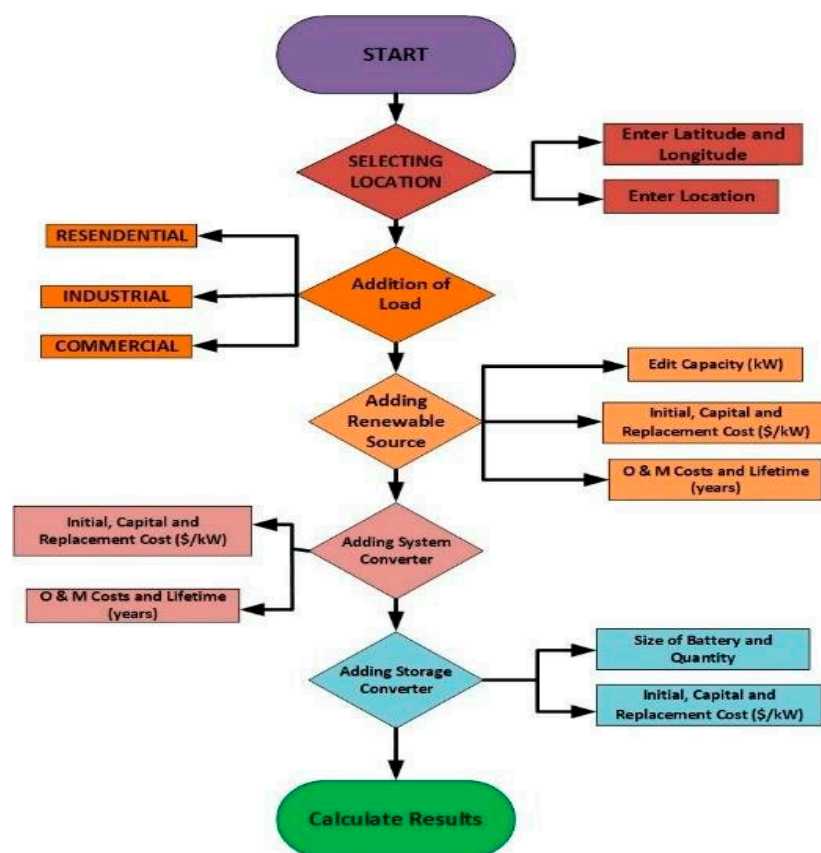


Figure 6. Hybrid generation system optimization general model.

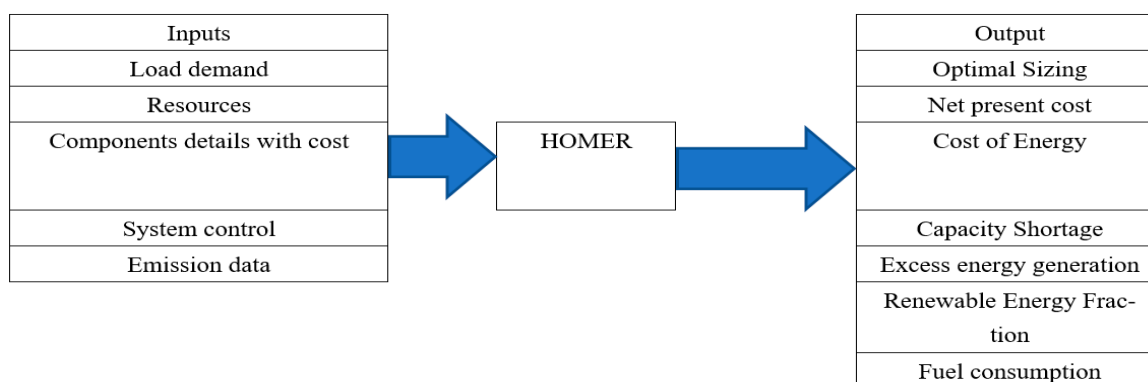


Figure 7. Schematic representation of HOMER.

5.3. Hybrid Tidal/Wind/Battery System

Figure 8 illustrates the platform diagram of the combined wind and tidal power generation system. Both the wind turbine and the tidal current turbine use horizontal shaft turbines, which are known for their high power generation efficiency [51]. The wind power generation device is installed above sea level, while the tidal power generation device is installed below sea level. By sharing the same base, these devices conserve space and significantly reduce both initial investment and ongoing maintenance costs. The primary types of wind power generation employed are doubly-fed induction generators and permanent magnet synchronous generators.

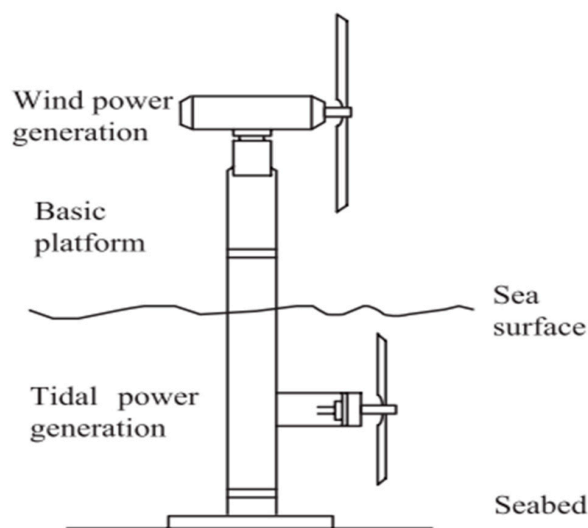


Figure 8. Diagram of the platform for the combined wind and tidal current power generation system.

5.4. Case Study

The research is conducted at a weather station located in the West Bank–East London region of Buffalo City Metropolitan Municipality (BCMM), Eastern Cape Province, South Africa. Positioned at latitude 33.0330° S and longitude 27.8330° E, this station monitors the entire West Bank–East London area. The study area features an ecosystem with ecologically sensitive vegetation. It is bordered geographically by the Indian Ocean to the south, the Igoda River to the west, East London City to the east, and the Buffalo River to the north. The terrain is characterized by rolling coastal plains, rock outcrops, and hills divided by steep valleys [41].

5.5. Loads Profile

The village, which lacks historical electrical load data [1] due to being non-electrified, relies on assumptions to estimate its electrical load:

Peak demand is estimated at 4500 kW for 150 houses in the case study [1], assuming an 80% load diversification for the base load without accounting for area-specific variations. Connected to the larger Bisho customer load network, the village adopts a scaled-down version of the Bisho demand profile (peaking at ~597 kWh) to project its demand. Detailed load data is recorded hourly, covering 8760 h (one year) for input into HOMER Pro[®]. The load primarily consists of residential properties, exhibiting two distinct peaks—smaller in the morning and larger in the evening—as illustrated in Figure 9, depicting average hourly loads throughout the year. Figure 10 presents yearly average loads, with higher expected demand during winter months (June–August) [52].

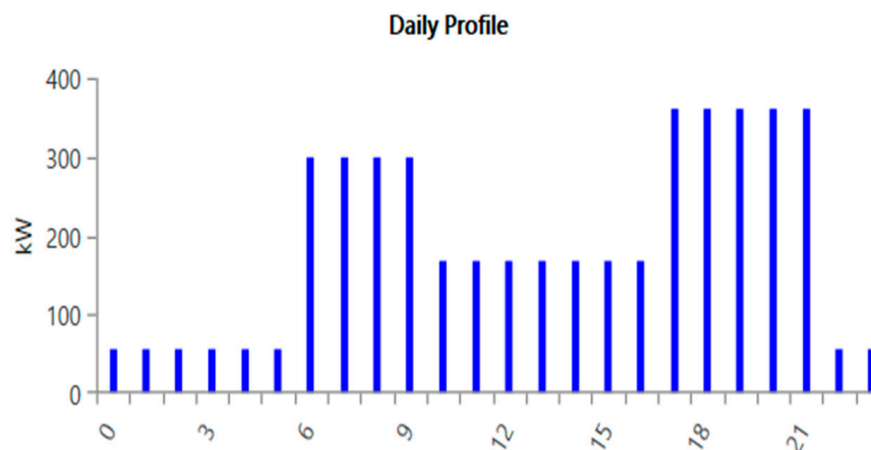


Figure 9. Variation of load demand for 24 h.

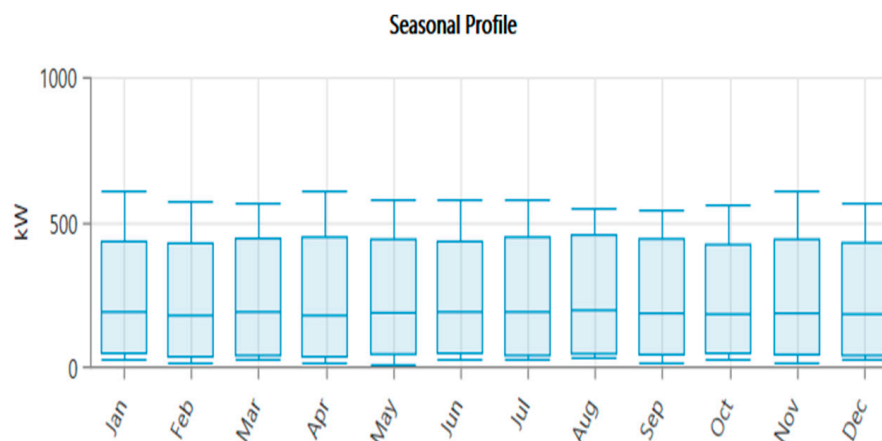


Figure 10. Seasonal profile of load demand throughout the year.

The seasonal load profile in Figure 10 highlights the fluctuations in electricity demand throughout the year for the West Bank community. Typically, there is higher demand during colder months due to increased heating needs and potentially during hot summer months if air conditioning is widely used. This profile underscores the peaks and troughs in electricity consumption, reflecting the community's usage patterns as influenced by seasonal changes.

According to a study conducted by Prinsloo and Davidson, the African village community, a house consumption is around 12.5 kW operating from 9:00 to 11:00 and 15:00 to 18:00. The bulbs can be lit from 18:00 to 23:00. A radio consumption (5 W) and a TV set (70 W) are to be switched usually around 6:00 p.m. to 11:00 p.m. [53].

To distribute the 20 MW load demand throughout the day, we'll consider typical consumption patterns for residential, commercial, industrial, and public service sectors. Here's a detailed breakdown of the daily load profile based on a total load demand of

20 MW; identifying Demand for West Bank, East London, South Africa Village Supply Authority data has been utilized in this case study to estimate monthly and hourly generation. The data indicates that peak values occur in June (69.29 kW) and during the 6–7 p.m. time slot (69.29 kW), while the lowest values are observed in January (162 kW) and between 3 and 4 p.m. (37 kW).

Tidal current data have been sourced from literature review papers [53]. For wind data in South Africa, the Global Wind Atlas extrapolates information from the National Renewable Energy Laboratory and NASA’s Prediction of Worldwide Energy Resources:

- Residential Loads (40% of total demand):
- Morning Peak (6 a.m.–9 a.m.): 25% of residential consumption
- Midday Dip (9 a.m.–4 p.m.): 15% of residential consumption
- Evening Peak (5 p.m.–10 p.m.): 40% of residential consumption
- Nighttime Baseline (10 p.m.–6 a.m.): 20% of residential consumption
- Commercial Loads (30% of total demand):
- Business Hours (8 a.m.–6 p.m.): 60% of commercial consumption
- Off-Peak Hours (6 p.m.–8 a.m.): 40% of commercial consumption
- Public and Community Services (10% of total demand):
- School and Public Buildings (7 a.m.–4 p.m.): 70% of public services consumption
- Evening Community Activities (4 p.m.–10 p.m.): 30% of public services consumption.

Key Considerations

- Peak Demand Management: Understanding when peaks occur helps in planning storage and backup systems to ensure reliability during high-demand periods.
- Renewable Integration: Match the generation profile of wind and tidal resources to the community load profile to maximize renewable energy utilization.
- Energy Efficiency Measures: Encourage energy-saving practices during peak hours to reduce overall demand and improve system stability.
- Scalability: Design the system to be scalable to accommodate future growth in the community’s energy needs.

Table 3 gives a rural African village’s hourly power energy load profile suitable for micro-CHP computer-modulated and simulated experimentally. According to these researchers, an electric load of a house in the rural villages of South Africa can be assumed to be composed of light bulbs, radio, television, 2 plate stove, iron, kettle, fan, and refrigerator t [53]. The load combination and energy demand estimation in Table 3 have been selected.

The environmental parameters of the site are comprehensively detailed in Table 4:

Table 3. The consumption of commonly used electrical appliances.

Appliances	Energy Consumption (Watthours)
Light bulbs	60 W × 5 h
Radio	50 W × 6 h
2Plate stove	2000 W × 2 h
Iron	1000 W × 1/4 h
Kettle	2000 W × 1/4 h
Refrigerator	5 W × 18 h
Fan	6 W × 7 h
Television(colour)	50 W × 6 h

Table 4. Key location parameters for tidal and wind energy assessment.

Location	Latitude (deg)	Longitude (deg)	Annual Average Water Speed (m/s)	Water Depth (m)	Annual Average Wind Speed (m/s)
West Bk-EL	−33.0330 S	27.8330 E	0.52	30	8.31

Current data on Tidal were obtained from the official SAN Hydrographic Office website. The simulation included high-resolution nested domains, specifically targeting the region around East London Harbour. Figure 11 illustrates the bathymetry and the environmental parameters of the site indicated in Table 4 around southern Africa, highlighting the major coastal towns such as Port Nolloth (PN), Saldanha Bay (SB), Cape Town (CT), Mossel Bay (MB), Port Elizabeth (PE), East London (EL), Durban (DN), Richards Bay (RB), and Luderitz [54,55]. Thus, the annual water speed for West Bank East London South Africa is presented in Figure 12.

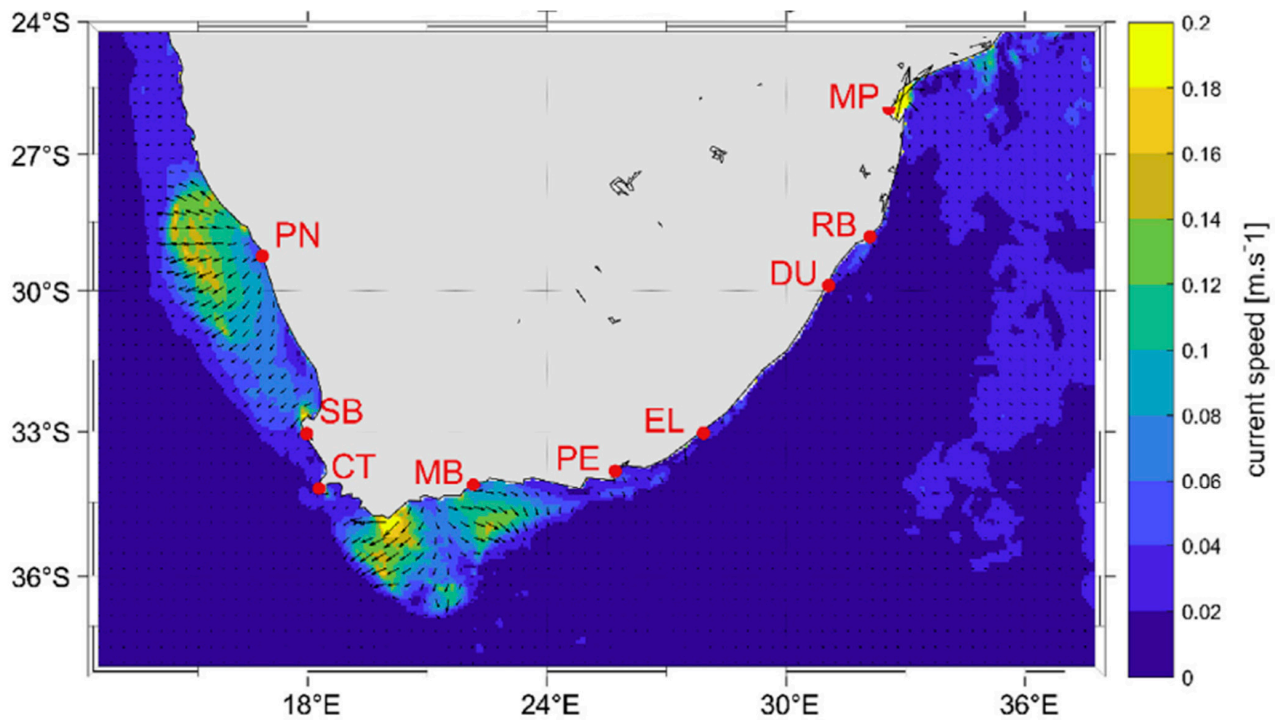


Figure 11. Bathymetry and key coastal cities of Southern Africa [54].

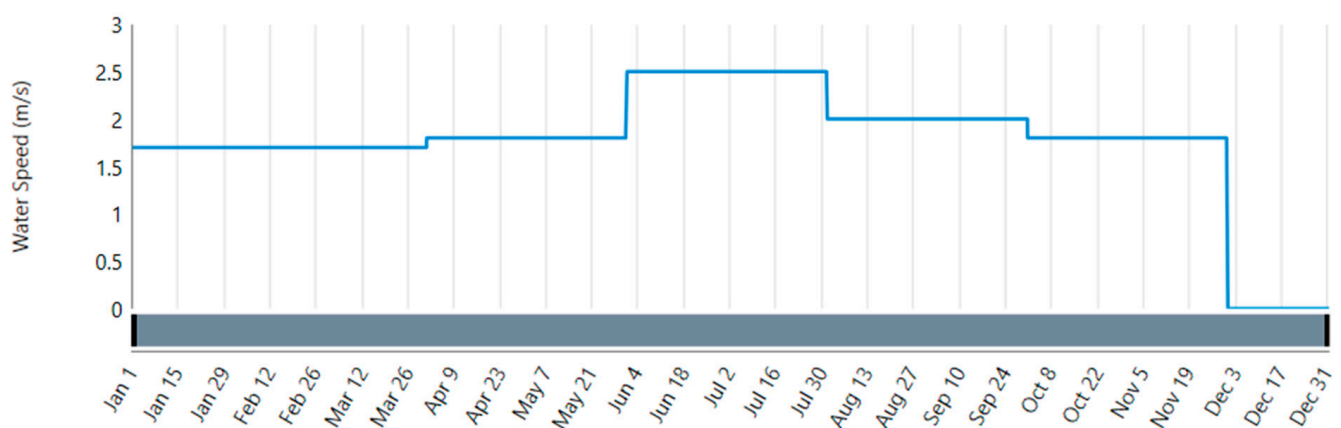


Figure 12. Annual water speed for West Bank East London South Africa.

In the West Bank area of East London, South Africa, wind resources indicated in Figure 13 (<https://globalwindatlas.info/en/area/South%20Africa>, accessed on 10 December 2023), the annual average wind velocity, and the wind speed histogram (as shown in Figures 14 and 15) illustrate their complementarity. Wind power is more abundant in winter and less so in summer, while tidal current energy is less abundant in winter and more so in summer [56,57]. This seasonal complementarity ensures that the two

energy sources can balance each other. The combined utilization of wind and tidal energy improves the stability of the power generation system’s output.

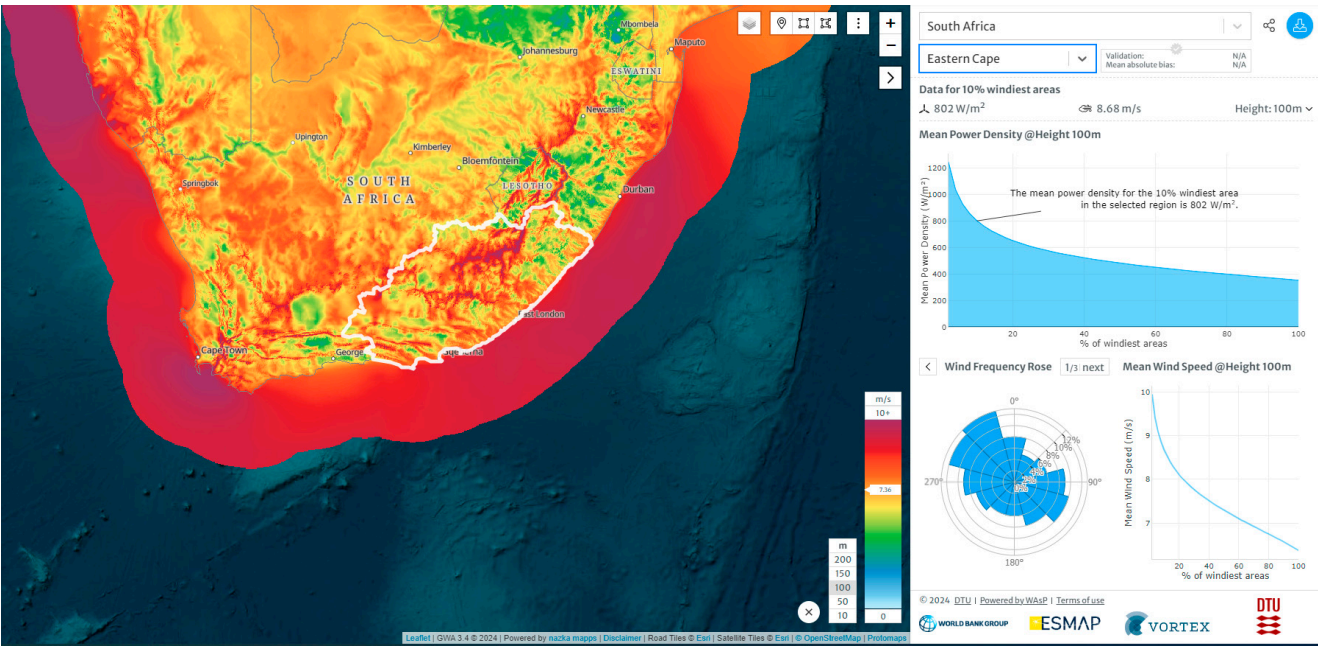


Figure 13. South Africa’s offshore wind resource.

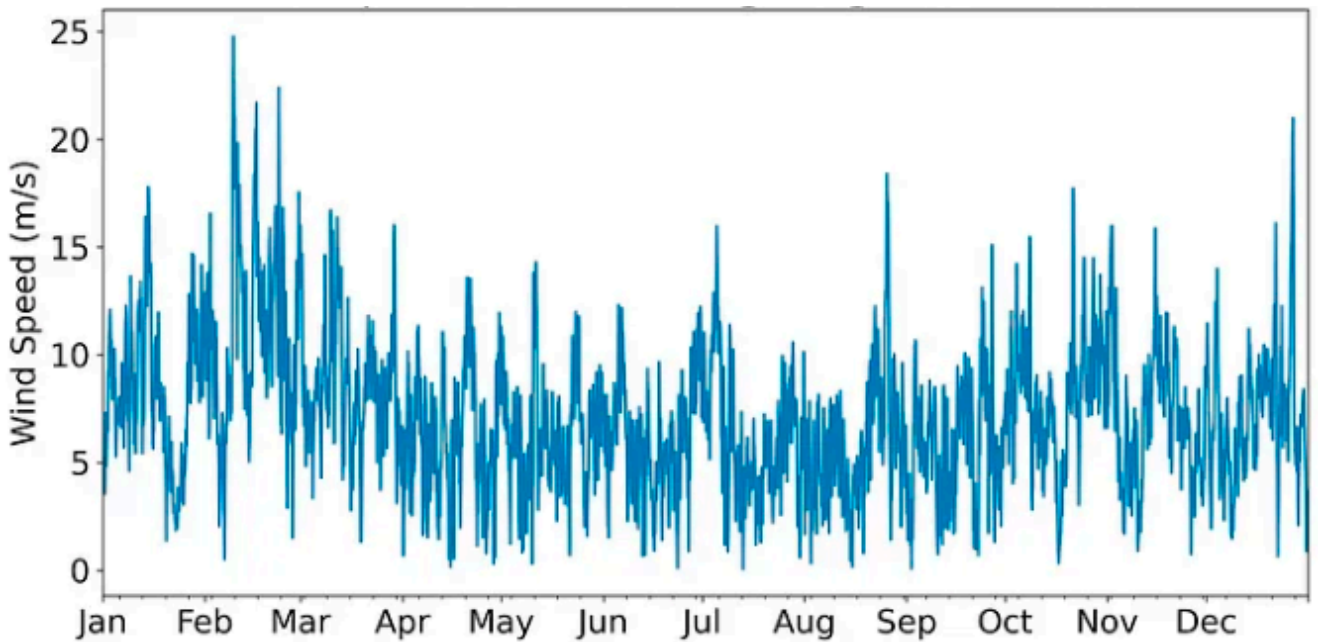


Figure 14. Annual wind speed for West Bank East London South Africa.

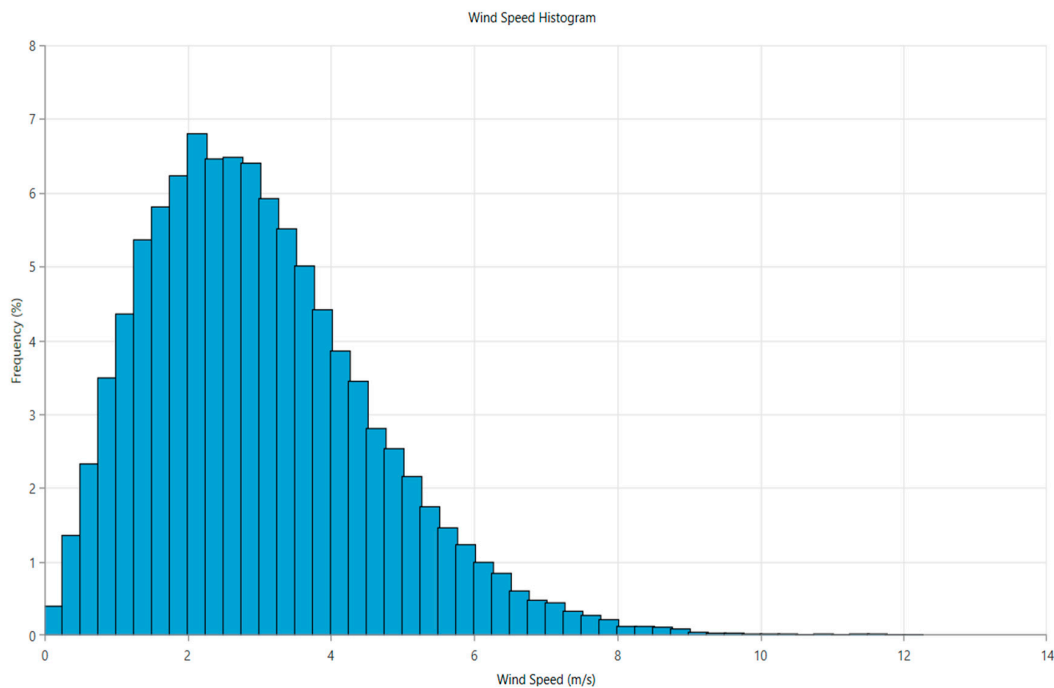


Figure 15. Wind speed histogram.

6. Microgrid Components

This study focuses on offshore microgrid energy systems, both grid-connected and off-grid. The microgrid system under analysis includes wind and tidal turbines and battery energy storage systems (BESS), as illustrated in Figure 16. All components are interconnected via both AC and DC buses. Grid-connected microgrid energy systems offer several advantages, including enhanced reliability, improved power quality, and the ability to sell excess energy back to the main grid. Off-grid microgrid energy systems, on the other hand, provide energy independence, increased resilience in remote or disaster-prone areas, and the potential for cost savings by reducing reliance on traditional energy sources.

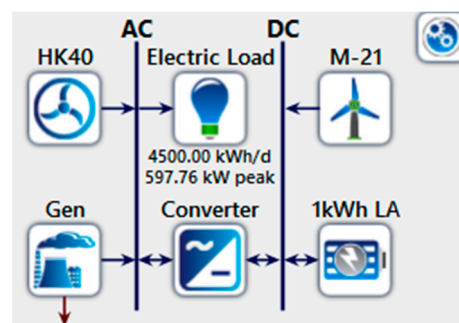


Figure 16. Off-Grid Microgrid Systems: Tidal, Wind, and Storage Integration.

6.1. Wind Turbine

The XANT M-21 (XANT, Brussels, Belgium) 100 kW wind turbine was selected for its low cut-in speed and its capacity to effectively meet peak load demands while providing a substantial share of the peak load at minimal overall costs. With a capital and replacement cost of \$300,000 each and an annual operation and maintenance (O&M) cost of \$10,000, the turbine offers a cost-effective solution over its 20-year lifespan [2]. The turbine's performance, including its power output at 4 m/s wind speed intervals, is shown in Figure 14 and explained in Equation (11).

$$P_{Wind} = 0.0018 V^6 - 0.07V^5 + 1.0826 V^4 - 8.4544 V^3 + 36.229 V^2 - 78.056 V + 66.38 \text{ for } V \leq 10 \text{ m/s} \quad (11)$$

Additional details for the XANT wind turbine are provided in Table 5.

Table 5. Wind System Components.

Wind Turbine	XANT M-21 (100 kW)
Model name	XANT
Rated power	100 kW
Cut-in wind speed	3 m/s
Cut-out wind speed	20 m/s
Hub height	31.8 m
Swept area	346.36 m ²
Rotor diameter	21 m
Capital cost	\$300,000
Replacement cost	\$300,000
O&M	\$10,000
Lifetime	20 years

HOMER Pro software was used to generate wind frequency distribution data for the West Bank-East London area based on downloaded wind speed data from the software. As depicted in Figure 17, wind speeds exceed the XANT M-21 turbine's cut-in speed for 90.5% of the year, confirming that this wind turbine is well-suited for electricity generation at the West Bank-East London site. Similarly, as shown in Figure 18, water speeds exceed the cut-in speed for the Schottel 54 kW tidal turbine for 68.4% of the year, making it an appropriate choice for tidal energy generation at the same location.

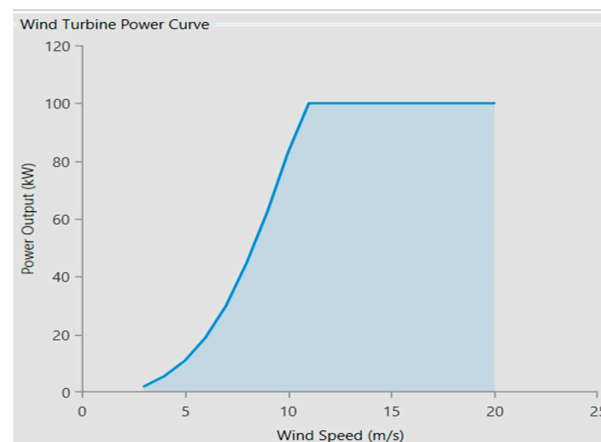


Figure 17. The power curve of the XANT M-21 turbine.

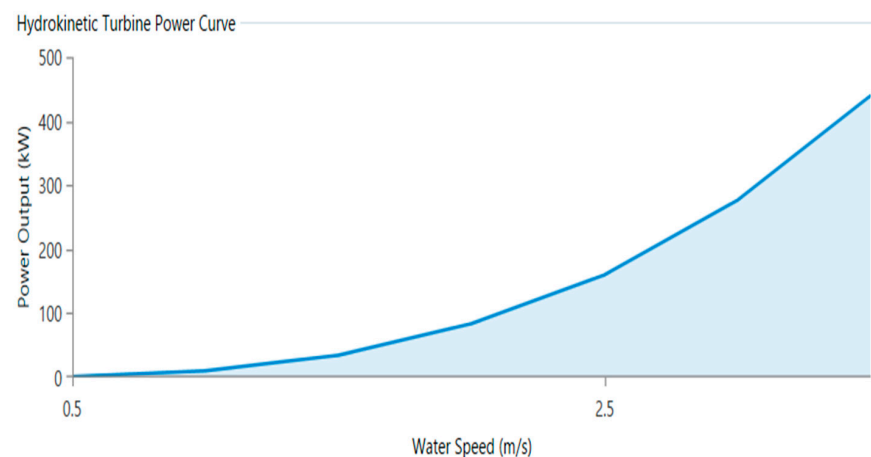


Figure 18. The water speed.

6.2. Tidal Turbine

The Schottel (Schottel, Spray, Germany) 54 kW bidirectional turbine parameters indicated in Table 6 are selected for their low cut-in speed and their capability to meet peak load demands while supplying a significant portion of the peak load at minimal purchase, installation, and maintenance costs [58]. The capital costs, including installation, wiring, and mounting, are \$54,000, with replacement costs also at \$54,000 [58], an annual maintenance cost of \$2700, and a lifespan of 10 years [58]. The power curve and generation percentage at 0.5 m/s intervals, shown in Figure 18, are described by Equation (12):

$$P_{tidal} = 2.0978V^3 + 2.7163V^2 - 1.7909V - 0.2358 \text{ for } V \leq 2.5 \quad (12)$$

Table 6. The power curve of the Schottel 54 kW tidal turbine.

Tidal Turbine	Schottel (54 kW)
Model name	Schottel
Rated power	54 kW
Cut-in tidal speed	0.7 m/s
Cut-out tidal speed	4.6 m/s
Rated power at	2.6 m/s
Swept area	7.06 m ²
Rotor diameter	3 m
Capital cost	\$54,000
Replacement cost	\$54,000
O&M	\$2700
Lifetime	20 years

6.3. Battery Energy Storage

Energy storage plays a critical role in integrated systems that generate power from diverse renewable sources. To ensure dependable performance and cost-effective operation, a standard 12-volt lead-acid battery with 1 kWh of storage capacity is recommended [59]. Detailed specifications in Table 7 outline capital and replacement costs of \$200 each, an annual maintenance cost of \$20, and a lifespan of 10 years [58].

Table 7. Battery Components.

Battery	Values
Model name	Generic 1 kWh Lead Acid
Nominal capacity	1
Roundtrip efficiency	80%
Min State of charge	40%
Float life	5 years
Max Charge rate	1
Max Charge current	16.7 A
Capital cost	\$200
Replacement cost	\$200
O&M cost	\$20
Lifetime throughput	9600 kWh

6.4. Converter

A standard system converter is proposed as a cost-effective alternative to bidirectional converters to convert the AC output of the generator to DC. The HOMER (Homer Energy, Boulder, CO, USA) optimizer optimizes the converter's size. Capital and replacement costs are both \$54,000, with an annual maintenance cost of \$1500 [40]. The converter operates at 90% efficiency and has a lifespan of 15 years.

6.5. Controller

A load-following (LF) controller is selected for its ability to precisely match power generation to demand requirements. Capital and replacement costs for the controller are \$200 each, with an annual maintenance cost of \$5.00. The controller is designed to operate efficiently over a lifespan of 25 years [40].

7. Results and Discussion

Seasonal variations play a critical role in influencing electricity demand at the West Bank site. The analysis indicates that demand peaks during the winter months of June and July, primarily due to increased heating requirements and reduced daylight hours, which result in higher electricity consumption. Conversely, during warmer months, the demand is generally lower as heating needs diminish. Accurately assessing these seasonal fluctuations is essential for the design of turbine systems capable of efficiently meeting the variable demand throughout the year.

This section examines off-grid hybrid systems—comprising tidal, wind, storage, and diesel generator turbines—to meet the electricity demand at the West Bank, East London site. Figures 9 and 10 present an analysis of the average hourly and monthly loads, while Figure 11 visually depicts this data. The peak hourly load is recorded at 597.76 kW. The HOMER software analysis, as shown in Figure 15, reveals that the average daily load fluctuates around 4500 kWh/day. The corresponding graph illustrates the load variations throughout the year, with June and July identified as periods of peak demand. After applying a load factor of 0.69, the total annual demand is computed to be 3,187,017 kWh. The power output variability of the tidal turbine and wind turbine is indicated in Figures 19 and 20.

Figure 21 shows the power demand fluctuations over three days, comparing the outputs from a tidal turbine, a wind turbine, and a diesel generator. The red line represents the total power generated by the system, while the green line indicates the power demand. The data suggest that to decrease the West Bank coastal area's reliance on diesel generators, it is essential to implement a hybrid system with multiple wind and tidal turbines.

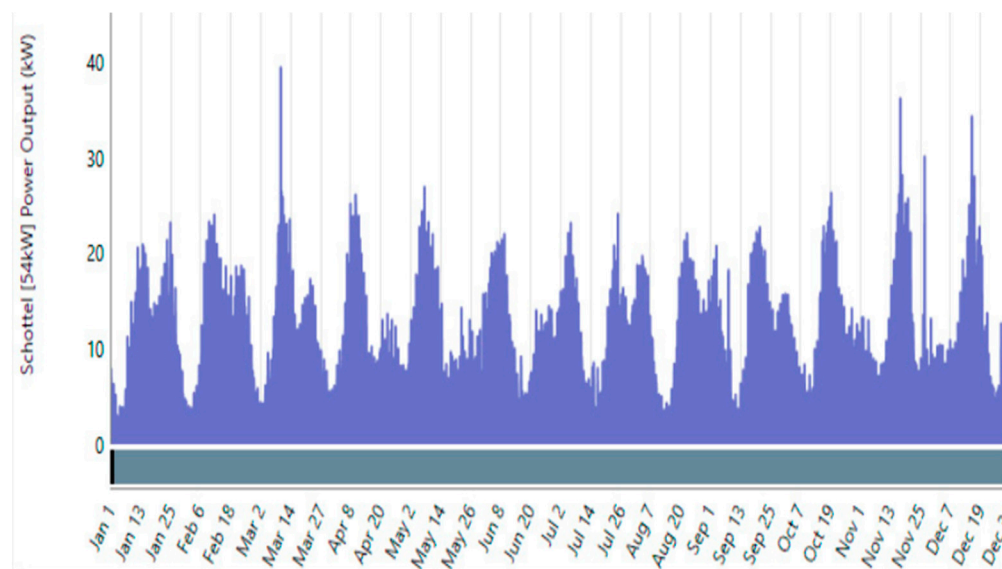


Figure 19. Power output variability for the tidal turbine at the West Bank East London site.

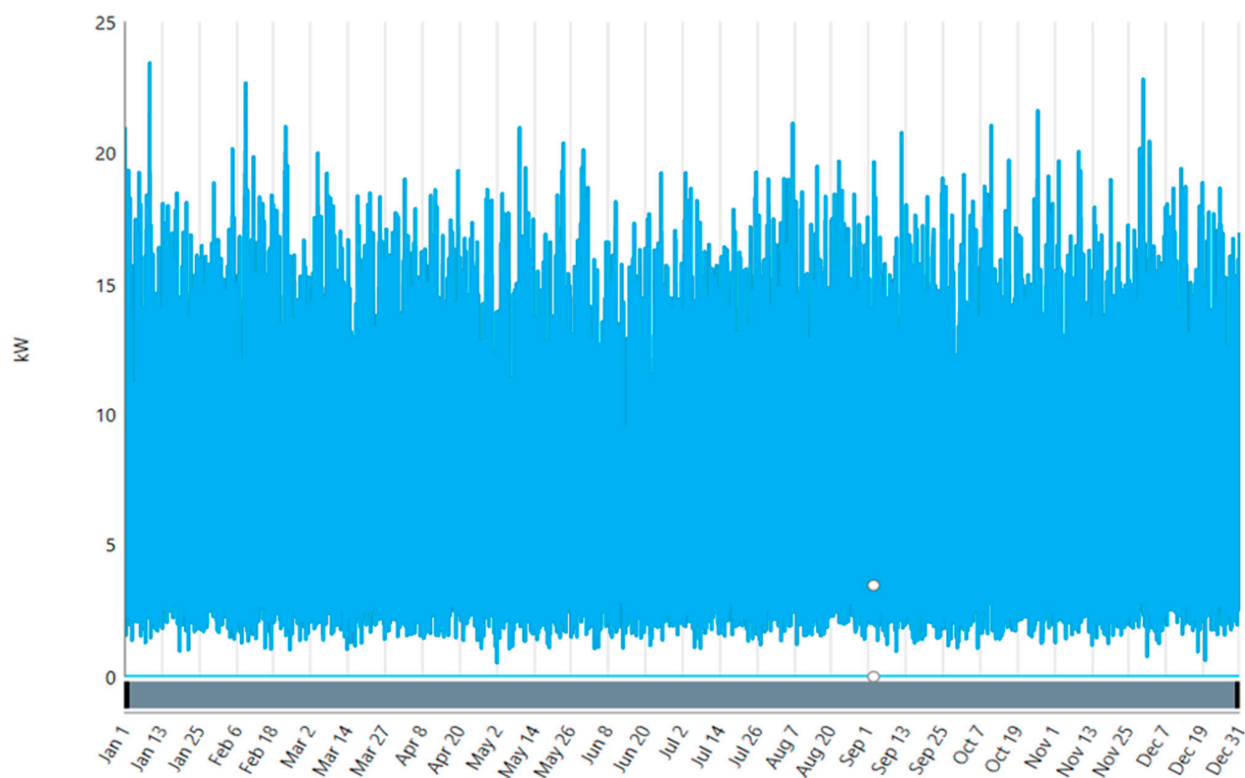


Figure 20. Power output variability for a West Bank East London site wind turbine.

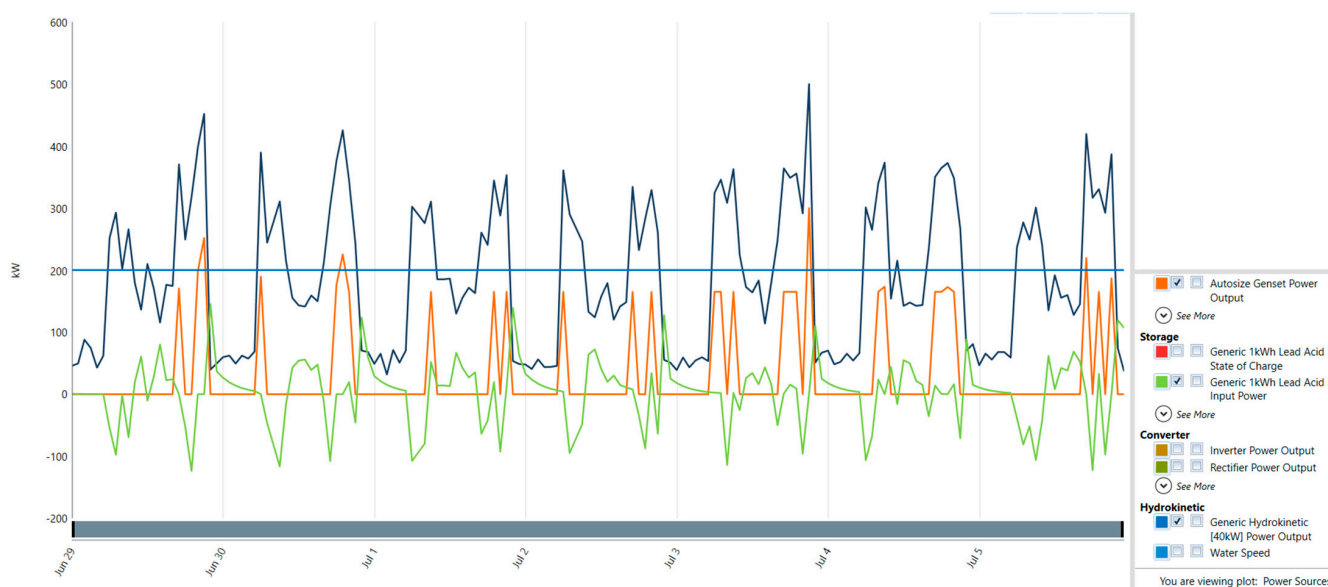


Figure 21. Fluctuations in power production and consumption over three days at West Bank East London.

7.1. Financial Analysis Results

Figure 16 illustrates how HOMER software evaluates and optimizes various configurations of turbines and generators to manage demand fluctuations throughout the year. The scenarios analyzed include different combinations of wind turbines (W), tidal turbines (T), energy storage systems (S), and diesel generators (G). Sections 7.1–7.3 delve into the outcomes of these configurations, with a focus on power generation efficiency, cost-effectiveness, and environmental emissions.

Operating costs, which are crucial to the analysis, encompass all expenses related to preliminary studies, project development, environmental impact assessments, permitting procedures, and project management. These costs can vary significantly depending on the project's location, the national policies in place, and the scale of the installation. Consequently, a broad range of cost estimates is presented, as shown in the subsequent figures.

This study employs HOMER software to conduct a thorough financial analysis of a hybrid wind-tidal energy storage system. The analysis is based on predefined parameters and assumptions in Table 8, providing a comprehensive understanding of the system's economic viability.

Table 9 presents the optimization results for an alternative scenario that balances wind and tidal generation with a configuration of 2 wind turbines and 5 tidal turbines in rank (b) (2W + 5T), achieving a renewable fraction of 52.7%. However, this configuration results in higher capital costs, operating costs, and Net Present Costs (NPC) compared to the configurations of 1 wind turbine and 5 tidal turbines in rank (d), (h), (j) (1W + 5T). As a result, the Cost of Energy (COE) is also higher. Table 10 summarizes the total electricity production and the percentage contributions from each energy source, demonstrating that in the storage + 20T scenario, two-thirds of the production is sourced from renewables. The 5 tidal turbines (2 + 5T) are more cost-effective in terms of installation and operation. Table 9 in rank (b), (d), (h), (j), and (k) present the optimization results for each scenario, showing renewable fractions of 30.2%, 32.5%, 57.1%, and 61.1%, respectively. A renewable fraction of 61.1% indicates that 61.1% of the electricity is generated from wind and tidal turbines, while the remaining electricity is provided by the diesel generator. Hybrid systems with a renewable fraction exceeding 66% are generally more profitable. The 1W + 5T and 2W + 5T scenarios nearly meet this criterion and have lower operating costs, fuel costs, and Net Present Costs (NPC) compared to the 20W + 5T scenarios.

Table 8. Economic Analysis of Balanced Alternative of the Hybrid Energy Systems: Cost Summary and NPC Component Breakdown.

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Savage (\$)	Total (\$)
Auto size Genset	\$300,000	\$790,403.24	\$822,102.75	\$2,273,714.20	\$45,108.53	\$4,171,111.66
Generic 1 kwh Lead Acid	\$268,200	\$436,780.18	\$11,283.20	\$0.00	\$0.00	\$819,263.39
Gen Hydro (40 kw)	\$70,000	\$60,913.97	\$0.00	\$0.00	\$8154.95	\$122,759.01
Homer Load Following	\$200	\$0.00	\$255.67	\$0.00	\$0.00	\$455.67
System Converter	\$44,578.37	\$18,601.00	\$0.00	\$0.00	\$3154.95	\$59,717.13
XANT M-21 (100 KW)	\$300,000	\$77,951.18	\$127,833.56	\$0.00	\$43,687.24	\$462,097.50
System	\$1,012,978.37	\$1,384,649.57	\$1,064,475.18	\$2,273,714.20	\$100,412.96	\$5,635,404.36

Table 9. The optimization results for an alternative.

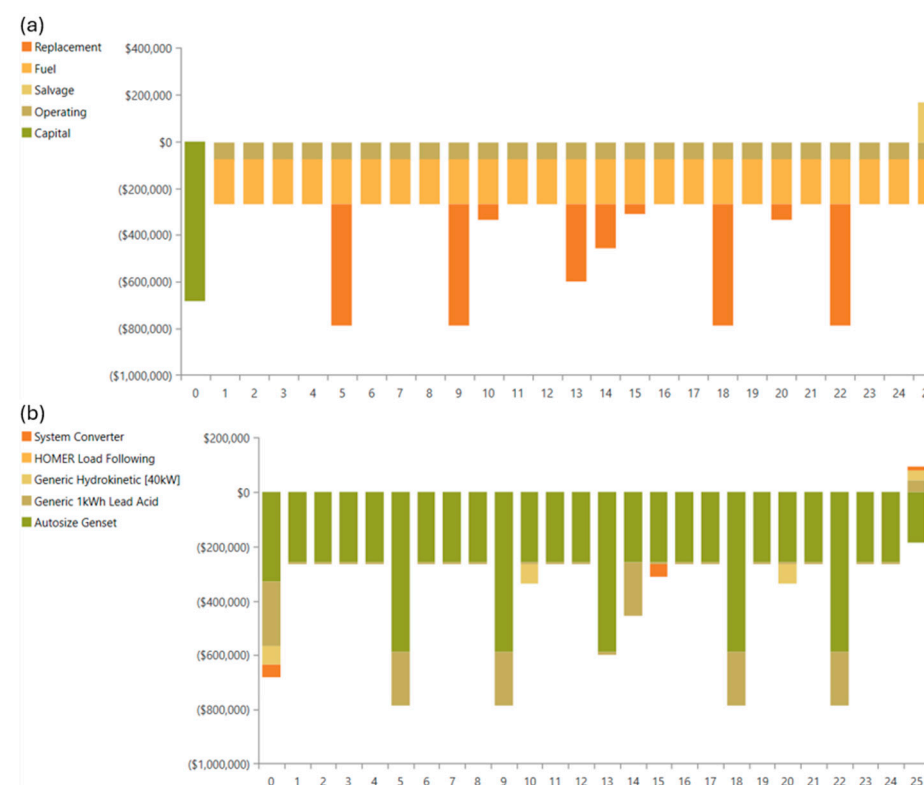
Rank	Architecture					COST			
	M-21 (kW)	Gen (kW)	1 kwh LA	HK40	Converter kW	Dispatch	NPC (\$)	COE (\$)	Operat-Cost
a		660	787	5	149	LF	\$5.43 M	\$0.259	\$371,620
b	2	660	911	5	321	LF	\$4.74 M	\$0.226	\$263,918
c		660	2132	5	428	LF	\$3.48 M	\$0.171	\$136,140
d	1	660	1088	5	163	CC	\$8.23 M	\$0.392	\$582,768
e		660	7192	5	427	CC	\$5.49 M	\$0.271	\$190,567
f		660	787	5	149	LF	\$5.43 M	\$0.259	\$371,620
h	1	660	894	5	149	LF	\$5.64 M	\$0.268	\$361,617
i		660		5		CC	\$6.97 M	\$0.332	\$513,742
j	1	660		5	18.7	CC	\$7.37 M	\$0.351	\$521,439
k	20		7192	5	455	CC	\$13.9 M	\$0.690	\$435,050

Table 10. Economic metrics of the optimized system.

Descriptions	Values
Simple payback:	2.05 yr
Return on Investment:	46.1%
Internal Rate of Return:	57.2%
Net Present Value:	\$1.54 M
Capital Investment:	\$281,063
Annualized Savings:	\$142,122

It proposes adding 788 kWh of battery capacity. This would reduce your operating costs to \$371,620/yr. The investment has a payback of 2.05 years and an IRR of 57.2%.

Figure 22a,b illustrate that increasing the number of tidal turbines raises the system's capital, operating, replacement, and salvage costs. Despite this, the overall fuel cost remains unchanged. Additionally, the construction expenses are higher due to the need for extra floating platforms and cables required for the additional tidal turbines.

**Figure 22.** The economic and component chronological cash flow.

Based on the results in Table 9 and Figure 23, a modest investment can yield long-term societal benefits, with a payback period of less than 7 years over a 25-year project lifespan. Technological advancements and improved materials may extend the lifespan of wind and tidal turbines beyond 25 years. Consequently, using tidal stream turbines with a 30–40-year lifespan could significantly impact future economic calculations. Additionally, emerging tidal technologies can further enhance economic outcomes by reducing the payback period.

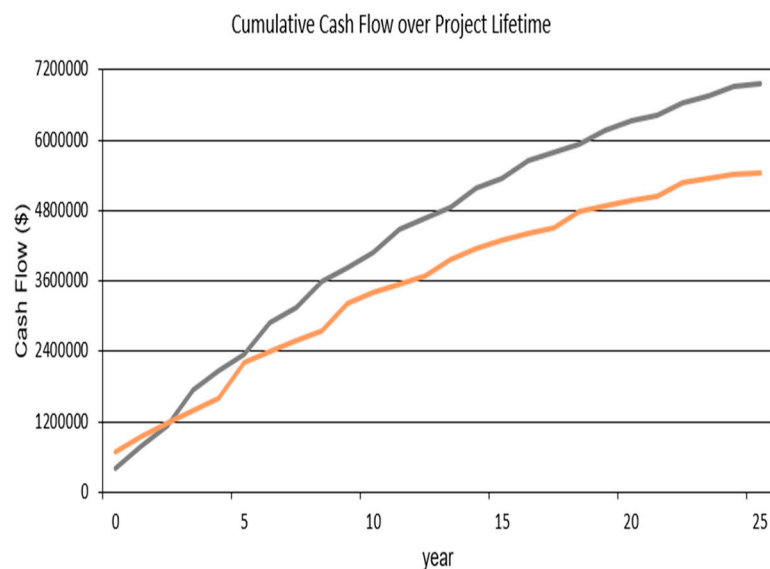


Figure 23. A simple payback period is based on cumulative cash flow throughout the project's lifetime.

7.2. Analysis of Power Generation Results

Figure 24 presents the average output, operational hours, and total production for each scenario. Increasing the number of wind and tidal turbines leads to a reduction in both the operational hours and the total output of diesel generators. In all scenarios, the total power production surpasses the West Bank coastal area's annual demand of 1,260,332 kWh.



Figure 24. Monthly and yearly average output power for (a) 5T + Gen, (b) 1W + 20T, (c) Gen + 20T.

This microgrid requires 7200 kWh/day and has a peak of 300 kW. In the proposed system, the following generation sources serve the electrical load.

Figure 23 presents the average power output for different scenarios. West Bank East London coastal site has an average power demand of 4500 kW for 150 community houses, which is satisfied by all scenarios evaluated. Particularly noteworthy are scenarios involving 1 wind turbine and 5 tidal turbines, as well as 1 wind turbine and 20 tidal turbines, both of which surpass the peak demand of 597.96 kW with their average outputs. Further analyses of the optimal result from Section 1 are detailed as follows

Over time, this initial cost is offset by the system's positive salvage value. The generator consumed a total of 224,316 L of fuel over the study period, representing the aggregate amount of diesel used for electricity production indicated in Figure 25. On average, the generator uses 615 L of fuel per day, calculated by dividing the total fuel consumption by the number of days in the study period. This provides insight into the daily fuel requirement for the generator's operation. Additionally, the generator consumes an average of 25.6 L of fuel per hour, derived by dividing the daily average fuel consumption by 24 h. This value indicates the generator's fuel efficiency and typical hourly fuel usage.

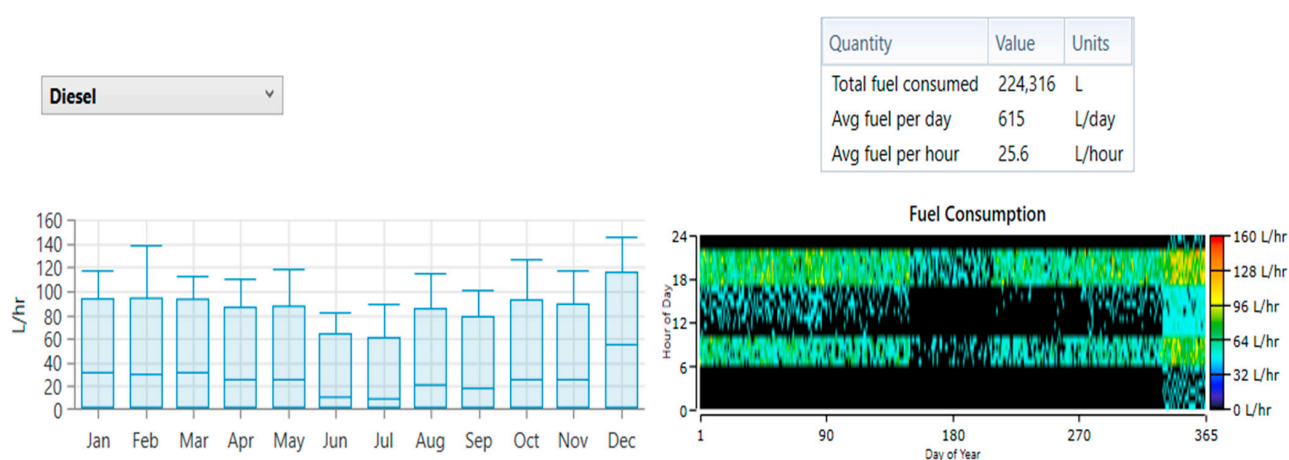


Figure 25. Diesel generator fuel consumption.

In summary, these values offer a detailed overview of the generator's fuel usage, helping to understand its operational efficiency and the overall fuel costs involved in running the generator over the given period.

Figure 26 and Tables 11 and 12 provide a detailed overview of the generator's power output values. Electrical Production: The generator produces a total of 783,387 kWh of electrical energy per year, representing the annual electricity generated by the diesel generator. The mean Electrical Output is the generator's average electrical output of 226 kW. This figure is derived by dividing the total annual electrical production by the number of hours in a year (783,387 kWh/year, 8760 h/year).

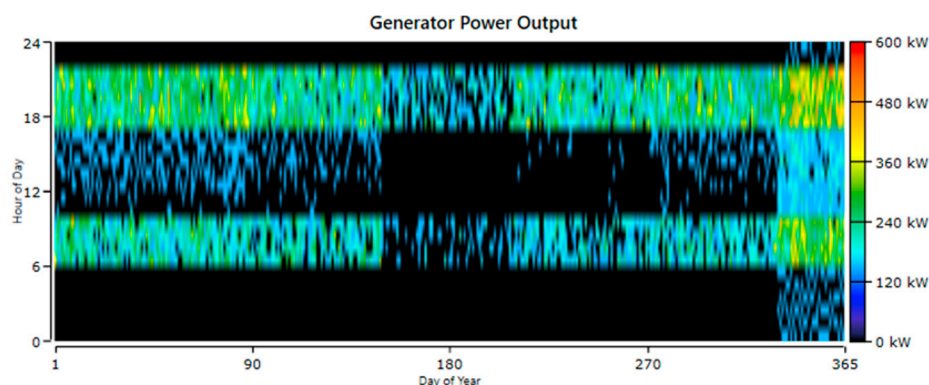


Figure 26. Generator power output.

Table 11. Generator Power Output Parameters.

Quantity	Value	Units
Hours of Operation	3469	Hrs/yr
Number of Starts	1124	Starts/yr
Operation Life	4.32	yr
Capacity Factor	13.5	%
Fixed Generation Cost	51.5	\$/h
Marginal Generation Cost	0.201	\$/kWh
Electrical Production	783,387	kWh/yr
Mean Electrical Output	226	kW
Minimum Electrical Output	165	kW
Maximum Electrical Output	565	kW
Thermal Production	569,551	kWh/yr
Mean thermal output	164	kW

Table 12. Generator Power Output Parameters.

Quantity	Value	Units
Fuel consumption	224,316	L
Specific fuel consumption	0.286	L/kWh
Fuel Energy Input	2,207,266	kWh
Mean Electrical Efficiency	35.5	%

Minimum Electrical Output is the generator’s minimum electrical output of 165 kW, indicating the lowest level of electrical power it produces at any point during its operation. Maximum electrical output: The generator’s maximum electrical output is 565 kW, representing the highest level of electrical power it can produce.

Thermal production: The generator also produces 569,551 kWh of thermal energy per year, representing the total amount of heat generated annually, which can be utilized for heating purposes. The mean Thermal Output is the average thermal output of the generator, which is 164 kW. This value is calculated by dividing the total annual thermal production by the number of hours a year (569,551 kWh/year, 8760 h). Figure 27 illustrates the battery bank’s state of charge, starting at 30%.

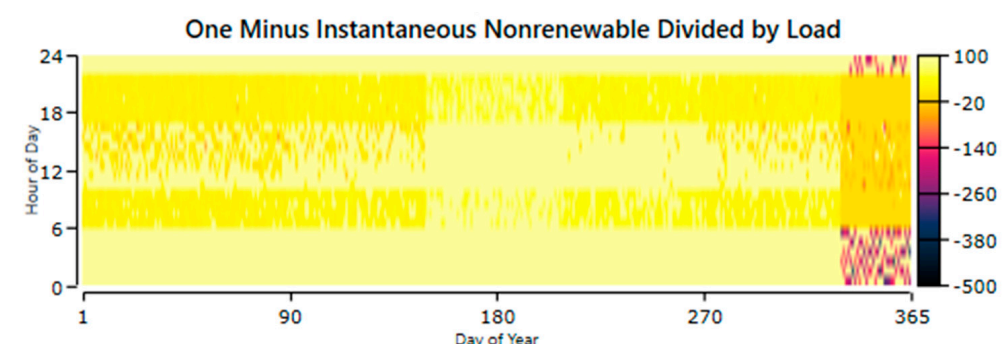
**Figure 27.** One minus instantaneous non-renewable divided by the load.

Figure 27 provides an analysis of the instantaneous renewable output of the load, offering key insights into the renewable energy contributions and their impact on overall energy production. Total Renewable Production Divided by Load—this metric indicates that 61.1% of the total load demand is met by renewable energy sources. It highlights the substantial contribution of renewable energy in covering the community’s electricity needs, demonstrating the effectiveness of integrating renewable sources into the power system. Total Renewable Generator: This value represents that 56.1% of the total energy generated by the system comes from renewable sources. It underscores the dominance of

renewable energy in the generation mix and reflects the system’s reliance on sustainable energy production.

One Minus Total Non-renewable Production Divided by Load: This metric, calculated as $1 - (\text{total non-renewable production} / \text{load})$, shows that 52.3% of the load is met without relying on non-renewable energy sources. It illustrates the extent to which the system reduces dependence on non-renewable energy, highlighting its environmental benefits and contribution to sustainability.

In the context of a research paper, these parameters from the simulation or analysis tool for the battery system indicated in Tables 13 and 14, and Figure 28 provide crucial insights into its operational characteristics and economic feasibility. Here’s how each parameter contributes to understanding the battery system’s performance. The Battery Bank State of Charge Functional Characteristics: This parameter elucidates how the battery’s state of charge (SOC) evolves, reflecting its ability to store and discharge energy efficiently under varying operational conditions. Understanding SOC dynamics is critical for optimizing battery usage and ensuring a reliable energy supply. Anatomy 2.52 h: While not fully defined in the context provided, it likely pertains to a specific operational or design aspect of the battery system, potentially related to its discharge or charge profile over a defined period.

Storage Wear Cost is quantified at \$0.3335 per kWh; this parameter assesses the economic impact of wear and tear on the battery due to its usage. It underscores the importance of lifecycle cost considerations in evaluating the economic viability of battery deployment. Nominal Capacity: At 473 kWh, this parameter denotes the total energy storage capability of the battery system, influencing its ability to meet energy demands and integrate renewable energy sources effectively.

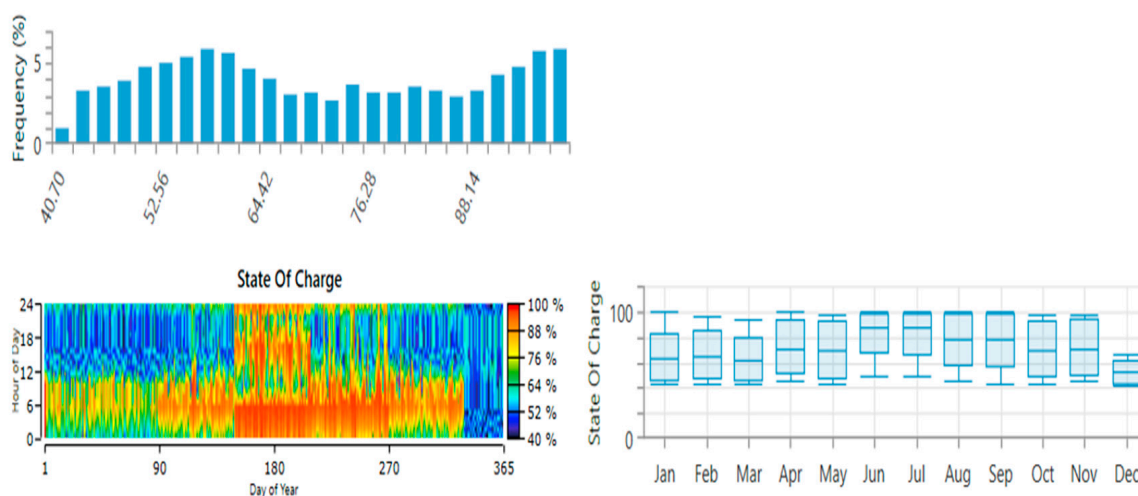


Figure 28. Battery Bank State of Charge.

Table 13. Battery Bank State of Charge parameters.

Quantity	Value	Units
Batteries	787	Qty.
String Size	1.00	batteries
Strings in Parallel	787	strings
Bus Voltage	12.0	v
Autonomy	2.52	h
Storage Wear Cost	0.335	\$/kWh
Nominal Capacity	788	kWh
Usable Nominal Capacity	473	kWh
Lifetime Throughput	629,600	kWh
Expected Life	4.36	yr

Table 14. Battery Bank State of Charge parameters.

Quantity	Inverter	Units
Average Energy Cost	161,060	\$/kWh
Energy In	129,205	kWh/yr
Energy Output	0	kWh/yr
Storage Depletion	129	kWh/yr
Losses	9.39	kWh/yr
Annual Throughput	144,456	kWh/yr

Lifetime Throughput is 629,600 kWh processed over its operational lifespan; this metric quantifies the total energy handled by the battery, offering insights into its long-term performance and durability. Expected Life is projected at 4.36 years, and this parameter estimates the operational duration of the battery system, guiding decisions on maintenance schedules, replacement planning, and overall economic return on investment.

The average energy cost is noting \$0 per kWh. This parameter implies that the cost of energy storage and discharge does not contribute to an additional financial burden beyond initial setup costs, affecting the overall economic feasibility positively. Energy in and Out Annual figures of 161,060 kWh and 129,205 kWh, respectively, illustrate the energy flow into and out of the battery system annually. These metrics gauge operational efficiency and energy supply reliability under real-world conditions.

Storage Depletion and Losses are these parameters—399 kWh/year and 32,254 kWh/year—highlight the amount of energy drawn from the battery annually and the losses incurred within the system, influencing overall efficiency and operational costs.

Annual Throughput: Summing to 1,444,456 kWh/year, this metric reflects the total energy processed annually by the battery system, encompassing both input and output energy.

In the context of our study on the standalone offshore hybrid wind-tidal storage energy system, the inverter and rectifier parameters indicated in Table 15 and Figure 29 provide essential insights into their operational efficiency and capacity. The inverter, with a capacity of 149 kW, handles an average output of 14 kW and peaks at 129 kW, indicating its ability to manage variable power demands efficiently. Its capacity factor of 9.39% and 2039 h of operation per year reflect moderate utilization levels. The annual energy output of 122,745 kWh and input of 129,205 kWh, with losses amounting to 6460 kWh, underscores the importance of minimizing conversion losses to enhance overall system efficiency.

Similarly, the rectifier, also with a capacity of 149 kW, demonstrates a higher average output at 18 kW and a capacity factor of 12.3%, operating for 4426 h annually. Its energy output of 161,060 kWh and input of 169,537 kWh, alongside losses of 8477 kWh, highlight its critical role in converting and storing energy effectively. These parameters collectively inform the design and operational strategies to optimize the performance and reliability of the energy system.

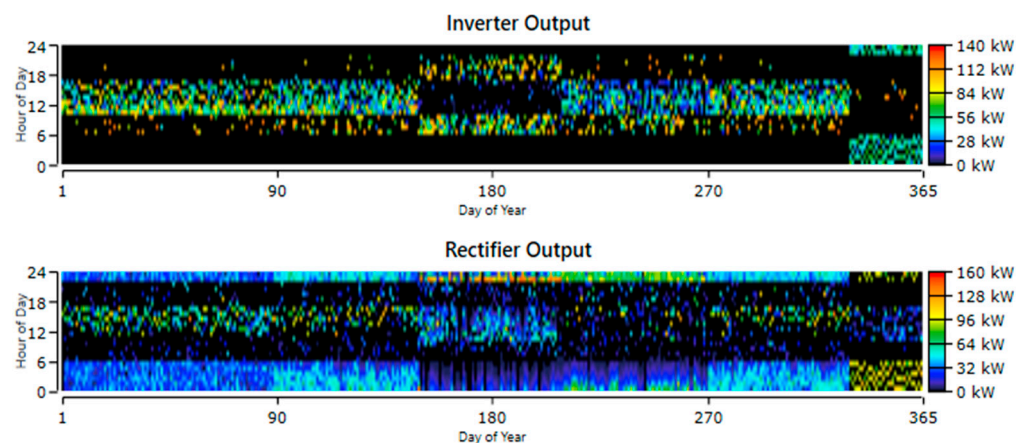
**Figure 29.** Inverter and rectifier out.

Table 15. Inverter and rectifier out parameters.

Quantity	Inverter	Rectifier	Units
Capacity	149	149	kW
Mean Output	14.0	18.4	kW
Minimum Output	0	0	kW
Maximum Output	129	149	kW
Capacity Factor	9.39	12.3	%

In summary, understanding the detailed functioning of the inverter and rectifier is vital for ensuring efficient energy management and maximizing the benefits of integrating renewable energy sources within the hybrid system.

Table 15 and Figure 29 highlight the outputs of the inverter and rectifier, with the inverter output showing higher oscillations than the rectifier.

Table 16 illustrates the surplus electric energy generated by a standalone microgrid equipped with wind and tidal storage, highlighting its capacity to meet a significant portion of the 24-h power demand. In contrast, the diesel generator can only cover a small fraction of the load. The table provides details on excess energy, unmet loads, and capacity shortages within the system. Excess energy refers to the power generated but not utilized by any load. The analysis of the microgrid's components offers valuable insights into the system's design, economic viability, and operational efficiency. The microgrid's rated capacity of 1080 kW indicates its nominal power output, while the capital cost of approximately \$58,000 represents the initial investment required. Engineered for continuous and reliable power generation, the system is designed to operate 8760 h per year.

Table 16. A surplus of generated electricity.

Quantity	Value	Units
Excess Electricity	17,913,435	Kg/yr
Unmet Electric	0	Kg/yr
Capacity Shortage	0	Kg/yr
Renewable Fraction	100	%
Max. Renew. Penetration	321,133	%

The levelized cost of \$0.00081/kWh underscores the cost-effectiveness of this energy production method, ensuring affordable electricity over the system's lifespan. The exceptionally high capacity factor of 141% warrants further investigation but suggests that the system might be oversized or there are unique operational conditions leading to such high utilization.

With a total annual production of 13,334,303 kWh, the microgrid component demonstrates significant energy generation capability, supporting substantial energy demands. The annual maintenance cost of approximately \$2900 is a modest investment to keep the system in optimal condition.

The maximum output of 3200 kW highlights the system's robustness in handling peak power demands. However, the hydrokinetic penetration level of 5883 is unusually high, indicating an overwhelming reliance on hydrokinetic energy. This could potentially exceed local demand, suggesting energy export opportunities or possible reporting inaccuracies.

In conclusion, these parameters provide a comprehensive overview of the microgrid component's performance, highlighting its capacity, economic efficiency, operational longevity, and energy production dominance, particularly from hydrokinetic sources. These insights are crucial for optimizing the design and operation of hybrid energy systems to ensure sustainable and cost-effective power supply.

The microgrid wind-tidal storage system produces 17,913,435 kW/yr of excess electricity with zero unmet load and capacity shortages. It achieves a 100% renewable fraction and a maximum renewable penetration of 321.133%. This system ensures a reliable, sustainable

energy supply, significantly reduces emissions, lowers operational costs, and provides economic benefits by potentially selling excess electricity back to the grid.

7.3. Environmental Emissions

The fuel consumption of diesel generators primarily drives annual environmental emissions. Table 16 compares yearly emissions of various pollutants across different study locations in Bangladesh. With renewable energy sources and battery storage, the diesel generator solely meets the load demand, leading to higher fuel consumption and increased environmental emissions. Figure 18 illustrates the annual diesel fuel consumption and corresponding CO₂ emissions for different locations.

The emission proportions from the wind-tidal microgrid system are significantly lower than those from fossil fuel-based systems, with annual emissions of 587,172 kg of CO₂, 3701 kg of CO, 162 kg of unburned hydrocarbons, 22.4 kg of particulate matter, 1438 kg of SO₂, and 3477 kg of NO_x. These reductions highlight the environmental benefits and sustainability of integrating wind and tidal energy. The wind-tidal combination is the optimal choice for minimizing environmental impact and ensuring cleaner air in the microgrid, demonstrating a substantial advantage over traditional fossil fuel systems. The emissions contribute to climate change and pose significant health risks.

The environmental emissions of the Tidal/Wind/Diesel/Battery system (Table 17) in the studied areas are comparable to those of a microgrid that combines wind, diesel, and battery storage. However, due to the intermittency of wind energy, the system often relies on the diesel generator, as wind energy contributes minimally to the total load demand. In contrast, the hybrid Tidal/Diesel/Battery system achieves a significant reduction in environmental emissions compared to the diesel-only system.

Table 17. Emissions of pollutants and fuel consumption.

Quantity	Value	Units
Carbon Dioxide	587,172	Kg/yr
Carbon Monoxide	3701	Kg/yr
Unburned Hydrocarbons	162	Kg/yr
Particulate Matter	22.4	Kg/yr
Sulphur Dioxide	1438	Kg/yr
Nitrogen Oxides	3477	Kg/yr

The Homer software facilitates sensitivity analysis of system parameters, particularly the wind speed and current velocity, which is essential for informed decision-making in practical applications. Figure 30 illustrates the outcomes of this sensitivity analysis, depicting power flow scenarios for independent power generation systems, combined wind power flow systems, and independent wind power generation systems from top left to bottom right. By utilizing actual wind speed and current velocity data from specific marine environments, this analysis aids in identifying the most cost-effective power generation scheme that minimizes the Net Present Cost (NPC).

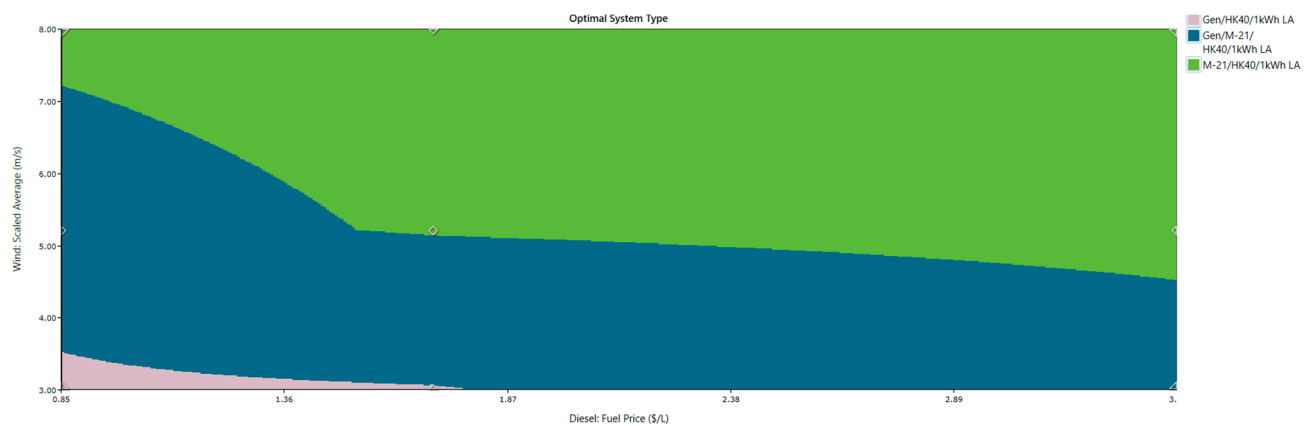


Figure 30. The outcomes of this sensitivity analysis.

8. Conclusions

Renewable energy is critical in mitigating climate change and reducing reliance on fossil fuels. Among various renewable sources, marine energy, particularly offshore wind, and tidal power, holds significant potential for sustainable power generation. This study demonstrates the feasibility and benefits of a hybrid offshore wind and tidal energy system for off-grid coastal communities in South Africa, contributing to the country's renewable energy transition and broader sustainability goals.

The integration of offshore wind, tidal energy, energy storage, and diesel backup addresses key challenges related to the intermittency and unpredictability of renewable sources. By ensuring a stable and reliable energy supply, the system significantly reduces greenhouse gas emissions while minimizing environmental impacts. Optimization via HOMER software has shown that this hybrid configuration not only improves energy reliability but also increases the renewable energy fraction and reduces the net present cost—key factors in advancing sustainability.

The study underscores that hybrid systems can maximize resource utilization and enhance energy security in coastal regions. By leveraging the complementary characteristics of wind and tidal energy, the system mitigates the limitations of single-resource dependency, creating a more resilient and adaptable energy infrastructure. Moreover, incorporating externalities into the cost calculations reveals that renewable energy, when accounting for environmental costs, becomes more competitive with conventional sources, further closing the cost gap.

Future research and development in hybrid converter technologies and large-scale deployment will be essential to fully harness the potential of marine energy systems. This research provides a framework for the successful implementation of hybrid wind and tidal systems, aligning with South Africa's sustainability initiatives while offering a scalable model for other coastal regions. In doing so, it supports the global shift towards cleaner, more resilient, and sustainable energy systems.

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CHAPTER 9: COST OPTIMISATION MODEL FOR A GRID-CONNECTED OFFSHORE WIND AND TIDAL POWER GENERATION SYSTEM USING HOMER: A CASE STUDY IN BUFFELS BAY SOUTH AFRICA

Chapter Nine of the dissertation presents a case study from Buffels Bay, South Africa, that focuses on a cost optimisation model for a grid-connected offshore wind and tidal power generation system. The research leverages HOMER software to design and analyse a hybrid power system that integrates wind turbines, tidal energy, and battery storage with the local grid. The main goal was to identify the most cost effective solution for generating renewable energy, through or by minimising the LCOE for a proposed 20 MW load. Through various simulation configurations system using HOMER, the research evaluated the combined potential of offshore wind and tidal energy in producing sustainable power. The optimised model reveals that tidal power contributes 62% of the total energy generation, while wind power contributes 20%. This gives an indication of the substantial role both tidal and wind renewable energy sources can play in the energy mix. The findings demonstrate that the hybrid wind-tidal system not only enhances system reliability but also provides economic benefits by reducing energy costs. Despite the relatively low cost of coal-generated electricity in South Africa, the study shows that offshore wind and tidal energy can still present a sustainable and economically viable alternative, contributing significantly to South Africa's transition to renewable energy, and supporting national energy security goals. The chapter also underscores the feasibility of deploying hybrid renewable energy systems in the coastal regions, offering valuable insights for future projects in South Africa and other regions with similar environmental and economic conditions. The Buffels Bay case study serves as a model for achieving energy security, economic sustainability, and environmental responsibility through the integration of offshore wind and tidal energy. In conclusion, the potential of combining offshore wind and tidal power to meet energy needs in coastal and other similar areas has been highlighted in this chapter. Also, the chapter provides a potential cost-effective solution that aligns with South Africa's renewable energy objectives, contributing to both economic sustainability and energy security for the region.

Cost Optimization Model for a Grid-Connected Offshore Wind and Tidal Power Generation System Using Homer: A Case Study in Buffels Bay South Africa

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Abstract – This study presents a cost optimization model for a grid-connected offshore wind and tidal power generation system, using Buffels Bay, South Africa, as a case study. The research utilizes the Hybrid Optimization Model for Electrical Renewable (HOMER) software to design and analyze a hybrid power system that integrates wind turbines, tidal energy, and battery storage with the local grid. Various system configurations were simulated to identify the most cost-effective solution, targeting the lowest Levelized Cost of Energy (LCOE) for a proposed 20 MW load. The optimized model combines tidal and wind power, contributing 62% and 20% of the total energy, respectively, demonstrating significant potential for renewable energy integration. The findings highlight the benefits of using a hybrid system to enhance reliability and reduce energy costs. Despite the low cost of coal-generated electricity in South Africa, the study shows that offshore wind and tidal energy can provide a sustainable and economically viable alternative, contributing significantly to the region's energy mix. This work offers valuable insights for future renewable energy projects in coastal regions with similar environmental and economic conditions.

Keywords: grid-connected, HOMER Pro, microgrid, tidal energy, wind energy

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I. Introduction

In 2008, South Africa was confronted with a stark reality; the constitutional promise of secure and sustainable electricity access could not be met. The country, which depends on non-renewable fossil fuels for over 95% of its electricity, experienced a peak and subsequent decline in these resources [1]. The remaining coal is either inexpensive but low-quality surface coal or costly high-quality deep-level coal [2]. As a result, the cost of electricity generation is rising to meet increasing demand, further escalating prices. Notably, 20% of this demand originates from the domestic housing sector [3]. Electricity generation, primarily dependent on coal, gas, and oil, significantly contributes to global warming through substantial greenhouse gas emissions [4]. The ongoing conflict between Russia and Ukraine has exacerbated this issue, causing a sharp rise in fossil fuel prices [5]. Conversely, electricity generated from secure, sustainable, and renewable sources could greatly promote sustainable development, economic growth, and climate change mitigation [3]. For example, implementing a 50 kWh/month solar system for low-cost housing could save

the country over R100 billion annually and reduce national grid electricity consumption by 9,720 GWh per year, equivalent to 5.8million tonnes of CO₂ [6]. Renewable energy sources, such as tidal energy, are widely recognized for being clean, natural, and abundant, making them essential for advancing sustainable development. These resources are particularly crucial for coastal cities and villages with limited electricity access. To improve the efficiency and reliability of tidal stream turbine systems, distributed energy storage devices like electrolyzers, super capacitors, hydrogen banks, and batteries have been integrated. These technologies effectively manage excess power and address energy deficits [7]. Despite these advances, offshore wind power faces challenges, notably its high cost, approximately double that of onshore wind power [8]. Moreover, relying solely on offshore wind power results in significant output fluctuations and poor predictability, necessitating careful consideration of its integration into the grid [9]. In contrast, tidal current energy demonstrates more predictable periodic output fluctuations, highlighting its success as an application of ocean energy [10]. While many planned wind farms are

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located in areas with water depths exceeding 30 meters, where traditional support structures may no longer be feasible, resulting in higher capital costs for the necessary systems. Consequently, the levelized cost of energy is likely to remain higher than that of gas or coal generation, making large-scale wind deployment dependent on ongoing government incentives [11].

To reduce electricity generation costs, co-locating wind farms with other renewable technologies has been proposed. Consequently, there is growing interest in combining offshore wind power with tidal current power generation systems. [12]–[14] et al. proposed an innovative combined generation approach integrating offshore tidal current and wind power to effectively manage system costs.

This study examines the co-location of offshore wind turbines with tidal stream turbine farms. Although tidal stream turbines are less mature than offshore wind or solar technologies, tidal arrays are currently being installed. The UK, for example, has the potential to generate an estimated 18 TWh/year from tidal stream resources, with the Pentland Firth alone capable of providing over 2 GW of average power. Co-location offers advantages such as shared electrical infrastructure and potentially shared support structures [15]. Additionally, co-located farms may experience reduced power variability compared to operating wind or tidal farms independently. Existing offshore wind farms have typically been established in areas with low tidal stream velocities [16]. Furthermore, extensive research has been directed towards enhancing the competitiveness of tidal energy, including its integration with other renewable sources and optimizing performance through combined use with wind turbines and storage [17]. The inception of offshore wind power projects, initially driven by onshore wind power developments, began early in their research and development stages [8].

Globally, grid-connected systems of this type have gained widespread adoption, particularly in smart city initiatives. Techno-economic analyses have consistently shown the feasibility of both standalone and grid-connected hybrid energy systems [18]. While many studies have utilized tools like HOMER for renewable energy simulations, this study represents the inaugural application of HOMER Grid in simulating a grid-connected system for a public institution. A significant barrier impeding South Africa's broader adoption of renewable energy is the lack of critical mass among society and government regarding commercial electricity generation from renewable sources. Therefore, this study aims to conduct a techno-economic analysis and optimization of a campus grid-connected tidal–wind turbine system using HOMER pro Grid. Its goal is to cultivate critical mass from grassroots levels of society and future generations. This study focuses on optimizing the cost of a grid-connected offshore wind and tidal power

generation system using HOMER pro software, with a case study in Buffels Bay, South Africa. The primary objective of this paper is to assess the economic feasibility of a hybrid power system that integrates both tidal and wind turbines to meet the specific load requirements of the area. For comparison, an off-grid hybrid power system that incorporates tidal, wind, and battery storage is also designed. The paper is structured as follows: section II provides a detailed description of the system model, section III outlines the methodology, section IV presents the simulation models used, section V analyzes the optimization results and section VI concludes the findings.

II. Literature Review

This research facilitates the selection of the optimal hybrid tidal-wind energy system for a coastal city by incorporating specialized displays along with environmental and economic considerations [19]. A highly practical and reliable alternative to conventional power grids for electrifying rural regions is the Hybrid Renewable Energy System (HRES). They play a crucial role in reducing fossil fuel consumption and mitigating climate change [20]. HRES offer several advantages over single-energy-source systems, including enhanced reliability, decreased energy storage requirements, improved efficiency, modularity, and a lower Levelized Cost of Energy (LCOE) [21]. This systematic literature review delves into various configurations and optimization strategies for hybrid renewable energy systems (HRESs), focusing on developments from 2015 to 2024. Solar energy, characterized by its intermittent nature, often necessitates energy storage (ES) systems to mitigate supply and demand fluctuations in [22]. Similarly, wind turbines can effectively utilize ES units such as batteries to stabilize power output and store excess energy in [23]. Studies, such as those by Ghayoor [24], have explored the feasibility of small-scale wind turbines for consumers in Africa [25]. As Sanedi, et al., (2017) [2] argue that solar-ES configurations are more advantageous than wind-ES due to wind speed variability, although contrasting findings by Maleki et al. [26] underscore the regional variability in hybrid system resource selection based on meteorological conditions and load characteristics.

Another effective configuration is the wind-solar-energy storage (wind-solar-ES) system, which leverages the complementary characteristics of wind and solar energy to enhance system reliability and minimize storage requirements.

Hybrid Renewable Energy Systems (HRES) enhance the overall stability and reliability of energy generation by effectively addressing the intermittency issues of individual renewable sources. Solar energy is most productive during the day, while wind energy can be harnessed even when sunlight is minimal [26].

Integrating diverse energy resources enhances the reliability of the energy supply, decreasing the risk of blackouts during adverse weather conditions. Furthermore, the incorporation of energy storage technologies within hybrid systems enables the capture of excess energy produced during peak output periods. This stored energy can subsequently be utilized during times of lower generation, thereby improving overall system efficiency and reducing energy wastage [18].

Standalone renewable energy sources are intermittent, which can place stress on existing power systems, resulting in voltage and frequency fluctuations. The integration of hybrid systems with energy storage capabilities helps manage these fluctuations more effectively, allowing excess energy to be supplied to the grid during peak demand periods. This approach improves grid stability and mitigates congestion, facilitating a smoother integration of renewable energy into current power infrastructures [6].

The optimal design of hybrid renewable energy systems (HRES) is a well-researched topic, and extensive literature is available. The design problem involves determining the best configuration of the power system and the optimal location, type, and sizing of generation units to meet load requirements at minimal cost [27]–[29]. Optimal sizing remains crucial in HRES design, aiming to achieve desired reliability at minimal costs [30]. Objective functions encompass economic, reliability, social, and environmental aspects, driving the use of optimization tools ranging from classical techniques to modern meta-heuristic algorithms like Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) [31]–[32]. The evolution of these methodologies from 2015 to 2024 highlights advancements in overcoming local optima and improving convergence efficiency in complex HRES sizing problems. Widely adopted software tools such as Hybrid Optimization Model for Electric Renewables (HOMER) and Improved Hybrid Optimization by Genetic Algorithm (iHOGA) continue to play a pivotal role in optimizing HRES configurations [14].

Ssenoga et al.,(2018)[33] provided statistical modeling of solar-wind HRES based on annual cost, battery autonomy, sizing criteria, and ecological factors, employing step-by-step optimization to achieve optimal results. Hirose et al.,(2012) [34] developed a solar-wind hybrid system model incorporating diesel generators with renewable energy sources, based on long-term simulations. Modu [35] presented a logistical model of HRES to evaluate fuel and energy savings, addressing issues related to combining renewable and conventional energy sources. This model introduces a supplementary fictitious source to maintain power balance during simulations.

Suchitra et al., (2019) [36] used the loss of power supply probability (LPSP) to develop an integrated renewable energy system model, deriving the probability density function of the storage based on load distribution.

Simulation programs are widely used to evaluate the performance of HRES, with many available for download from research laboratories and universities [37]. These programs help find the optimal configuration by comparing different system setups' performance and energy production costs. The National Renewable Energy Laboratory (NREL) in the United States is recognized for developing the widely respected HOMER software. HOMER models various energy components, including photovoltaics (PV), tidal stream turbines, wind turbines, hydropower, batteries, diesel generators, and other fuel-based generators, as well as electrolysis units and fuel cells. It also evaluates optimal solutions by considering both costs and the availability of energy resources.

III. Methodology

A. Tidal Stream Turbine

The objective of the tidal stream turbine (TST), as shown in Fig. 1, is to maximize power extraction from the wind or tidal flow. The following equations describe the torque produced by the turbine rotor and the power transferred to it.

$$P_t = C_p P_{flow} = \frac{1}{2} A V_{flow}^3 C_p (\beta, \lambda) \quad (1)$$

$$T_t = \frac{P_t}{\omega_{rot}} \quad (2)$$

where P_{flow} (W) represents the power of the air or tidal stream flow, as illustrated in Fig. 2. The fluid density is 1025 kg/m^3 . A (m^2) denotes the rotor's swept area, V_{flow} (m/s) is the upwind free wind speed or tidal stream flow speed, C_p is the power coefficient, and ω_{rot} (rad/s) represents the rotor's angular speed [16]. Table II details the tidal parameters.

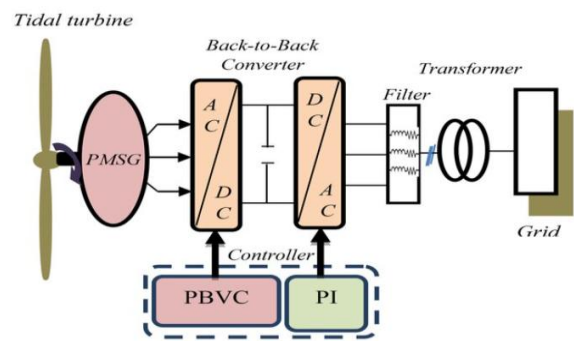


Fig.1.Tidal energy systems configuration based on a PMSG [38]

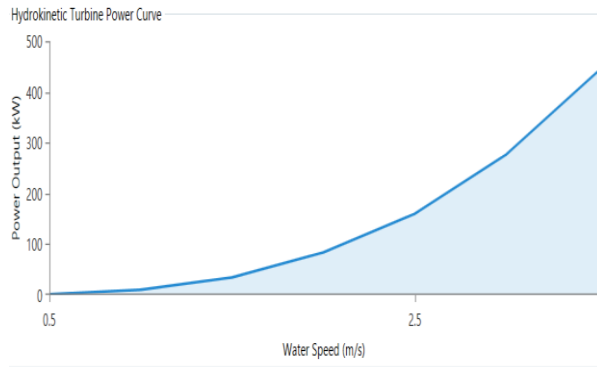


Fig.2. Power Output Curve for the Schottel 54 kW Tidal Turbine

TABLE I
TIDAL PARAMETERS

Parameters	Symbols	Values
Cut-in tidal speed	V_{cuttid}	< 1 (m/s)
Rated tidal speed	$V_{ratedtid}$	3 m/s
The cross-sectional area of turbine	A	201.06 m ²
Power coefficient	C_p	0.44
Cut-out tidal speed	$V_{cututtid}$	>5 m/s

B. Tidal Stream Turbine

Fig. 3 illustrates a wind energy conversion system. The wind turbine converts wind kinetic energy into AC or DC electricity based on its power curve, and HOMER estimates the turbine's hourly electricity production through a four-step process [7].

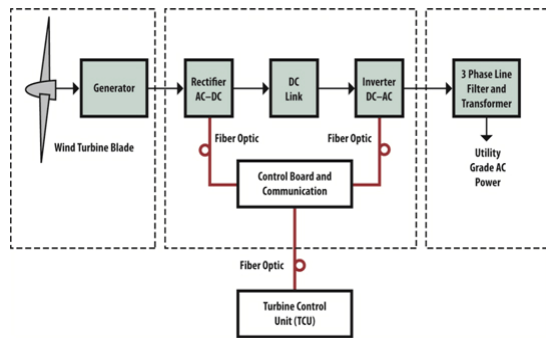


Fig. 3. Block diagram illustrating the components of a wind energy conversion system [39]

The process begins by determining the hourly average wind speed using wind resource data, which is then adjusted to the turbine's hub height using logarithmic or power-law equations. Next, the power output is calculated based on the turbine's power curve, and this output is further adjusted by considering the air density ratio. HOMER uses the power-law formula to extrapolate wind speed data [40].

$$U_{hub} = U_{anem} \left(\frac{Z_{hub}}{Z_{anem}} \right)^\alpha \quad (4)$$

Wind turbine performance is usually defined by power curves under standard conditions. HOMER adjusts the power output by applying the actual air density ratio to the estimated power value from the curve, which assumes an air density of 1.225 kg/m³.

$$P_{WTG} = \left(\frac{\rho}{\rho_0} \right) X P_{WTG,STP} \quad (5)$$

The power coefficient of a wind turbine is influenced by both the tip-speed ratio (TSR) and the blade pitch angle. Fig. 4 presents the typical variation of the power coefficient as a function of TSR for various pitch angles (β).

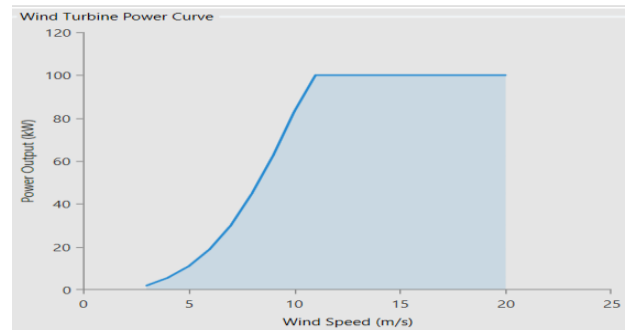


Fig.3. Power generation distribution for the XANT M-21 turbine

The E-70 wind turbine is utilized in this study, with key parameters outlined in Table II.

TABLE II
WIND TURBINE PARAMETERS

Parameters	Symbols	Values
Cut-in wind speed	V_{cuttid}	5 m/s
Rated wind speed	$V_{ratedtid}$	15 m/s
The cross-sectional area of turbine	A	3959 m ²
Power coefficient	C_p	0.44
Cut-out tidal speed	$V_{cututtid}$	25 m/s
The maximum output power	P_{wmax}	2300 W
Rotor diameter		71 m
Hub height		25 m and 100 m

C. Battery Sizing

HOMER models a single battery as having fixed energy efficiency, with constraints on charging and discharging rates and total energy throughput. The software assumes that battery characteristics remain constant over time and

are unaffected by environmental conditions. A battery bank, consisting of one or more batteries, has its lifespan calculated using a specific equation [41].

A battery is an energy source when discharging and a load when charging. Energy is stored in the batteries when the power generated by the tidal or wind turbine exceeds the load demand. A battery serves as an energy source when discharging and as a load when charging. It stores energy when the power output from tidal or wind turbines exceeds the load demand. Conversely, it supplies energy when the generated power is insufficient. The state of charge (SOC) is used to control charging and discharging. When SOC reaches its maximum value, the control system disconnects the load to prevent overcharging. In an integrated renewable energy system, batteries have two main functions: storing excess energy during charging and providing additional energy to meet load demands. If SOC drops to a minimum level, the control system adjusts to manage the excess power and ensure that the load's energy needs are met. Mathematically, this is expressed by maintaining SOC above a minimum level throughout any cumulative time t within a specified period T [42].

$$R_{bat} = MIN\left(\frac{N_{bat} \times Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) \quad (6)$$

where R_{bat} represents the lifespan of the battery bank (in years), N_{bat} is the number of batteries in the storage bank, $Q_{lifetime}$ is the total energy throughput of a single battery over its lifetime (in kWh), Q_{thrpt} is the annual energy throughput of the storage system (in kWh/year) and $R_{batt,f}$ is the float life of the storage system (in years) [42].

D. Sizing Procedure Based on Supply Reliability

Supply reliability is a key factor in designing an integrated tidal/wind-battery system and influences various sizing procedures. It refers to the probability that the power system will operate correctly over a specified period under given conditions without failure. This study presents a program for optimizing the sizing of components in the integrated energy system (tidal and wind-battery) by assessing generation adequacy through a reliability index. The Loss-of-Power Supply Probability (LPSP) parameter is one method used to quantify supply reliability [43] as in (7).

$$LPSP = P_r(E_B(t) \leq E_{Bmin}; \text{ for } t \leq T) \quad (7)$$

E. Converter

A converter is a device that converts electrical power from DC to AC during inversion and from AC to DC

during rectification. HOMER models both solid-state and rotary converters. The size of the converter is determined by its inverter capacity, which indicates the maximum AC power that can be produced from DC electricity. The rectifier capacity, expressed as a percentage of the inverter capacity, denotes the maximum DC power that can be generated from AC power, making it a dependent variable. HOMER assumes that both inverter and rectifier capacities are continuous and free from surges, ensuring stable load management. The inverter can operate in parallel with other AC power sources, such as a generator or the grid. The inverter can operate in parallel with other AC power sources, such as generators or the grid. HOMER assumes that the key physical attributes of the converter, including inversion and rectification efficiencies, remain constant. The economic characteristics of the converter include capital cost, operation and maintenance (O&M) costs, replacement costs, and expected lifespan, all expressed in US dollars per year [44].

F. Economic Analysis

Conducting a techno-economic analysis of an engineering system requires specific economic data, including the nominal discount rate, expected inflation rate, and project lifetime. The necessary economic data for this analysis are presented in Table III.

1. Net Present Value (NPV)

$$NPV = \sum_{t=0}^n \frac{C_t}{(1+r)^t} \quad (8)$$

where C_t is Net cash flow at time t , r is the nominal discount rate and n is the project lifetime.

2. Main Internal Rate of Return (IRR)

The IRR is the discount rate r at which the NPV equals zero.

$$\sum_{t=0}^n \frac{C_t}{(1+IRR)^t} = 0 \quad (9)$$

3. Levelized Cost of Energy (LCOE)

$$LCOE = \frac{\sum_{t=0}^n \frac{C_t}{(1+r)^t}}{\sum_{t=0}^n \frac{E_t}{(1+r)^t}} \quad (10)$$

where E_t is the energy generated at time t .

4. Simple Payback Period

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Net Cash Flow}} \quad (11)$$

5. Annualized Cost

$$\text{Annualized Cost} = \frac{C_{\text{total}} \cdot r \cdot (1+r)^n}{(1+r)^n - 1} \quad (12)$$

6. Salvage Value

$$\text{Salvage Value} = C_{\text{initial}} \cdot \left(\frac{R_{\text{rem}}}{R_{\text{total}}} \right) \quad (13)$$

where C_{initial} is initial capital cost, R_{rem} is the remaining life of the component and R_{total} is the total expected life of the component.

7. Loss-of-Power Supply Probability (LPSP)

$$\text{LPSP} = \frac{\sum_{t=0}^n \text{Power Deficit}_t}{\sum_{t=0}^n \text{Load Demand}_t} \quad (14)$$

where Power Deficit_t is power deficit at time t and Load Demand_t is the load demand at time t .

8. Discount Factor

$$DF_t = \frac{1}{(1+r)^t} \quad (15)$$

where DF_t is discount factor at time t .

9. Cost of Energy (COE)

$$\text{COE} = \frac{\text{Total Annualized Cost}}{\text{Total Annual Energy Production}} \quad (16)$$

10. Simple Payback

The simple payback period is defined as the number of years required for the cumulative cash flow difference between the optimized and reference case systems to transition from negative to positive. This metric indicates the time needed to recover the initial investment cost difference between the optimized system and the reference system.

11. Total Annualized Cost

The total annualized cost of a component is the uniform annual expense that, over the project's lifespan, equates to the net present cost of the component's actual cash flows. This cost is calculated by multiplying the net present cost by the capital recovery factor, as indicated in the following equation.

$$C_{\text{ann,tot}} = \text{CRF}(i, R_{\text{proj}}) \times C_{\text{NPC,tot}} \quad (17)$$

where $\text{CRF}(i, R_{\text{proj}})$ is the capital recovery factor, i is the discount rate, R_{proj} is the project lifetime and $C_{\text{NPC,tot}}$ is the total net present cost.

12. Emissions Reduction

The reduction in emissions is determined by the amount of energy generated by the renewable energy system, which replaces the energy that would otherwise be produced from fossil fuels. This reduction is expressed as emissions per unit of energy consumed. The emission data used for these calculations are detailed in Table IV. By applying these formulas, HOMER evaluates the economic performance of the integrated energy system, enabling comprehensive techno-economic analysis and informed decision-making.

G. System Description

The primary objective of this study is to develop a cost-optimization model for a grid-connected hybrid energy system using HOMER Pro software. The model seeks to identify the optimal configuration that minimizes costs while ensuring a reliable power supply for a local coastal community in South Africa. This paper involves designing both on-grid offshore hybrid power systems using HOMER software to assess and determine the costs associated with various configurations. Specific input data is required for the HOMER simulation software to evaluate optimization outcomes across different combinations, as detailed in the subsequent section.

The proposed hybrid system in HOMER software involves determining the load profile of a remote area, acquiring meteorological data for solar irradiance and hydroflow rates, and configuring the system components. Economic parameters and component sizes are established, and simulations are conducted for cost optimization. The levelized cost of energy (LCOE) is evaluated to ensure that the selected solution meets the study's objectives. HOMER ranks the results based on cost, with the most optimized solution being the one with the lowest Net Present Value (NPV). Fig. 5 shows the steps of the model in HOMER.

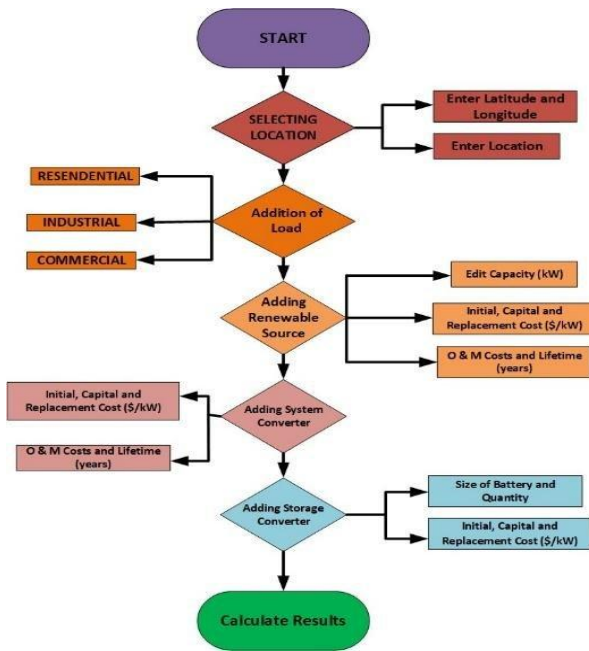


Fig.4. Steps of the model in HOMER

Whether the choice of selected result fulfils the objective of this work. HOMER ranked its result based on the least cost combination. The most optimized result by mean is the most optimal solution which is at the lowest cost of Net Present Value (NPC).

H. Site Selection

Buffels Bay, 657, South Africa (34°5.1'S,2258.2'E), was chosen as a case study to assess the feasibility of a hybrid system combining wind and tidal turbines connected to a microgrid to supply power to remote coastal communities isolated from the national grid. Buffels Bay is a small seaside village located 20 kilometres from Knysna as shown in Fig. 6, within the Garden Route District Municipality in South Africa's Western Cape province. The village is named after the nearby bay that extends eastward.

It is a well-known vacation spot, featuring a small waterfront area with shops. This area, a small tourist destination near Cape Town, experiences unstable electricity access due to load shedding by ESKOM in Fig. 7. Currently, the community relies on a diesel power station located in the island's main settlement for electricity.

Ongoing research at the Centre for Renewable and Sustainable Energy Studies CRSES is examining the relationship between diesel usage and load shedding as indicated in Fig. 7. In the meantime, these two metrics are presented together for comparison [6].

- Optimizing the design involves identifying the optimal location, and size of devices required to harness these energy resources.
- Conducting a feasibility analysis and assessing the financial viability of the optimized microgrid design.

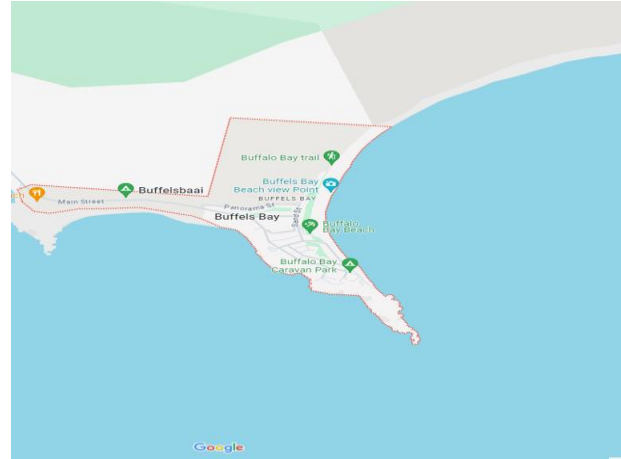


Fig. 6. Buffels Bay is a small seaside village location

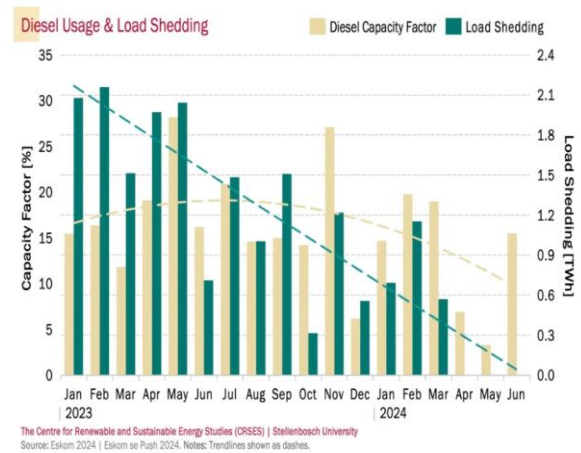


Fig.7. The relationship between diesel consumption and load shedding [6]

I. Data Collection

The east coast of South Africa, as illustrated in Fig. 8, features current flows that make this region suitable for potential tidal farm locations. To ensure economic viability, a stream velocity of at least 2 m/s is necessary for a tidal farm. This study, therefore, proposes a tidal Stream Energy conversion system. Buffels Bay has been identified as a promising site based on tidal data from the South African Navy Hydrographic Office (SANHO) [45].

Fig. 9 illustrates an example of the fortnightly spring-neap water level cycle observed at Mossel Bay. Similar to the conditions in Mozambique, the spring-neap cycle and daily inequality are significant along the South African

coast. Mean High Water Spring (MHWS) refers to the annual average height of high-water during spring tide periods, relative to Chart Datum. This average is calculated once every fortnight. The difference between MHWS and Mean Low Water Spring (MLWS) can also be considered the Mean Spring Tide Range (MSR), which is approximately 1.5 meters along the South African coastline [46].

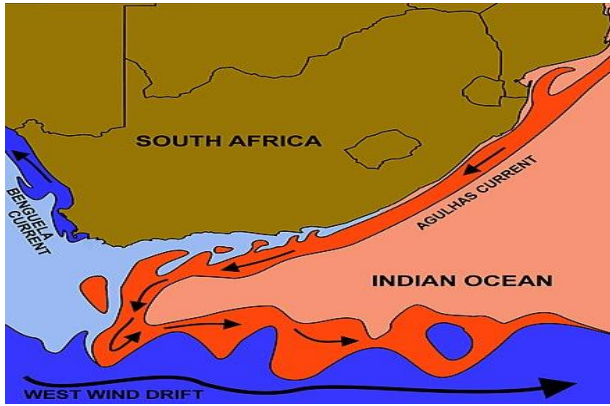


Fig. 5. Agulhas Currents systems [45]

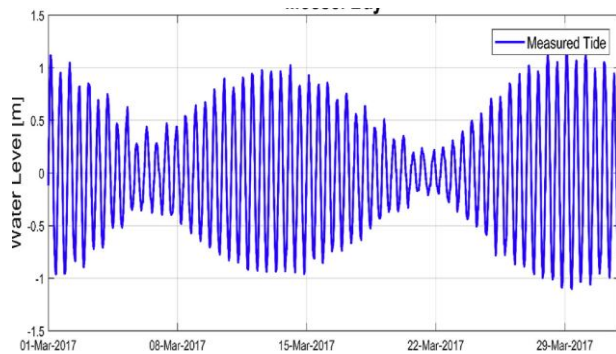


Fig.6. Tidal water levels were measured over two spring tide cycles, emphasizing the significance of the tidal cycle [46]

Wind speed and community load demand data for Buffels Bay, South Africa, were gathered from local meteorological stations and historical records.

This study evaluated seven sites in Cape Town, South Africa - Cape Town with their geographical locations are shown in Fig. 10. Hourly mean wind speed data from 2000 to 2019 as shown in Fig. 11, measured at 10 meters above ground level, were analyzed to identify the most suitable sites for wind power development. The wind speed data were extrapolated to various heights using a power law with a wind shear exponent of 0.14. The analysis covered annual, monthly, and diurnal variations in wind speed. Factors such as annual energy yield, plant capacity, and power duration were assessed to recommend the best sites and wind turbines. Key findings include:

- Port Elizabeth recorded the highest mean wind speed at 6.01 m/s, while Bloemfontein had the lowest at 3.86 m/s.
- Coastal sites (Cape Town, Durban, East London, and Port Elizabeth) showed an increasing trend in wind speed with higher latitudes [47].



Fig.7.Coastal sites

The data, typically provided in hourly, daily, or monthly time series, was imported into HOMER using meteorological databases, local weather stations, and NASA's Surface Meteorology and Solar Energy (SSE) database. Additionally, tidal data for Buffels Bay was obtained from the Tide Forecast website, including specific tide conditions and charts for East London and Cape Town. Fig. 12 shows the monthly average micro-hydro resources.

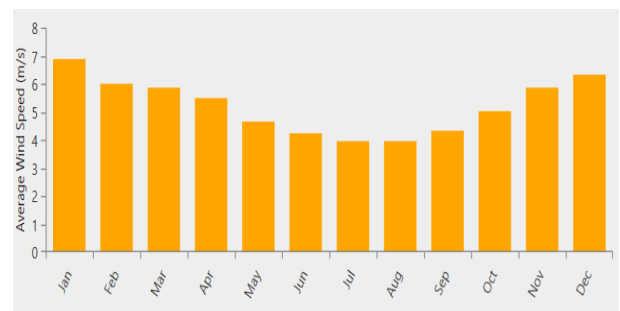


Fig. 8. Monthly Average Wind Speed

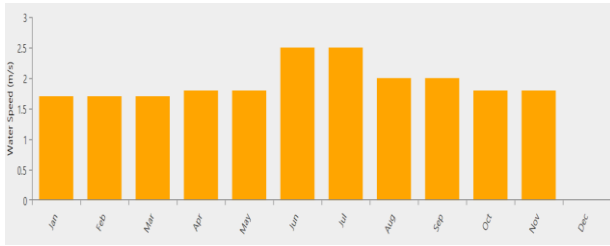


Fig. 9. Monthly Average Micro-Hydro Resources

The village, which currently lacks historical electrical load data due to its non-electrified status, estimates its electrical load through assumptions. For a case study involved, the peak demand is estimated at 4500 kW, with an 80% load diversification applied to the base load without accounting for area-specific variations. The village is connected to the Buffels Bay customer load network and uses a scaled-down version of the demand profile, peaking at approximately 597 kWh to project its own demand. Detailed load data is recorded hourly, covering a full year (8760 hours), and is used as input for HOMER Pro®. The load primarily consists of residential properties, showing two distinct peaks: a smaller one in the morning and a larger one in the evening. Fig. 13 illustrates the average hourly loads throughout the year, while Fig. 14 shows the yearly average loads, indicating higher demand during the winter months (June-August) [40].

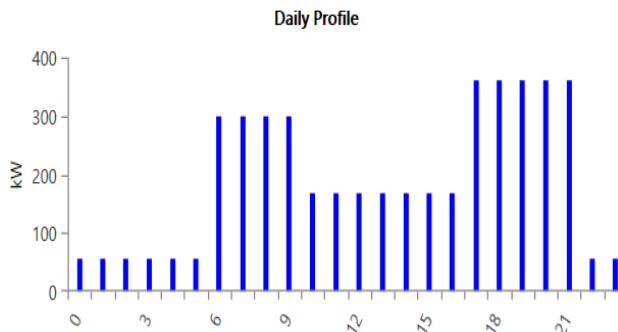


Fig.10.Variation of load demand for 24 hours

Fig. 14 illustrates the seasonal variations in electricity demand for the West Bank community. Generally, demand rises during the colder months due to greater heating requirements and may also increase during hot summer months if air conditioning is commonly used. This profile highlights the fluctuations in electricity consumption, showcasing the community's usage patterns in response to seasonal changes.

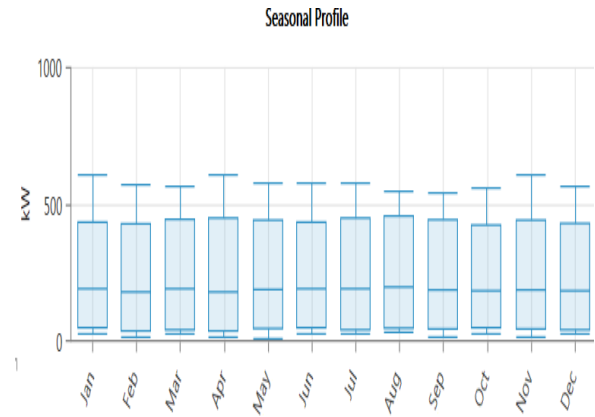


Fig.11. Seasonal profile of load demand throughout the year

A study by Prinsloo and Davidson found that in an African village, the average household consumes about 12.5 kW, with usage peaks between 9:00-11:00 and 15:00-18:00. Lighting is used from 18:00 to 23:00, and appliances such as a radio (5W) and a TV (70W) are typically operated during this time. To address a 20 MW load demand throughout the day, typical consumption patterns across residential, commercial, industrial, and public service sectors will be considered. This detailed daily load profile is based on a total demand of 20 MW. The data shows peak demand in June (69.29 kW) and between 6:00-7:00 PM (69.29 kW), with the lowest demand in January (162 kW) and between 3:00-4:00 PM (37 kW) [48].

J. Proposed System Architecture

Fig. 15 depicts the circuit model of a Hybrid Offshore Tidal Turbine (HOTT) system integrated with a battery [13]. In this setup, the output of the induction generator connected to the tidal turbine can be modulated to stabilize frequency and manage active power fluctuations [12].

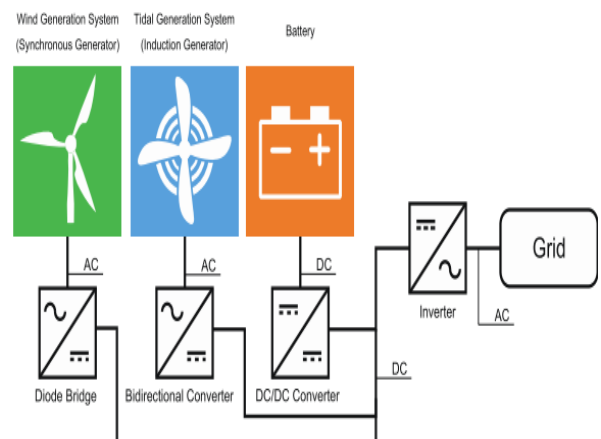


Fig. 12. Conceptual System Schematic of HOTT with Battery [49]
Before simulating the renewable energy system,

designing the system architecture is essential. This design includes lead-acid batteries and a converter for energy storage, supported by power sources like tidal and wind turbines. For tidal energy, the Schottel 54 kW bidirectional turbine was selected due to its low cut-in speed, ability to meet peak load demands, and cost-effectiveness in purchase, installation, and maintenance.

The turbine's costs are \$54,000 for capital and replacement, \$2,700 annually for maintenance, and it has an operational lifespan of 10 years. The proposed wind turbine has a capacity of 100 kW, a hub height of 31.80 meters, and an operational lifespan of 25 years.

Energy storage is managed by lead-acid batteries, each with a nominal voltage of 12 V, a nominal capacity of 1 kWh, a capacity ratio of 0.403, a roundtrip efficiency of 80%, a maximum state of charge of 100%, a minimum state of charge of 40%, a throughput of 800 kWh, and a lifespan of 10 years.

The system's converter has a capacity of 100%, with inverter and rectifier efficiencies of 95%, and a lifespan of 15 years. All equipment specifications were sourced from the software's catalogue. Fig. 16 provides a schematic diagram of the proposed system architecture, with detailed specifications in Table III. A DC bus interconnects all components, with wind and tidal turbines as the primary energy sources.

In HOMER, selecting the appropriate load profile for residential, commercial, industrial, or community is crucial. For this study, a residential load profile was chosen. When energy storage is included, HOMER requires specifying the storage type.

To ensure the proposed microgrid can operate independently, the ion lithium battery was selected for energy storage after extensive simulations [14]. The grid-connected system integrates wind and tidal turbines with a battery energy storage system (BESS) to compensate for

periods with insufficient wind and tidal currents [50].

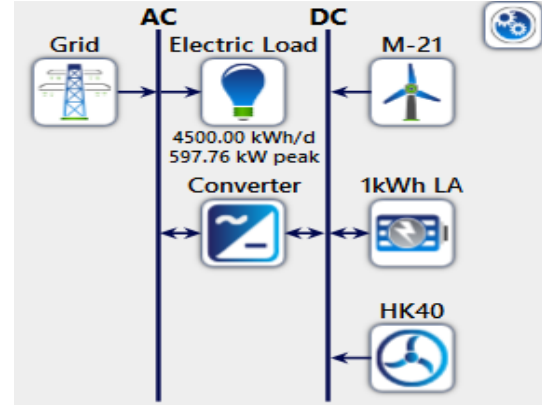


Fig. 13. Proposed system architecture

IV. Results and Discussion

Table IV displays the comprehensive results of the cost optimization analysis, ranked in descending order. In this study, the selected configuration is on the third line, comprising The XANT M-21 (100 kW) and Schottel (54 kW) turbines are efficient for meeting peak load demands with low costs. The XANT M-21 has capital and replacement costs of \$50,000 each, maintenance costs of \$2,500/year, and a lifespan of 20 years.

The Schottel turbine costs \$54,000 for capital and replacement, \$2,700/year for maintenance, and has a 10-year lifespan. Additionally, a generic 12-volt lead-acid battery offers reliable performance with capital and replacement costs of \$154 each, \$15.40/year for maintenance, and a 10-year lifespan.

TABLE III
NET PRESENT COSTS

Component	Name	Capital Cost (USD)	Replacement	O&M Cost (USD)	Lifetime	Ref
Grid	ESKOM					[24]
Tidal turbine	(Schottel, Spray, Germany) (54 kW)	\$54,000.00	\$54,000.00	\$2700/year	10 years	[51]
Wind turbine	XANTM21	210,000.00	210,000.00	3500/year	25 years	[14]
Storage	1 kWh Lead Acid	300/kW	300/kW	25/year	10 years	[52]
Converter	System Converter	300/kW	300/kW	0	15 years	[53]
Controller		\$200.00	\$200.00	0		[54]

TABLE IV
ANNUALIZED COSTS

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Savage (\$)	Total (\$)
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Gen Hydro (40kw)	\$70,000.00	\$60,913.97	\$0.00	\$0.00	\$8,154.95	\$122,759.01
Grid	\$0.00	\$0.00	\$816,533.04	\$0.00	\$0.00	\$816,533.04
System Converter	\$59,003.14	\$24,619.95	\$0.00	\$0.00	\$4,582.55	\$79,040.54
XANT M-21 (100KW)	\$300,000.00	\$77,951.18	\$127,833.56	\$0.00	\$43,686.72	\$462,097.50
System	\$429,003.14	\$163,485.10	\$944,366.60	\$0.00	\$56,424.75	\$1,480,430.09

The inflation rate was set at 5.2% (South Africa), with a discount rate of 0%. Two primary tests were conducted in this study. This section investigates multiple scenarios to assess how the grid electricity purchase and sellback prices (Grid power price/Grid sellback price) affect the financial returns of renewable energy investments over a 25-year period.

Resources are external parameters essential for HOMER in microgrid system analysis. The choice of these resources, which depends on the location, directly impacts both power generation and the financial feasibility of the microgrid design. Therefore, selecting the right resources is crucial for an effective analysis. For this microgrid design, the key resources are wind speed data (sourced from NASA) and water speed data (obtained from <https://www.tide-forecast.com>) for the year 2024. Fig. 17. shows the power generation potential of the wind and tidal turbines at the Buffels Bay site based on this data.

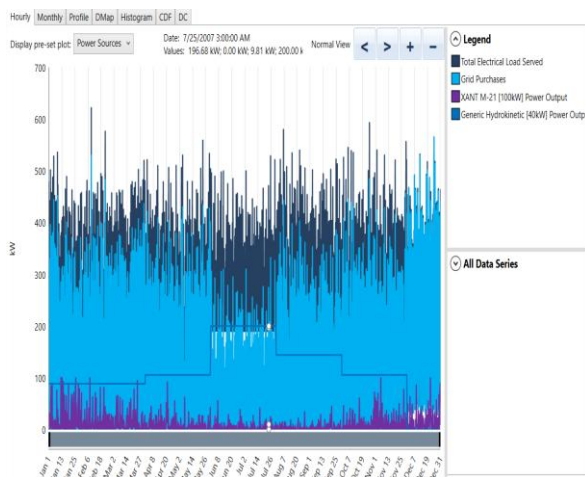


Fig. 14. Variations in power output for tidal turbines and wind turbines at the Buffels Bay site

A. Power Generation Results

Figs. 18(a) – (b) illustrates the monthly average power output (kW) and resource distribution for various scenarios. The renewable energy share for the wind-only scenario (36 kW) is 66.3%, which exceeds that of the tidal-only scenario (63.9%) and the combined wind and tidal sources (65.4%).

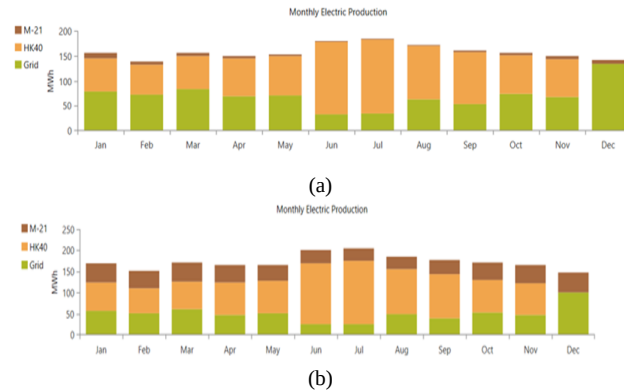


Fig. 15. Annual average output, operational hours, and power production for the proposed scenarios at Buffels Bay

Fig. 19 and Fig. 20 illustrate the energy generation portfolio is as follows: wind turbines generate 465,822 kWh/year, accounting for 22% of the total energy output; the 40-kW generic hydrokinetic system produces 1,003,094 kWh/year, representing 48%; and grid purchases add 608,805 kWh/year, constituting 29.3% of the energy mix. In total, the system generates 2,077,721 kWh/year, resulting in 17,548 kWh/year of excess electricity. This leads to a cumulative surplus of 367,925 kWh/year. These results highlight the system's capability to efficiently meet energy demands while maintaining a significant surplus, demonstrating its effectiveness in integrating renewable energy sources.

Quantity	Value	Units
Total Rated Capacity	100	kW
Mean Output	6.94	kW
Capacity Factor	6.94	%
Total Production	60,753	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	100	kW
Wind Penetration	3.70	%
Hours of Operation	4,872	hrs/yr
Levelized Cost	0.595	\$/kWh

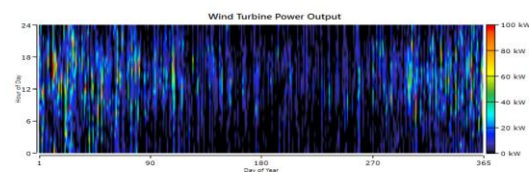


Fig. 16. Wind turbine power output

The wind turbine system, with a total rated capacity of 100 kW, has an average output of 6.94 kW and a capacity factor of 6.94%, indicating that it operates below its maximum potential most of the time. The system generates 60,753 kWh per year, with a wide range of outputs from 0 kW to its maximum of 100 kW. The wind penetration of 3.70% shows a modest contribution to the overall energy mix. Operating for 4,872 hours annually, the system provides intermittent power. However, the

levelized cost of energy (LCOE) at \$0.595 per kWh is relatively high, suggesting that the system is not cost-competitive compared to other renewable energy sources.

Quantity	Value	Units	Quantity	Value	Units
Total Rated Capacity	200	kW	Minimum output	0	kW
Mean output	115	kW	Maximum output	200	kW
Capacity factor	57.3	%	Hydrokinetic penetration	61.1	%
Total Production	1,003,094	kWh/yr	Hours of operation	8,016	hr/yr
			Levelized Cost	0.00957	\$/kWh

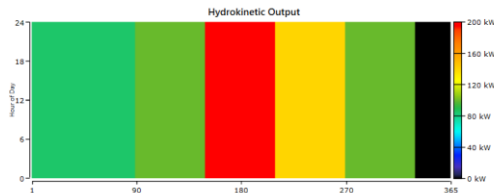


Fig. 17. Hydrokinetic Output

Energy needs are crucial for enhancing overall efficiency.

The HOMER Pro results reveal the following:

- **AC Primary Load:** Consumes 1,642,500 kWh/year, making up 89.7% of total consumption. This suggests AC loads are the main energy consumers in the system.
- **DC Primary Load and Deferrable Load:** No consumption is reported for these, indicating they are either not utilized or negligible.
- **Grid Sales:** The system sells 187,853 kWh/year back to the grid, representing 10.3% of total consumption. This helps balance the energy load and provides potential revenue.

Implications: The high AC load consumption highlights its importance. The lack of DC or deferrable loads might suggest they are not needed. Effective management of AC loads and leveraging grid sales can enhance overall system efficiency and performance.

The cost summary in Fig. 22 reveals that the Generic Hydrokinetic (40 kW) system has the highest total net present cost (NPC) of \$890,133 due to substantial capital, operating, and replacement costs. The Grid incurs operational expenses amounting to \$712,205. The XANT M-21 (100 kW wind turbine), with a total NPC of \$417,817, also reflects significant capital and replacement costs. The lead-acid battery and system converter contribute relatively lower NPCs of \$2,053 and \$71,764, respectively. Overall, the hybrid system's total NPC is \$2.09 million, indicating a need for cost optimization to improve economic viability. The simulation details the

cost allocation for each component, broken down into capital cost, replacement cost, operation and maintenance cost, and salvage value in Table V. A negative salvage value indicates no residual value at the project's end.

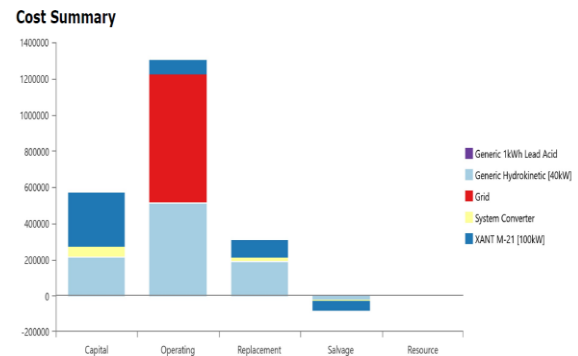


Fig. 22. Cost Summary

The net present cost (NPC) analysis in Fig. 23 provides a comprehensive overview of the economic impact of various components in the hybrid energy system. The Generic Hydrokinetic (40 kW) system shows the highest total NPC at \$890,133, driven mainly by its high operating costs (\$511,334) and replacement costs (\$187,963). The Grid contributes significantly to overall costs, with a substantial NPC of \$785,512 entirely due to operating expenses. The System Converter has a relatively lower NPC of \$61,061, with notable contributions from capital costs (\$45,581) and replacement costs (\$19,019). Overall, the total system NPC is \$1.74 million, indicating the need for strategies to minimize costs, especially in operating and replacement expenditures, to enhance the system's economic feasibility.

The DCCFs over 25 years in Fig. 24 shows a substantial initial value of \$12,000,000, indicating strong early performance. However, this value decreases significantly to \$1,000,000 and eventually to \$0, reflecting declining cash flows or increasing costs over time. The trend suggests that while the project was initially profitable, its long-term financial viability is in

question. This decline necessitates a review of financial strategies and operational efficiency to address the decreasing returns and manage risks effectively. Investors should consider these trends when making decisions about ongoing investment or project adjustments.

TABLE V
PRESENT COSTS

Component	Capital(\$)	Replacement (\$)	O&M(\$)	Fuel (\$)	Salvage (\$)	Total(\$)
Gen Hydro (40kw)	70,000.00	60,913.97	0.00	0.00	8,154.95	122,759.01
Grid	0.00	0.00	816,533.04	0.00	0.00	816,533.04

System Converter	59,003.14	24,619.95	0.00	0.00	4,582.55	79,040.54
System	126,958.00	887,682.00	0.00	0.00	12,579.00	1.09M

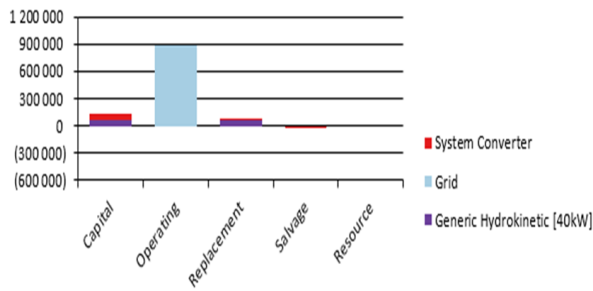


Fig. 18. Net Present Cost analysis

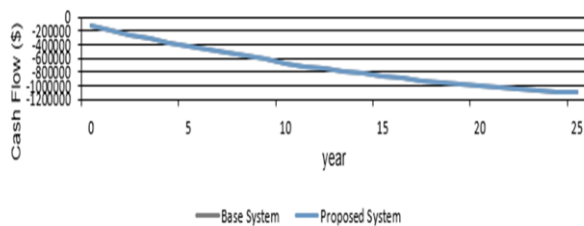


Fig. 19. Cumulative Discounted Cash Flows

B. Environmental Impact

The tidal and wind grid-connected system emits 399,999 kg/year of CO₂, which, while lower than fossil fuels, still represents a significant greenhouse gas footprint. Notably, there are no emissions of carbon monoxide, unburned hydrocarbons, or particulate matter, which is beneficial for air quality. However, the system produces 1,734 kg/year of sulfur dioxide (SO₂) and 848 kg/year of nitrogen oxides (NO_x) indicated in Table VI. While these levels are relatively low, they can contribute to environmental issues such as acid rain and smog. Continuous efforts to minimize CO₂, SO₂, and NO_x emissions are crucial for improving the system's overall sustainability.

TABLE VI
POLLUTANT EMISSIONS

Quantity	Value	Units
Carbon Dioxide	399,999	Kg/yr
Carbon Monoxide	0	Kg/yr
Unburned Hydrocarbons	0	Kg/yr
Particulate Matter	0	Kg/yr
Sulphur Dioxide	1,734	Kg/yr
Nitrogen Oxides	848	Kg/yr

IV. Conclusion

This study explores the feasibility and advantages of a grid-connected offshore wind and tidal storage power

system in Buffels Bay. By using HOMER Pro software, the optimized model reveals substantial cost savings and environmental benefits, making it a valuable example for similar renewable energy projects in coastal regions. The research focused on a DC-linked wind-tidal battery-grid system in South Africa, leveraging the area's abundant wind and tidal resources to design an efficient and eco-friendly microgrid.

Simulations were conducted to develop a DC-linked microgrid that integrates seamlessly with the national grid to supply residential loads in Buffels Bay, Cape Town. The design utilized data on wind speeds and tidal currents to evaluate capacity and cost-effectiveness.

Key findings include:

- **Tidal Power:** Tidal currents can generate electricity for 69.3% of the year, providing a reliable energy source.
- **Wind Power:** Wind speeds are insufficient for electricity generation 78.2% of the year, highlighting the need for optimization.
- **Microgrid Integration:** The proposed design enables DC power from Buffels Bay to be efficiently integrated into the national grid. This involves installing wind and tidal turbines on a single offshore platform, connecting them to a DC-linked system, and transmitting power through a DC marine cable to an onshore DC-AC converter, followed by transmission via an AC land cable to the utility grid station.

The integration of offshore renewable sources, as demonstrated by HOMER Pro, shows strong potential for meeting energy demands. Combining wind and tidal power into a hybrid system offers distinct advantages: tidal energy provides a stable and predictable base load, while wind turbines can boost energy production when wind conditions are favourable. This hybrid approach mitigates the intermittency and variability typically associated with wind energy, enhancing the system's overall reliability. However, the relatively low wind energy contribution and high levelized cost of energy (LCOE) from wind indicate areas for potential improvement. Strategies such as better turbine placement or the adoption of more efficient technologies could enhance wind energy production and reduce costs. Expanding the tidal component or optimizing its integration with wind could further improve the hybrid system's efficiency and cost-effectiveness. In conclusion, the hybrid system effectively balances the variability of wind power with the stability of tidal energy, resulting in a robust renewable energy solution. To maximize the potential of this system, it is crucial to optimize both

components, ensuring economic viability and a reliable energy supply.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Author 1 was responsible for the design and simulation of the HOMER Pro model and took the lead in authoring the methodology and results sections of the paper. Author 2 concentrated on optimizing the model, designing the input parameters, overseeing data collection, and managing the site selection process. Meanwhile, Author 3 contributed by assisting in the design of input parameters, handling data collection, and writing the discussion and conclusion sections. Each author played a critical role in different aspects of the research, ensuring a comprehensive and collaborative effort.

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CHAPTER 10 SUMMARY: A FUZZY LOGIC CONTROLLER ENERGY MANAGEMENT STRATEGY FOR OFFSHORE HYBRID WIND-TIDAL STORAGE SYSTEMS

Chapter Ten presents an fuzzy logic controller (FLC) -based EMS designed to optimise the performance of hybrid offshore wind-tidal storage systems. This chapter focused on integrating wind turbines, tidal stream turbines, a BESS, and grid connectivity to effectively manage the complexities of energy distribution in smart environments, including smart cities and institutions powered by integrated microgrids. The primary aim was to develop an EMS that maximises the use of renewable energy, improves system stability, and reduces operational costs. The proposed FLC-based EMS optimises the energy management process by prioritising renewable energy sources and ensuring efficient power distribution. The system uses fuzzy membership functions to regulate reference current I_{ref} and power output, managing the operational states of the system components (Low, Medium, High). The used of BESS played a crucial role in stabilising the system by mitigating short-term wind power fluctuations and long-term tidal variability which subsequently ensured a continuous and reliable power supply. Simulation results using MATLAB/Simulink demonstrate that the FLC-based EMS outperforms traditional fractional-order PID controllers in terms of performance. The system successfully achieves over 70% wind power utilisation and 30% tidal power contribution, while meeting 8.48% of the load power demand. Additionally, excess energy generated during high tidal periods is redirected to the grid when the battery reaches full charge, ensuring optimal energy management. The EMS operates with three key inputs: hybrid power, load demand, and the battery's SOC. Through the use of 27 rule sets, the FLC manages renewable energy resources and maintains grid stability. This approach addresses a critical gap in the existing energy management strategies for hybrid systems, demonstrating the potential of FLC in enhancing efficiency and reliability in renewable energy integration. The findings in this chapters have significant implications for smart grid applications and hybrid energy systems, offering a scalable and practical solution for optimising power distribution. The use of FLC presents a promising strategy for improving the performance and sustainability of renewable energy systems, supporting the transition toward more sustainable and resilient energy infrastructures. In conclusion, chapter nine findings underscore the potential of an FLC-based EMS in managing complex hybrid offshore wind-tidal storage systems, highlighting its ability to optimise renewable energy utilisation and ensure reliable and cost-effective power distribution. The study offers valuable insights for advancing smart grid technologies and supporting the global transition to sustainable energy solutions.

Research

Fuzzy Logic Controller Energy Management Strategy for Offshore Hybrid Wind-Tidal Storage Systems

Ladislav Mutunda Kangaji¹ · Atanda Raji¹ · Efe Orumwense²

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Abstract

The integration of offshore wind and tidal energy systems with storage and grid connectivity presents complex management challenges, especially in smart micro grid environments. This paper proposes a novel Fuzzy Logic Controller (FLC)-based Energy Management System (EMS) for optimizing power distribution in a hybrid offshore wind-tidal system supported by a Battery Energy Storage System (BESS). Unlike existing FLC-based strategies, which are typically limited to single-source or land-based applications, this study focuses on offshore hybrid configurations and introduces a 27-rule fuzzy logic framework that dynamically manages energy flows based on hybrid power generation, load demand, and battery state of charge (SOC). MATLAB/Simulink simulations demonstrate that the proposed EMS achieves over 70% wind power utilization, 30% tidal contribution, and supplies 8.48% of the total load demand while maintaining system stability and reducing operational costs. Surplus energy during peak tidal periods is efficiently dispatched to the grid, ensuring optimal energy utilization. These results highlight the effectiveness and scalability of FLC-based EMS in enhancing the resilience and sustainability of grid-connected hybrid marine energy systems.

Keywords Energy Management System (EMS) · Hybrid Energy Systems · Fuzzy Logic Control · Renewable Energy · Wind Turbines · Tidal Turbines · State of Charge (SOC)

Abbreviations

AC	Alternating current
DC	Direct current
DER	Distributed energy resources
DG	Distributed generation
EMS	Energy management system
ESS	Energy storage system
FLC	Fuzzy Logic Control
Kv	Kilo volt

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Discover Energy

KWh Kilowatt hour
MW Mega watt
SOC State of charge
Tidal Conversion System
Wind Conversion System

1 Introduction

Energy remains a cornerstone of socio-economic progress and a critical enabler for achieving the United Nations' Sustainable Development Goals (SDGs). For countries like South Africa—home to over 59 million people with a 1.43% annual population growth rate—meeting rising energy demands has become a pressing challenge. Historically, South Africa's energy infrastructure has heavily relied on coal, accounting for over 80% of electricity generation. However, environmental concerns, depleting fossil fuel reserves, and global climate commitments underscore the urgent need for a transition to cleaner, renewable energy solutions [1].

Amid growing political, environmental, and economic disruptions, energy systems must focus on resilience and sustainability. While traditional markets offer short-term stability, long-term energy security needs innovative solutions. Renewable technologies and distributed energy generation (DEG) systems, integrating local renewables, provide a cost-effective approach for meeting energy demands in grid-limited and off-grid areas[2]. These systems are pivotal in South Africa, where rural areas still face limited access to the national grid [3]. However, Over the last two decades, the global adoption of DEG systems has surged, driven by the escalating costs and environmental consequences of fossil fuels. Hybrid configurations of renewable energy resources such as solar, wind, tidal, and wave energy are gaining prominence due to their potential to enhance energy reliability and efficiency [4]. Among these, marine renewable energy, particularly tidal energy, has garnered significant attention due to its predictability, renewability, and minimal environmental footprint [5]. Tidal stream energy, with a global potential of 450 TWh/year, is a promising alternative to mitigate the intermittency of other renewable resources, such as wind [6].

Unlike wind turbines, tidal turbines benefit from water's high density—approximately 800 times that of air—resulting in compact designs capable of delivering significant power outputs with smaller rotor diameters [7]. However, the intermittent nature of renewable energy sources necessitates integrating energy storage systems (ESS) and advanced energy management systems (EMS) to maintain a reliable power supply. Recent research highlights the role of hybrid energy storage systems (HESSs) in mitigating fluctuations and optimizing the operation of renewable energy systems [8], [9], [10], [11]. This study aims to address the critical challenges associated with hybrid renewable energy systems by proposing an optimized energy management strategy based on FLCs. The proposed system integrates offshore wind and tidal energy with a battery energy storage system to ensure uninterrupted power supply, enhance energy security, and reduce operational costs. This research's novel contributions include the design of a hybrid offshore wind-tidal system architecture and the implementation of a fuzzy logic-based EMS to optimize energy distribution and storage.

The remainder of this paper is structured as follows: Section 2 outlines the system configuration and turbine classification. Section 3 presents the energy management strategy, while Section 4 describes the modeling of the proposed hybrid system. Section 5 discusses the simulation results, and Section 6 concludes with key findings and future research directions.

1.1 Existing works related to the energy management system of the hybrid grid system

Recent research highlights the role of hybrid energy storage systems (HESSs) in mitigating fluctuations and optimizing the operation of renewable energy systems [8], [9], [10], [11]. Fuzzy Logic Controllers (FLCs), as part of advanced EMS strategies, have emerged as a robust tool for enhancing the performance of hybrid energy systems. Unlike conventional proportional-integral-derivative (PID) controllers, FLCs effectively manage nonlinearities, prioritize renewable energy utilization, and adapt to dynamic load variations. For instance, Shyni & Ramadevi, (2019)[12] and Balakishan et al., (2023)[13] demonstrated the efficacy of FLCs in improving power reliability and mitigating voltage imbalances in hybrid renewable energy systems. Moreover, hybrid configurations, such as offshore wind-tidal systems, offer complementary benefits such as, wind energy's intermittent nature can be stabilized by tidal energy's predictability, while integrated storage ensures grid stability and cost-efficiency. This study proposes an optimized energy management strategy using fuzzy logic controllers (FLCs) to address challenges in hybrid renewable energy systems. By integrating offshore wind, tidal energy, and battery storage, the system ensures reliable power, enhances energy security, and reduces costs. Key innovations include a hybrid wind-tidal design and a fuzzy logic-based EMS.

Chronological Literature Review Discussion

The application of fuzzy logic in energy management systems (EMS) has evolved significantly over the past few years, especially in the context of hybrid energy systems and renewable integration. Early research established the foundation for fuzzy control in hybrid configurations. For instance, Shyni and Ramadevi (2019) [12] demonstrated the effectiveness of fuzzy logic controllers (FLCs) in improving power reliability and mitigating voltage imbalance in hybrid renewable energy systems. Their work highlighted the advantages of FLCs over conventional proportional-integral-derivative (PID) controllers, particularly in handling nonlinear system dynamics and adapting to variable load conditions.

Building on these foundations, Na Feng et al. (2022) introduced a more advanced fuzzy EMS by integrating a particle filter (PF) algorithm for battery state-of-charge (SOC) estimation in hybrid electric vehicles. Their strategy significantly improved SOC estimation accuracy and enabled more efficient charge-discharge cycles. By feeding the PF-based SOC output into a fuzzy controller, they achieved effective energy distribution between batteries and ultra-capacitors, showcasing the benefits of combining probabilistic estimation with fuzzy reasoning for real-time EMS.

More recent advancements have focused on optimizing EMS for standalone and micro grid applications. Umair Hussan et al. (2024) developed an intelligent Lyapunov-based adaptive fuzzy controller to manage power flow in a standalone DC micro grid comprising photovoltaic and wind sources, along with battery storage and a diesel generator. Their system dynamically regulated voltage and optimized power sharing under both high and low renewable penetration scenarios, ensuring continuous and stable operation. Simulation and hardware validations demonstrated its superiority over PID and sliding mode controllers.

In the same year, Muhammad Asghar Majeed et al. (2024) proposed a decentralized fuzzy-based droop control strategy for grid-forming inverters. Their controller managed voltage and frequency regulation across a distributed generator network—including PV panels, wind turbines, fuel cells, and batteries—without relying on a centralized EMS. The adaptive fuzzy logic algorithm not only achieved robust power sharing under dynamic load conditions but also enhanced overall system reliability and reduced complexity.

Simultaneously, the broader research landscape has increasingly emphasized the role of hybrid energy storage systems (HESSs) in enhancing renewable energy integration and grid resilience [8]–[11]. FLCs have been particularly effective in these systems due to their ability to accommodate fluctuating renewable outputs and prioritize energy dispatch intelligently. Recent work by Balakishan et al. (2023) [13] further demonstrated how fuzzy logic enhances EMS performance, particularly in maintaining voltage stability and optimizing renewable energy usage in hybrid systems.

Emerging hybrid configurations, such as offshore wind-tidal systems, leverage the complementary characteristics of each resource—tidal energy's predictability helps mitigate wind variability—while integrated storage systems ensure grid stability and operational flexibility. These configurations underscore the growing relevance of intelligent EMS design for future energy systems.

2 The architecture of a hybrid energy system

The Hybrid Offshore Tidal Turbine (HOTT) system integrates offshore wind and tidal energy generation with advanced battery storage to maximize energy harnessing and stability. This system features the following components [14]:

- A large-scale wind turbine equipped with a synchronous generator, converting alternating current (AC) to direct current (DC) via a diode rectifier.
- A small-scale tidal turbine employing an induction generator, connected to the DC circuit through a bidirectional converter.
- A DC/DC converter, managing battery operations to stabilize short-term power fluctuations.
- An energy storage system (ESS), providing critical buffering to address renewable energy intermittency. Figure 1 illustrates the conceptual design of the HOTT system, while Figure 2 provides a detailed schematic, including the integration of the battery energy storage system [15], [16].

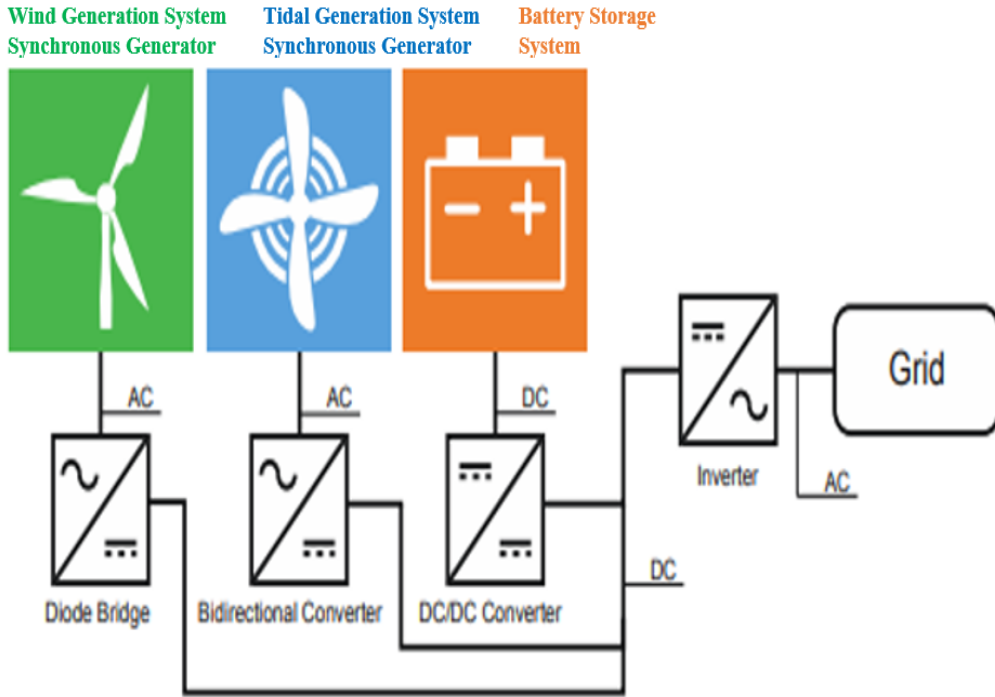
2.1 Hybrid Offshore Tidal Turbine (HOTT) systems

In the pursuit of a resilient, sustainable, and decentralized energy system, hybrid micro-grid architectures have emerged as a cutting-edge solution that integrates the benefits of diverse distributed energy resources, storage technologies, and intelligent control systems. Figure 1 indicates the structure of a hybrid micro-grid and the basic architecture includes a variety of each components of the offshore hybrid systems shows in Figure 2.

Fig. 1 Conceptual image of HOTT [17].



Fig. 2 Conceptual System
Schematic of HOTT with
Battery



3. Modelling Algorithm for each Component of the Hybrid Wind-Tidal Storage System

To accurately model each component of the hybrid wind-tidal energy storage system, it is essential to develop algorithms that capture the dynamic behaviour of the wind turbine, tidal turbine, Battery Energy Storage System (BESS), and the overarching control strategy. Below is a detailed, step-by-step algorithm for the modelling of each component:

3.1. Offshore Wind Turbine Model

The developed hybrid micro-grid architecture was applied to supply a variable AC load. Algorithm Steps:

Input Parameters:

- Wind speed (W_v)
- Air density (ρ)
- Rotor radius (R_r) = 40 m (typical for offshore turbines in the 2-5 MW class)
- Power coefficient (C_p) as a function of tip-speed ratio (λ) and pitch angle (β)

Calculate Tip-Speed Ratio (λ):

$$\lambda = \frac{\omega_w \cdot R_w}{v_w} \quad (1)$$

where ω_w is the angular speed of the turbine rotor.

Compute Power Coefficient (C_p):

$$C_p = f(\lambda, \beta) \quad (2)$$

Same function as Eq. (2a), adjusted for marine hydrodynamics. Derived from [Ref] where turbine performance under laminar tidal conditions was modeled.

Use an empirical or analytical function to determine C_p .

Calculate Mechanical Power (P_{mech}):

$$P_{mech} = \frac{1}{2} \rho \pi R^2 v_w^3 C_p \quad (3)$$

Convert Mechanical Power to Electrical Power (P_{elec}):

$$P_{elec} = \eta_g \cdot P_{mech} \quad (4)$$

where η_{gen} is the generator efficiency.

Output:

- Electrical power (P_{elec}).
- Turbine torque

$$T_w = \frac{P_{mech}}{\omega_w} \quad (5)$$

3.2. Offshore Tidal Turbine Model

Algorithm Steps:

Input Parameters:

- Tidal speed (T_v)
- Air density (ρ)
- Rotor radius (R_r)
- Power coefficient (C_p) as a function of tip-speed ratio (λ) and pitch angle (β). Calculate Tip-Speed Ratio (λ):

$$\lambda = \frac{\omega_t \cdot R_t}{v_t} \quad (6)$$

where ω_w is the angular speed of the turbine rotor.

Compute Power Coefficient (C_p):

$$C_p = f(\lambda, \beta) \quad (7)$$

Use an empirical or analytical function to determine C_p .

Calculate Mechanical Power (P_{mech}):

$$P_{mech} = \frac{1}{2} \rho \pi R^2 v_t^3 C_p \quad (8)$$

Convert Mechanical Power to Electrical Power (P_{elec}):

$$P_{elec} = \eta_g \cdot P_{mech} \quad (9)$$

where η_{gen} is the generator efficiency.

Output:

- Electrical power (P_{elec})
- Turbine torque

$$T_t = \frac{P_{mech}}{\omega_t} \quad (10)$$

3.3. Battery Energy Storage System (BESS) Model

To accurately model the dynamics of the Battery Energy Storage System (BESS), it is crucial to account for variations in charging and discharging efficiencies, which typically depend on factors such as the State of Charge (SOC), battery current, and temperature. The following algorithm has been refined to reflect these practical considerations.

Algorithm Steps:

Input Parameters:

- Initial State of Charge (SOC) (SOC_{init})
- Maximum and minimum SOC limits ($SOC_{max} - SOC_{min}$)
- Battery capacity (C_{Batt})
- Initial State of Charge (SOC_0)
- Battery current (I_{Batt})
- Time step (Δt)
- SOC-dependent charge/discharge efficiency curves ($\eta_{charg}, \eta_{disch}$)

Update Battery Efficiency Based on SOC

Battery efficiency is not constant; it varies with SOC and current. To capture this behaviour:

- $\eta_{ch} = \eta_{ch}(SOC_0)$
- $\eta_{disch} = \eta_{disch}(SOC_0)$

These efficiency values can be derived from manufacturer datasheets or empirical testing data and approximated using look-up tables or polynomial fitting.

Calculate SOC Update:

$$\text{If Charging: } SOC = SOC_0 + \frac{P_{batt} \cdot \Delta t}{C_{batt}} \quad (11)$$

$$\text{If Discharging: } SOC = SOC_0 - \frac{P_{batt} \cdot \Delta t}{C_{batt}}$$

- For charging, use η_{ch}
- For discharging, use η_{disch}

Check SOC Limits:

If $SOC > SOC_{max}$: Set $SOC = SOC_{max}$

If $SOC < SOC_{min}$: Set $SOC = SOC_{min}$

Calculate Battery Power (P_{Batt}):

$$\text{If charging: } P_{Batt} = P_{excess} \cdot \eta_{ch} \quad (12)$$

$$\text{If discharging: } P_{Batt} = P_{deficit} \cdot \eta_{disch} \quad (13)$$

Output:

- Updated SOC
- Battery power (P_{Batt}) to or from the grid

To model a three-phase inverter and its associated filter, we need to develop mathematical equations that describe the behaviour of the inverter in converting DC power to three-phase AC power and the filter equations to smooth out the output waveform. Below are the equations and their descriptions [18].

- Three-Phase Inverter Model

A three-phase inverter converts a DC voltage (V_{dc}) into three-phase AC voltages (v_a, v_b, v_c).

The output voltages are controlled by Pulse Width Modulation (PWM)[19].

Output Voltage in abc Frame:

$$v_a = \frac{V_{dc}}{2} m_a \quad (14)$$

$$v_b = \frac{V_{dc}}{2} m_b \quad (15)$$

where m_a, m_b, m_c are the modulation signals for phases a, b, and c, respectively, generated by the PWM technique. Output Voltage in dq0 Frame: Convert the three-phase voltages to the dq0 reference frame using Park's transformation:

$$\begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (16)$$

where θ is the phase angle of the reference frame. Output Currents in abc Frame: The output currents i_a, i_b, i_c are related to the load impedance and the inverter output voltages:

$$i_a = \frac{v_a - vL_a}{Z_L} \quad (17)$$

$$i_b = \frac{v_b - vL_b}{Z_L} \quad (18)$$

$$i_c = \frac{v_c - vL_c}{Z_L} \quad (19)$$

where Z_L is the load impedance, and vL_a, vL_b, vL_c are the voltages across the load.

3.4. Filter Model

Typically, a three-phase L or LC filter is used to smooth out the inverter output, reducing harmonic distortion.

3.5. L-Filter Model

Voltage Across Filter Inductance (L): The L-filter smooths the output current. The voltage across the inductance for phase a is given by:

$$v_L = L \frac{di_a}{dt} \quad (20)$$

Output Voltage After L-Filter: The output voltage across the load for phase a is:

$$vL_a = v_a - v_L \quad (21)$$

Similarly, for phases b and c

$$vL_b = v_b - L \frac{di_b}{dt} \quad (22)$$

$$vL_c = v_c - L \frac{di_c}{dt} \quad (23)$$

The LC-filter adds a capacitor to the L-filter to further reduce ripple.

Voltage Across Filter Inductance (L): For phase a, the inductor voltage is:

$$vL = L \frac{di_a}{dt} \quad (24)$$

Current Through Capacitor (C): The current through the filter capacitor for phase a is:

$$i_c = C \frac{dvC_a}{dt} \quad (25)$$

Current Balance Equation: The total current for each phase is the sum of the load current and the capacitor current:

$$i_a = iL_a + i_c \quad (26)$$

where iL_a is the load current for phase a.

Output Voltage After LC-Filter: The output voltage for each phase is given by:

$$vL_a = v_c - \frac{1}{C} \int i_c dt \quad (27)$$

Complete Three-Phase Inverter with Filter Equations

Combining the inverter and filter equations, we get the following set of differential equations:

Inverter Output Voltage:

$$v_a = \frac{V_{dc}}{2} m_a, v_b = \frac{V_{dc}}{2} m_b, v_c = \frac{V_{dc}}{2} m_c \quad (28)$$

3.6. Filter Inductor Voltage

$$C \frac{dvi_a}{dt} = v_a - vC_a \quad (29)$$

$$C \frac{di_b}{dt} = v_b - vC_b \quad (30)$$

$$C \frac{di_c}{dt} = v_c - vC_c \quad (31)$$

3.7. Filter Capacitor Voltage

$$C \frac{dvC_a}{dt} = i_a - iL_a \quad (32)$$

$$C \frac{dvC_b}{dt} = i_b - iL_b \quad (33)$$

$$C \frac{dvC_c}{dt} = i_c - iL_c \quad (34)$$

3.8. Load Current

$$iL_a = \frac{vC_a}{Z_L}, iL_b = \frac{vC_b}{Z_L}, iL_c = \frac{vC_c}{Z_L} \quad (35)$$

3.9. System Description

The control structure of the PMSG-based hybrid energy harvesting system and Control structure of PMSG based hybrid wind/tidal turbine, shown in Figure 3 and Figure 4, The control structure of the PMSG-based hybrid energy

harvesting system, shown in Figure 3, comprises two PMSGs, PWM-controlled AC/DC converters, a DC link, and a DC/AC inverter. The variable-speed PMSG outputs, which fluctuate in amplitude and frequency, require a stable DC link for grid integration or standalone operation. The HOTT system serves a 20 MW load demand, supported by tidal generation (5 MW), wind turbines (12 MW), and a 3 MW Battery Energy Storage System (BESS). The tidal turbine operates at 12 m/s (assumed standard at sea level; sensitivity analysis later discusses variations), as $\omega_t = 2.513 \text{ rad/s}$ (corresponding to 24 RPM) with a rotor speed of 24 RPM, delivering 600 kNm torque $t = 600 \text{ kNm}$: this value is based on simulations using the above parameters and a C_p curve optimized for low-speed high-torque operation. Sensitivity analysis confirmed its validity for flow speeds up to 3.5 m/s. through 6.6 kV medium-voltage submarine cables. An onshore transformer steps down the voltage for grid compatibility. To optimize power quality, the Grid Side Converter (GSC) facilitates reactive power exchange with the grid, operating independently of the Rotor Side Converter through the DC link. The GSC, modelled in MATLAB/SIMULINK, includes Grid Side Converter: Features ideal IGBT switches for bidirectional power flow. Grid Side Filter: An LC filter connects converter phases to the grid voltage. Voltage Matching Transformer: Ensures voltage compatibility between the rotor and grid sides, directly connected to the generator rotor. This setup optimizes the HOTT system for stable energy delivery while managing peak demands and grid integration. Based on previous findings, the tidal turbine produces 1.324 MW of active power with a torque of 600 kNm at a water speed of 12 m/s. To increase tidal energy's contribution, scaling up the system to 5 MW by using four 1.25 MW turbines or higher-capacity alternatives is recommended. Each turbine should maintain low THD using LCL filters, ensuring consistent power quality.

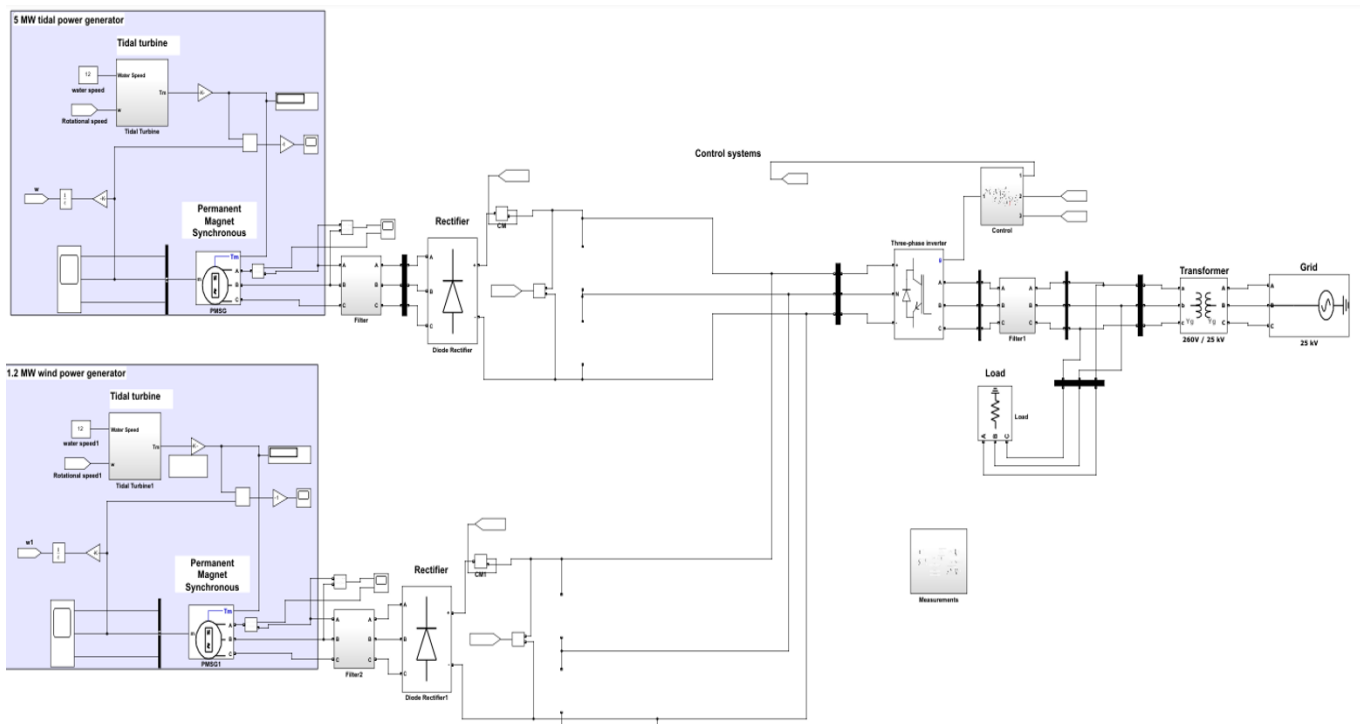


Fig. 3 Simulation Model of the Fuzzy Controlled Hybrid System

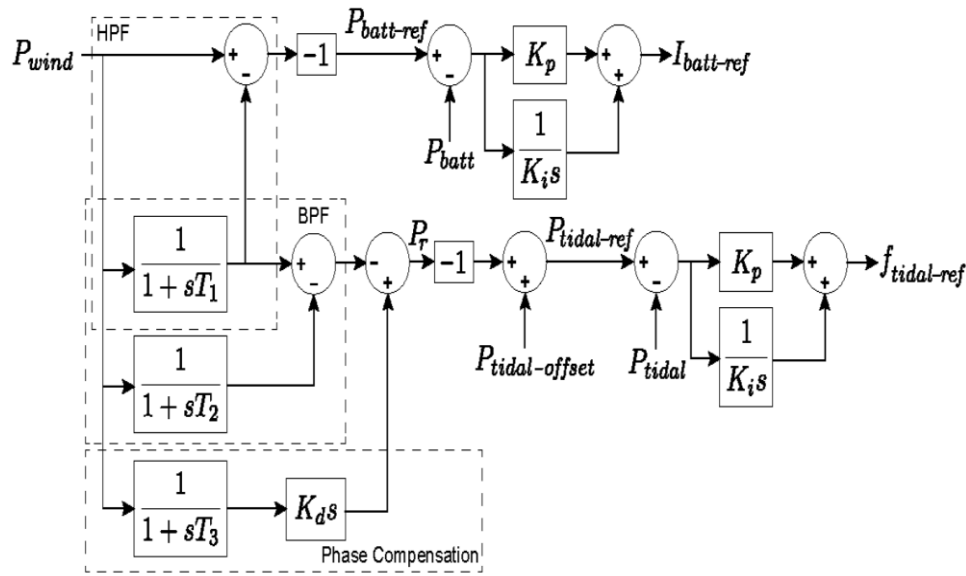


Fig. 4. Control structure of PMSG-based hybrid wind/tidal turbine

4. Energy Management System Control Methodology

4.1 Fuzzy Logic Control for Efficient Hybrid Offshore Wind and Tidal Systems

Ensuring system stability and safety is crucial in managing hybrid systems like Hybrid Offshore Wind and Tidal Turbine (HOTT) systems. These systems must be cost-efficient, user-friendly, easy to maintain, adaptable, and optimize performance. Achieving this requires a solid understanding of the system's structure and dynamics, often modelled mathematically. However, accurately modelling nonlinear systems is challenging, and implementing such models can add complexity and cost, potentially limiting effectiveness [20].

In such cases, expert knowledge becomes indispensable. Experts can express system behaviours in fuzzy or uncertain terms, which can be digitized and programmed to reduce human intervention and ensure more consistent control. Fuzzy logic achieves this by converting qualitative experiences into numerical rules, replacing ambiguous verbal expressions with precise, logical functions [2]. Everyday terms like "old," "young," "hot," or "cold" are often vague, without fixed boundaries. Fuzzy logic mimics the human mind's ability to make decisions based on such imprecise inputs [21]. Since the 1960s, fuzzy logic has been recognized for handling uncertainty, with Japan leading its adoption in the 1980s [22]. Today, fuzzy logic is widely used in systems characterized by uncertain or incomplete data, providing a powerful tool for managing complex hybrid systems [23].

4.2 Fuzzy Logic Controller for HOTT Systems

Figure 5 and Figure 6 illustrate an Energy Management System (EMS) for a HOTT system, managed by a Fuzzy Logic Controller (FLC). The FLC balances power flow between system components (wind turbine, tidal turbine, energy storage, and grid) to ensure stable and efficient operation. The controller optimizes battery charging and discharging operations based on system inputs, such as battery State of Charge (SOC) and power (P). The output is the reference current (I_{ref}) [24].

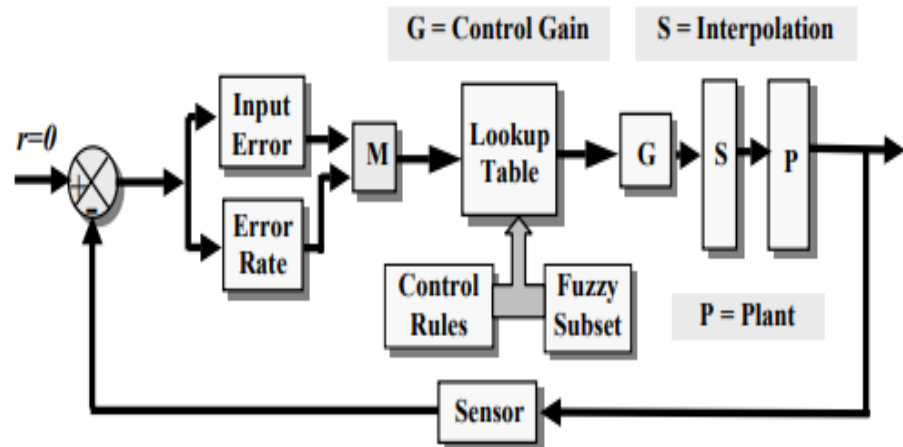


Fig. 5. Block diagram of a fuzzy control system [25].

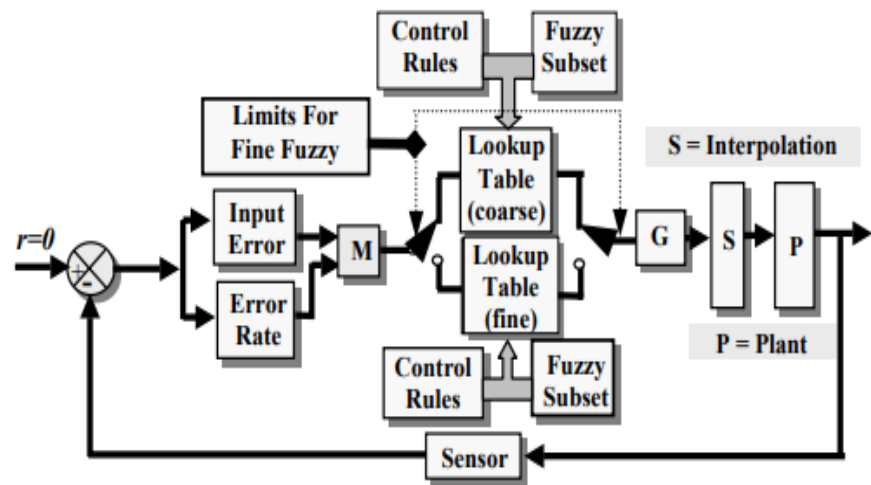


Fig. 1. Block diagram of an accurate fuzzy control system [25].

4.3 Fuzzy Logic Controller Design Overview

Each micro grid operates according to the block diagram illustrated in Figure 7, which is based on the micro grid energy rate-of-change (ERoC, $P_{AVG}(n)$), and the BESS's state of charge (SOC). It's important to note that $P_{AVG}(n)$ represents the local prediction of the battery SOC's future behavior if the grid power remains unchanged [26].

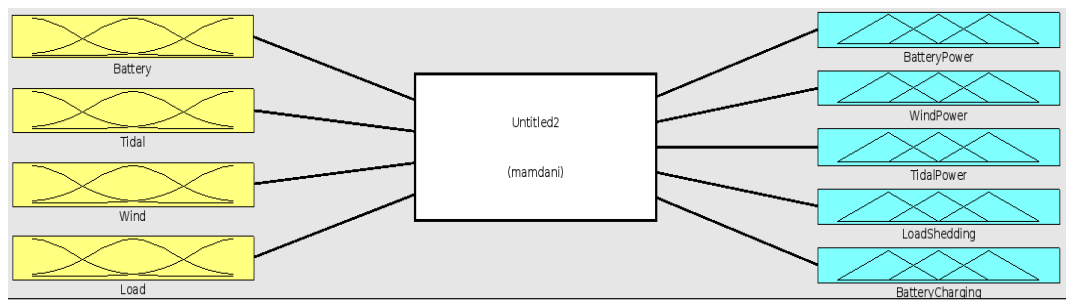


Fig. 2. Block diagram of the fuzzy-based EMS based on micro grid energy rate-of-change.

Inputs:

- State of Charge (SOC): Battery energy level.
- Power Demand (PD): Power required by the load.
- Power Generated (PG): Combined power from wind and tidal turbines.

4.4 Grid Status (GS):

Availability of grid connection.

Outputs:

- Battery Charging/Discharging Rate: Determines the power flow to/from the battery.
- Power Supply Mode: Defines whether power comes from renewable sources, the grid, or the battery.

4.5 Fuzzy Logic Controller Structure Input Variables

State of Charge (SOC):

- Range: [0, 100] (%)
- Fuzzy Sets: Low, Medium, High

Membership Functions: Triangular or trapezoidal.

Power Demand (PD):

- Range: [0, 1] (p.u.)
- Fuzzy Sets: Low, Moderate, High
- Membership Functions: Triangular or trapezoidal.

4.6 Power Generated (PG)

- Range: [0, 1] (p.u.)
- Fuzzy Sets: Low, Moderate, High
- Membership Functions: Triangular or trapezoidal.

4.7 Grid Status (GS)

- Binary Variable: 0 (Unavailable), 1 (Available)

Output Variables

4.8 Battery Charging/Discharging Rate

Range: [-1, 1] (p.u.), where:

- -1: Maximum Discharge
- 0: No Charge/Discharge
- 1: Maximum Charge
- Fuzzy Sets: Discharge, No Action, Charge
- Membership Functions: Triangular.

4.9 Power Supply Mode

- Options: Renewable, Grid, Battery
- Fuzzy Sets: Use Renewable, Use Grid, Use Battery
- Membership Functions: Singleton or triangular.

4.10 Fuzzy Rule Base

Rules are defined based on the interactions between SOC, PD, PG, and GS. Examples of FLC rules include:

- Rule 1: If (SOC is High) and (PD is Low) and (PG is High) and (GS is Available), then Battery Charging Rate is Charge, and Power Supply Mode is Use Renewable.
- Rule 2: If (SOC is Low) and (PD is High) and (PG is Low) and (GS is Available), then Battery Charging Rate is No Action, and Power Supply Mode is Use Grid.
- Rule 3: If (SOC is Medium) and (PD is Moderate) and (PG is Moderate) and (GS is Unavailable), then Battery Charging Rate is Discharge, and Power Supply Mode is Use Battery.
- Rule 4: If (SOC is High) and (PD is High) and (PG is Low) and (GS is Unavailable), then Battery Charging Rate is No Action, and Power Supply Mode is Use Battery.

4.11 Defuzzification Method

- Method: Centroid of Area (COA)
- Purpose: Converts fuzzy outputs into precise control actions.

4.12 Simulation and Validation

To verify the FLC's effectiveness, the system is tested in various scenarios using MATLAB/Simulink:

- Scenario 1: High wind and tidal power generation with low load demand.
- Scenario 2: Low renewable generation and high load demand with grid availability.
- Scenario 3: Moderate generation and load demand with grid unavailable.

5. Results Discussions

5.1 Energy Management Strategy

The proposed Energy Management System (EMS), utilizing Fuzzy Logic Control (FLC), manages power flows between wind, tidal, storage, and the grid. FLC is designed with inputs such as battery state of charge (SOC), wind output, tidal output, and load demand. The FLC optimizes the hybrid system's operation in various scenarios by dispatching power intelligently based on system conditions. Fuzzy rules are defined for different operating modes:

- High Generation Mode: Excess energy is stored or exported to the grid.
- Low Generation Mode: BESS is used to meet the demand, and the grid supplies power when needed.
- Medium Generation Mode: Both renewable generation and storage are used to maintain grid stability.

Table 1 outlines the relationship between the state of charge (soc) and the power difference (δp), with membership functions for both inputs and outputs.

SOC/ ΔP	NB (Negative Big)	NS (Negative Small)	Z (Zero)	PS (Positive Small)	PB (Positive Big)
L (Low)	Discharge Battery	Discharge Battery	Hold Output	Use Grid	Use Grid
M (Medium)	Discharge Battery	Hold Output	Charge Battery	Charge Battery	Export to Grid
H (High)	Use Grid	Hold Output	Charge Battery	Charge Battery	Export to Grid
VH (Very High)	Use Grid	Use Grid	Export to Grid	Export to Grid	Export to Grid

- NB: Negative Big power difference, large deficit (requires external support or grid use).
- NS: Negative Small power difference, small deficit (battery discharge).
- Z: Zero power difference, generation matches load.

- PS: Positive Small power difference, small surplus (battery charge).
- PB: Positive Big power difference, large surplus (export excess power to the grid).

This table can be used as the fuzzy logic rule set for your HOTT system's energy management system (EMS), implemented in MATLAB/Simulink using the Fuzzy Logic Toolbox. Table 2 for battery parameters, incorporating more detailed specifications and considerations to enhance performance and integration into your HOTT system.

Table 2 improved battery parameters

Parameter	Value	Description
Nominal Voltage	48 V	Standard operating voltage for the battery system.
Rated Capacity	2000 Ah	Total charge capacity defines how long the battery can supply a given load.
Internal Resistance	0.0356 Ω	Resistance that affects efficiency and heat generation; lower values indicate better performance.
Initial SOC	35%	Initial state of charge at system start-up.
Battery Fully Charged Voltage	55.9 V	Voltage when the battery is fully charged, used for charging algorithms.
Cut-off Voltage	42 V	Minimum voltage to which the battery can be discharged to avoid damage.
Charging Efficiency	90%	The efficiency of converting input energy into stored energy during charging.
Discharge Efficiency	95%	The efficiency of converting stored energy back into usable energy during discharge.

Table 3 Improved battery parameters continue.

Parameter	Value	Description
Cycle Life	3000 cycles	Number of charge-discharge cycles before the battery capacity falls below 80%.
Operating Temperature Range	-20°C to 60°C	Range of temperatures in which the battery can operate effectively.
Battery Chemistry	Lithium-Ion	Type of battery technology used, influencing capacity, weight, and lifespan.
Maximum Charge Current	200 A	Maximum current the battery can accept during charging.
Maximum Discharge Current	150 A	Maximum current the battery can supply during discharge.
Depth of Discharge (DoD)	80%	Maximum allowable percentage of capacity that can be used before recharging.

Key Improvements

- Cut-off Voltage: Ensures the battery is not overly discharged, protecting its lifespan.
- Charging and Discharge Efficiency: Important for calculating net energy availability.
- Cycle Life: Gives an idea of battery longevity and maintenance planning.
- Operating Temperature Range: Important for ensuring reliability in various environmental conditions.
- Battery Chemistry: Specifies the technology used, influencing other parameters like energy density and safety.

5.2 Energy Storage Unit/Battery System

Designing energy storage for hybrid energy systems (HES) requires careful sizing to meet load demands during adverse conditions [27]. Common technologies include lead-acid, lithium-ion, and advanced batteries like vanadium redox. Lead-acid batteries, known for cost-effectiveness and availability, are often used for durations of hours to days [28].

Several critical factors must be considered when selecting batteries for offshore energy applications: the capacity to withstand high discharge rates (70-80% depth of discharge), low current during both charging and discharging, the ability to sustain long-duration charge and discharge cycles, variability and unpredictability in charge/discharge behaviour, minimal self-discharge rates, and overall longevity.

This detailed parameterization will enhance the battery management within your Hybrid Offshore Wind-Tidal-Storage (HOTT) system, optimizing performance, reliability, and lifespan. Here are the tables for the HOTT (Hybrid Offshore Wind-Tidal-Storage) example based on your provided information:

Table 4 Rectifier control design parameters

Control Loop Parameters	Value
K_p	133.5
K_i	133500

Table 5 Rectifier control design parameters

Control Loop Parameters	Value
K_{pi}	3.24
K_{ji}	50.625

Table 6 Generator modelling parameters

Parameters	Values
Viscous Damping	0.01
Friction	0
N_p	48

Table 7 LCL filter parameters

Parameters	Values
Inverter Side Inductor L_i	0.9 mH
Grid Side Inductor L_g	0.072 mH
Capacitor Filter C_f	531 μ F

Table 8 Additional LCL filter parameters

Parameters	Values
Damping Resistor R_d	0.118 Ω
Resonant Frequency R_{ref}	845 Hz
Grid Side Inductor L_g	0.00761 Ω
Sampling Frequency f_s	10,000 Hz
Crossover Frequency f_c	254 Hz

Table 9 PWM regenerative rectifier modelling parameters

Parameters	Values
P_{nom}	1.5 MW
V_{DC}	1500 V
V_{ll}	600 V
C_{DC}	0.04 Farad
V_{nom}	600 V
R_s	0.006
L_{dq}	0.3e-3
ϕ	1.48
j	35000

The following tables outline key control parameters, modelling configurations, and filter specifications essential for implementing the HOTT system.

5.3 Turbine Types:

Horizontal Turbines: Commonly utilized, featuring components such as blades, gearbox, shaft, and generator located in the nacelle atop the tower.

Vertical Turbines: Less prevalent, used in specialized applications.

MATLAB Simulation Results: Fuzzy Membership Functions for State of Charge (SOC)

The fuzzy membership functions for the State of Charge (SOC) of the battery were defined and visualized using MATLAB. The following categories were used to classify the SOC:

- Low (L): SOC range from 0 to 0.5.
- Medium (M): SOC range from 0.2 to 0.8.
- High (H): SOC range from 0.5 to 1.
- Very High (VH): SOC range from 0.8 to 1.

Figure 8 demonstrates the SOC membership functions, where the triangular shapes for each category overlap, illustrating the transition between states. The SOC spans from 0% to 100%, with the membership degree varying accordingly.

5.4 Customization of Membership Functions:

The SOC range can be refined for greater resolution, and the parameters of the triangular membership functions can be adjusted to better fit system-specific requirements. These fuzzy membership functions offer a foundational approach for incorporating fuzzy logic in estimating SOC within energy storage systems.

5.5 Fuzzy Logic Controller (FLC) Design and Operation:

The FLC governs the power flow between renewable energy sources, energy storage, and the grid by fuzzifying the inputs, which include generation power (P_g), load power (P_L), and battery SOC. These inputs are categorized into fuzzy sets ("Low," "Medium," "High") using trapezoidal membership functions. Control signals are then generated for the grid (GD) and battery state (BS), ensuring optimal management of energy distribution. A battery energy storage system (BESS) connected to the DC bus ensures a stable power supply and compensates for fluctuations in renewable generation.

5.6 Power Modulation and Control:

Figure 8 illustrates the comparison between the d-axis current (I_d) and its reference (I_{dref}). The proportional-integral (PI) controller uses this comparison to regulate the q-axis voltage, to drive the I_q reference close to zero. The dq0 frame voltages (V_d and V_q) facilitate the calculation of modulation signals, which are fed into the Pulse Width Modulation (PWM) generator to produce control pulses for the three-level inverter. A Phase-Locked Loop (PLL) synchronizes the internal oscillator with the sinusoidal input, ensuring zero-phase difference.

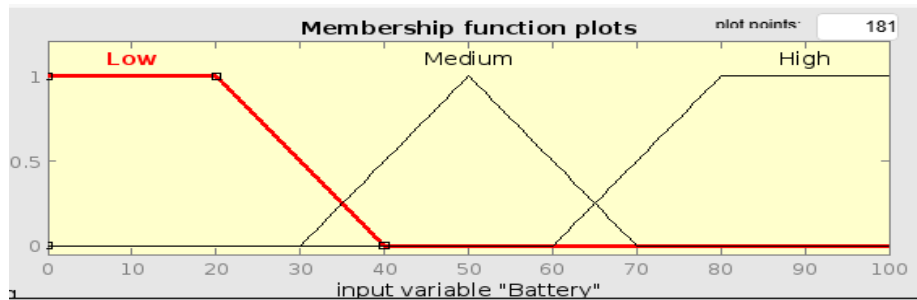


Fig. 3. Fuzzy Membership Functions for State of Charge

5.7 Fuzzy Membership Functions for Power Changes and Reference Current:

The fuzzy membership functions for change in power (ΔP) were defined within the range of -1 to 1, categorized as follows:

Negative (N): Represented by the triangular function $[-1, -1, 0]$.
 Zero (Z): Represented by $[-0.1, 0, 0.1]$, indicating a peak at zero.
 Positive (P): Represented by $[0, 1, 1]$.

The fuzzy membership functions for the reference current (I_{ref}), ranging from 0 to 1, are classified into:

- Low (L): Defined by $[0, 0, 0.5]$.
- Medium (M): Defined by $[0.2, 0.5, 0.8]$.
- High (H): Defined by $[0.5, 1, 1]$.

The overlapping regions of each membership function show the degree of membership for various values within the defined ranges. Load shown in (Fig 9) is categorized into: Low, Medium, and High, based on daily load profiles of coastal communities with demand peaks in morning and evening. Triangular MFs provide a smooth transition between states, allowing the controller to allocate energy flexibly and prioritize essential loads during scarcity.

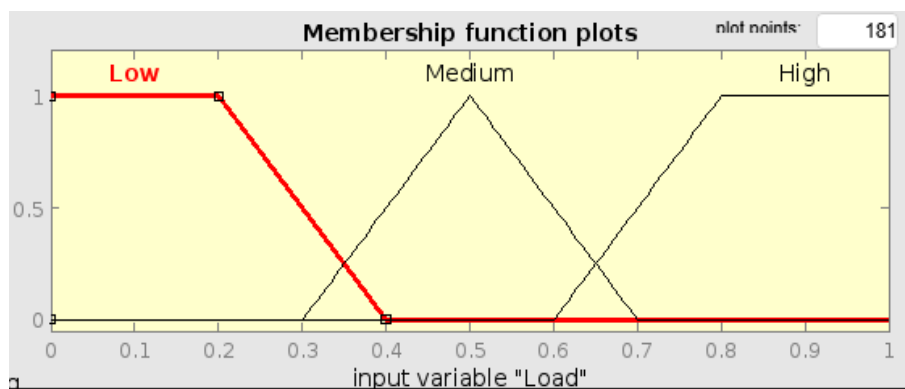


Fig. 4. Membership functions for Load Power

Tidal input indicates in (Fig 10) is modelled with Low, Medium, and High categories based on predicted tidal velocities. Since tidal energy is highly predictable and varies sinusoidally with time, trapezoidal MFs were used to reflect these cyclic changes and facilitate planning for energy dispatch.

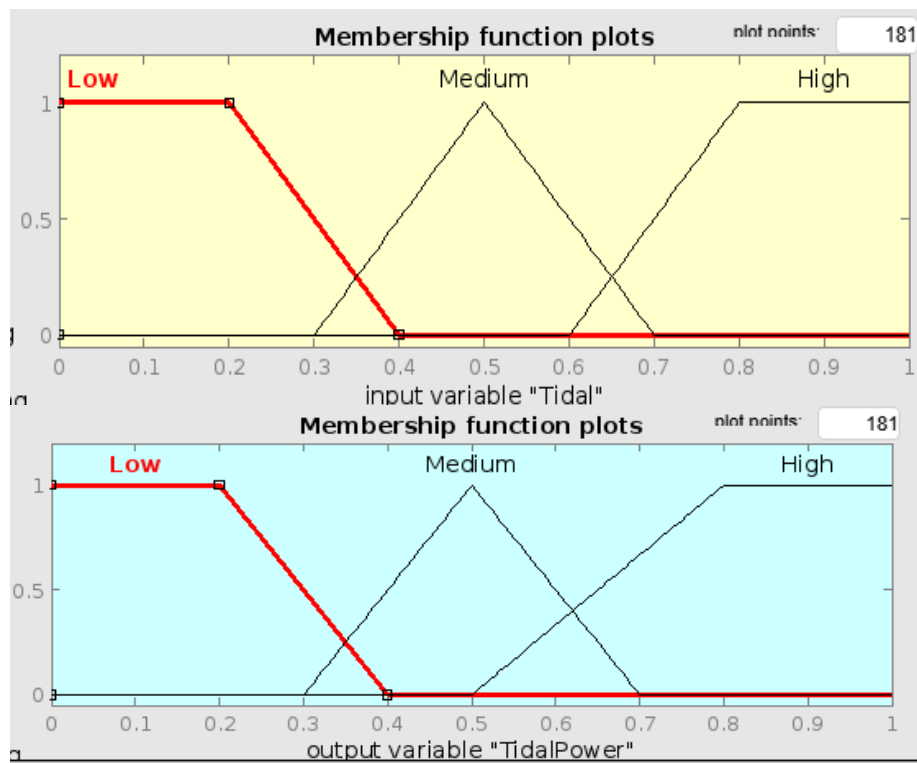


Fig. 10. Membership functions for Tidal.

Wind is unpredictable and intermittent, thus categorized as Low, Medium, and High using triangular MFs with wide overlap to reflect fluctuating wind speed indicates in (Fig 11). This design helps the controller make conservative decisions when wind data is uncertain or unstable.

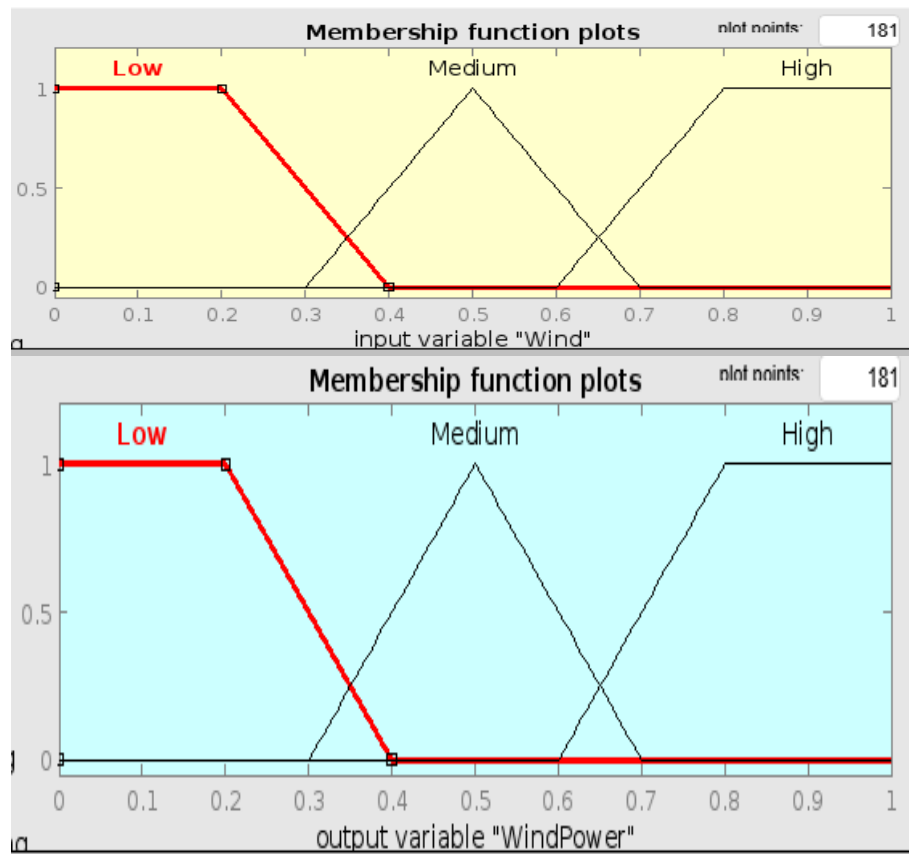


Fig. 11. Membership Functions for wind.

Load shedding shown in (Fig. 12) is defined as a **binary or fuzzy output** with categories such as: None, Partial, and Full. This allows prioritization of critical loads and graceful degradation during supply shortages. The use of fuzzy output (instead of binary) ensures a smoother transition between operational states, improving user experience.

- Negative (N) in red.
- Zero (Z) in green.
- Positive (P) in blue

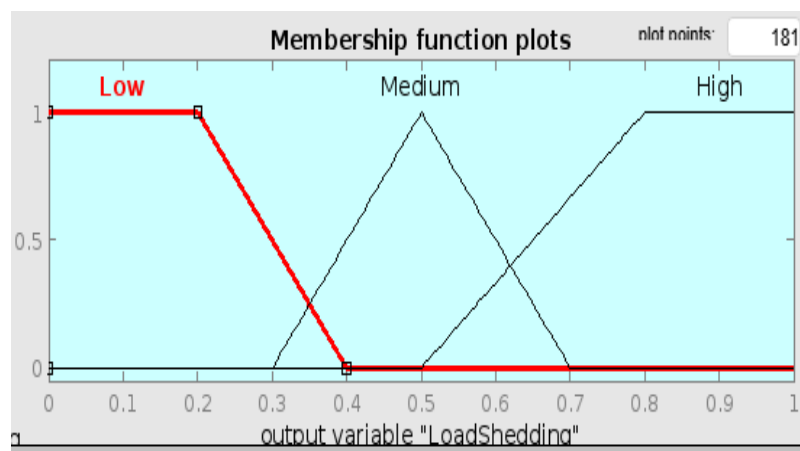


Fig. 12. Membership Functions for wind.

5.8 Fuzzy Membership Functions for Reference Current (I_{ref}):

I_{ref} Range: Defined from 0 to 1, representing reference current values.

Membership Categories:

- Low (L): Represented by a triangular function with points [0, 0, 0.5].
- Medium (M): Represented by points [0.2, 0.5, 0.8], peaking at 0.5.
- High (H): Represented by points [0.5, 1, 1].

The output graph visualizes the fuzzy membership functions for I_{ref} , showing the overlapping of categories (Low, Medium, High) within the range of reference current values from 0 to 1. These results illustrate how fuzzy membership functions can represent different states for both ΔP (change in power) and I_{ref} (reference current), allowing visualization of overlapping membership degrees across various ranges. Justification: The battery's SOC is divided into five linguistic terms:

Very Low (0-20%), Low (15-35%), Medium (30-60%), High (55-80%), and Very High (75-100%) using trapezoidal and triangular MFs.

This overlapping ensures smooth decision boundaries, reflecting real operational behavior and safety margins of lithium-ion batteries. Over-discharge (<20%) and overcharge (>95%) are avoided through rule constraints. Battery charging indicators in (Fig. 13) is divided into No Charging, Slow Charging, Medium Charging, and Fast Charging. These categories are based on SOC, load demand, and available renewable input. This approach helps optimize battery life, avoid overheating, and improve round-trip efficiency.

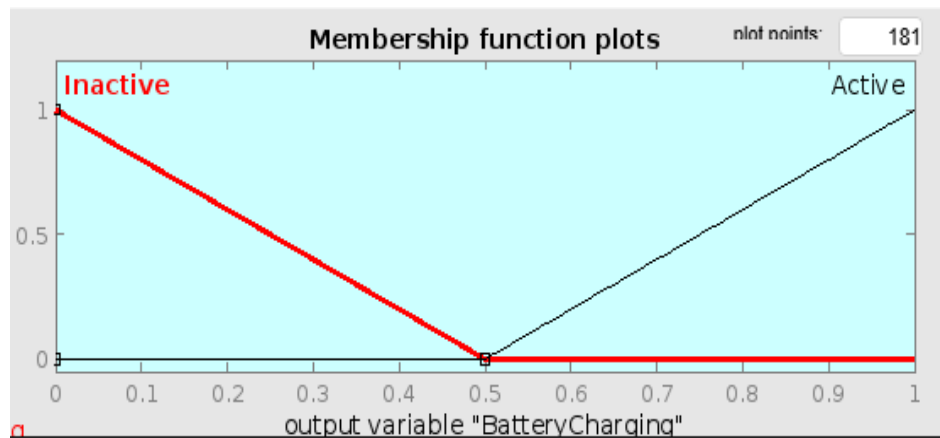


Fig.13. Membership Functions for the State of Charge (SOC) of the Battery

Fuzzy Membership Functions for Reference Current (I_{ref}): A graph was generated to visualize the fuzzy membership functions for the output reference current (I_{ref}). The categories are:

- Low (L): Represented in red.
- Medium (M): Represented in green.
- High (H): Represented in blue.

The graph clearly illustrates the degree of membership for each category, with overlapping regions indicating the transitions between them across the reference current range.

Fuzzy Membership Functions for System Outputs:

Figures 14 and 15 depict the fuzzy membership functions for the utility grid and battery state, respectively. The tidal generator produces a 6.6 kV AC voltage, while the wind turbine provides 690 V. The battery charges to 120 V during generation. A converter integrates the DC voltages from the tidal and wind systems, boosting the voltage to 250 V, which is then converted to AC by an inverter. The fuzzy-controlled hybrid system ultimately generates an AC voltage of 250 V, with simulation results shown in Figures 16-19 for the tidal/wind integration.

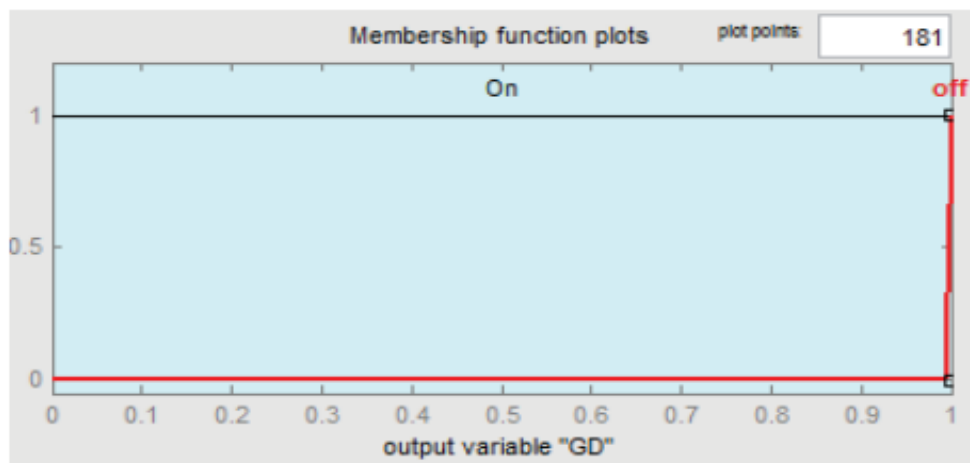


Fig. 14. Membership Functions for the Utility Grid.

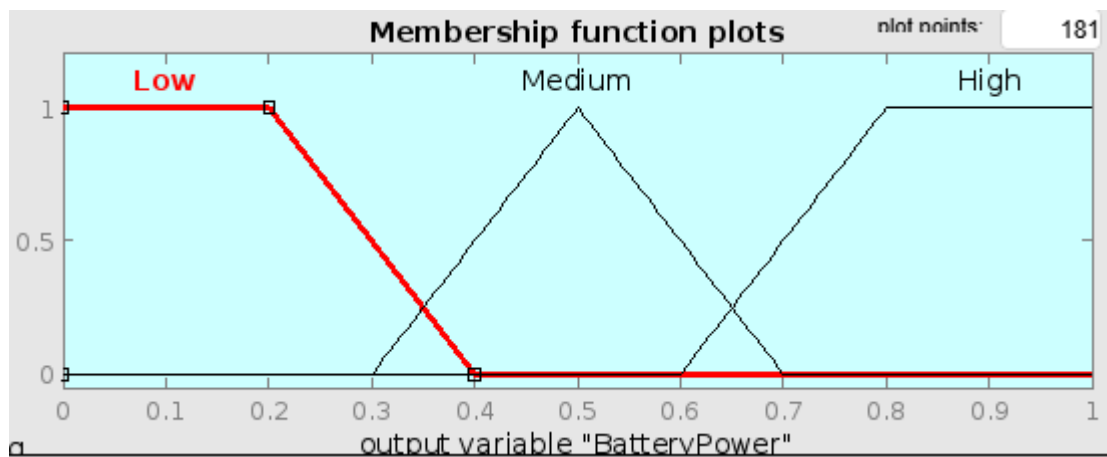


Fig.15.Membership Functions of State of Battery

System Overview and Performance: Figure 15 illustrates the system configuration, which integrates a Permanent Magnet Synchronous Generator (PMSG) linked to 12 MW of wind and 5 MW of tidal generation, supported by a 3 MW Battery Energy Storage System (BESS) to meet a 20 MW load demand. Key system features include:

- (a) Stable DC-bus voltage controlled by a PI controller.
- (b) and (c) Grid-side dq currents.
- (d) and (h) Zoomed views of the grid-side converter voltage in the ABC phase.
- (e) Comparison of measured vs. desired grid current.

5.9 Power Quality Improvement with LCL Filters:

LCL filters significantly reduce Total Harmonic Distortion (THD), enhancing both voltage and current quality. In this hybrid system, LCL filters ensure smooth integration of tidal and wind energy with storage, reducing THD to 0.07% and 0.12%, respectively. This results in cleaner, more stable energy with minimal losses. The filters also minimize voltage and current overshoots during inverter operation, ensuring effective grid synchronization and stable operation (Fig. 16. Output Voltage).

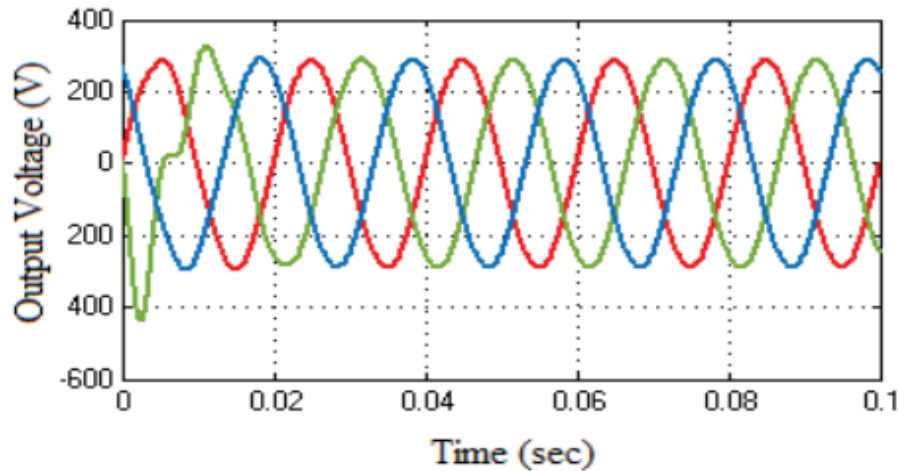


Fig.16. Output Voltage.

5.10 Tidal Power Output Analysis:

The tidal turbine generates 1.324 MW of power with a torque of 600 kNm at a constant water speed of 12 m/s. Under steady-state conditions, tidal energy contributes 5-10% of the total 20 MW load demand. Voltage-Oriented Control (VOC) effectively maintains the DC-link voltage at 1500 V, ensuring smooth power conversion and seamless integration with the hybrid system's variable energy sources (Fig. 17. Tidal turbine active power, reactive power and voltage).

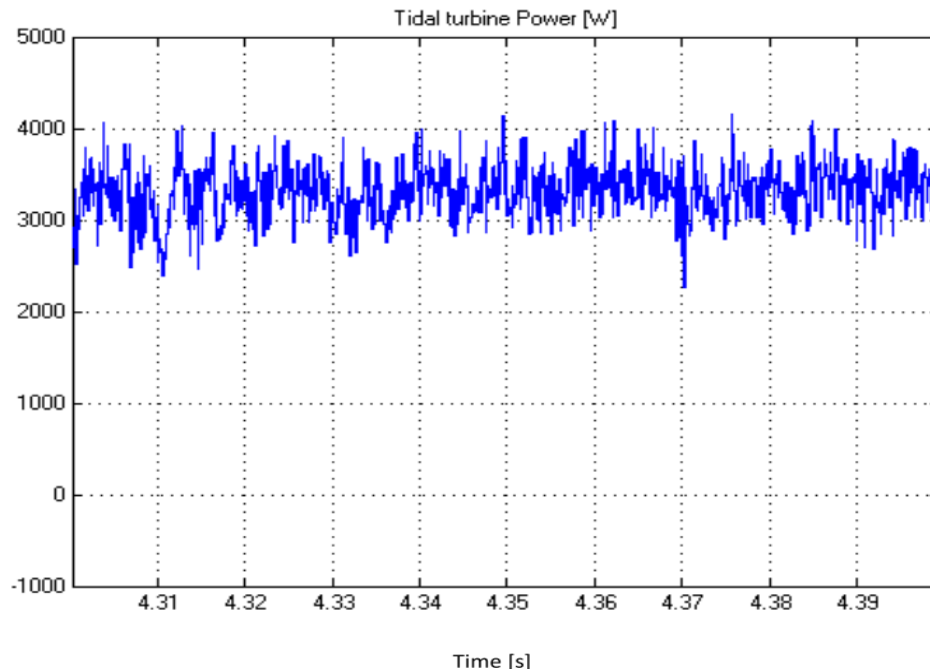


Fig.17. Tidal turbine active power, reactive power and voltage

5.11 Wind Power and Storage Integration:

Wind turbines contribute between 6-10 MW, depending on capacity factors, and are synchronized with tidal output through LCL filters and Phase-Locked Loop (PLL) synchronization. The 3 MW Battery Energy Storage System (BESS) with a capacity of 12 MWh compensates for the intermittency of tidal and wind generation, stabilizing the grid

during periods of peak demand (Fig. 18. Battery Voltage).

Figure 16 demonstrates the effectiveness of the PI regulator in maintaining stability even during abrupt changes in the tidal turbine's output. This ensures reliable grid-side converter operation, independent of the rotor-side converter. Comprehensive modelling and simulation of the key components—wind and tidal turbines, doubly-fed induction generators, and power converters—conducted in MATLAB/SIMULINK, validate the proposed control strategy, confirming stable performance under varying conditions.

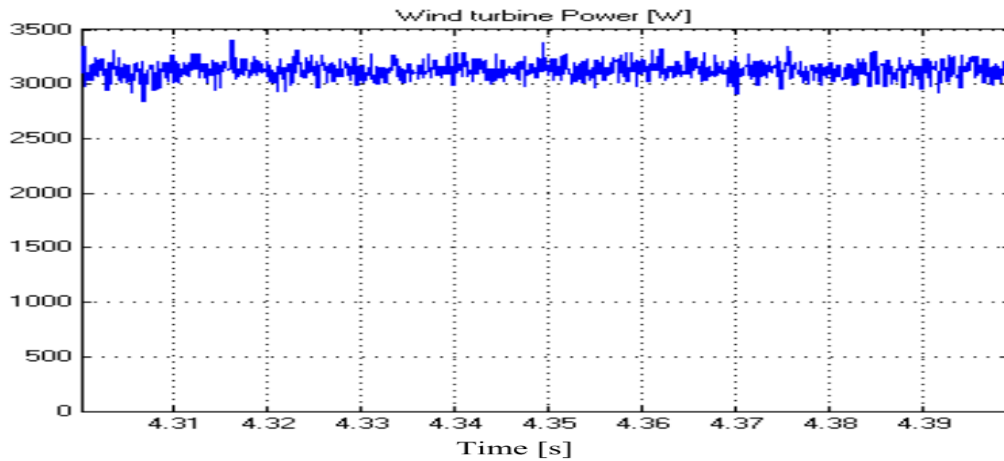


Fig.18.Offshore-wind turbine active power, reactive power and voltage

The regulated parameters of the grid-side converter, including active and reactive power control, ensure stable operation and smooth energy transfer from renewable sources to the grid (Fig. 19. Regulated Parameters of the Grid Side Converter).

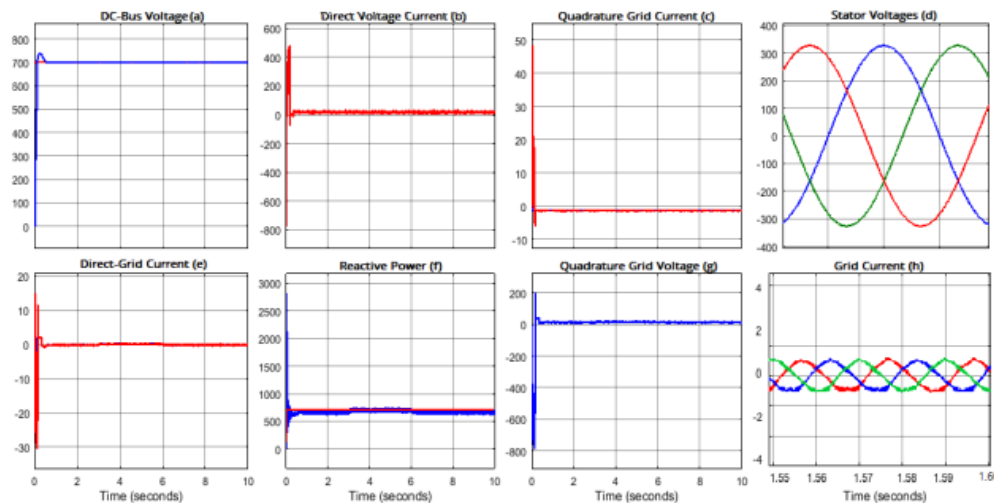


Fig. 19. Regulated Parameters of the Grid Side Converter

5.12 Inverter and Converter Adjustments:

The three-level Voltage Source Inverter (VSI) introduces harmonic distortion, but LCL filters mitigate these effects. Without filtering, the THD was recorded at 45.01%, emphasizing the critical role of LCL filters in maintaining power quality. Current Source Inverters (CSI) are also considered for their enhanced short-circuit protection, direct current control, and superior boosting capabilities, making them ideal for integrating wind and tidal systems in the Hybrid Offshore Tidal-Turbine (HOTT) system. The turbine power must match the PMSG's nominal capacity for optimal performance (Fig.20. Grid Side Converter for PMSG-Based Tidal Turbine).

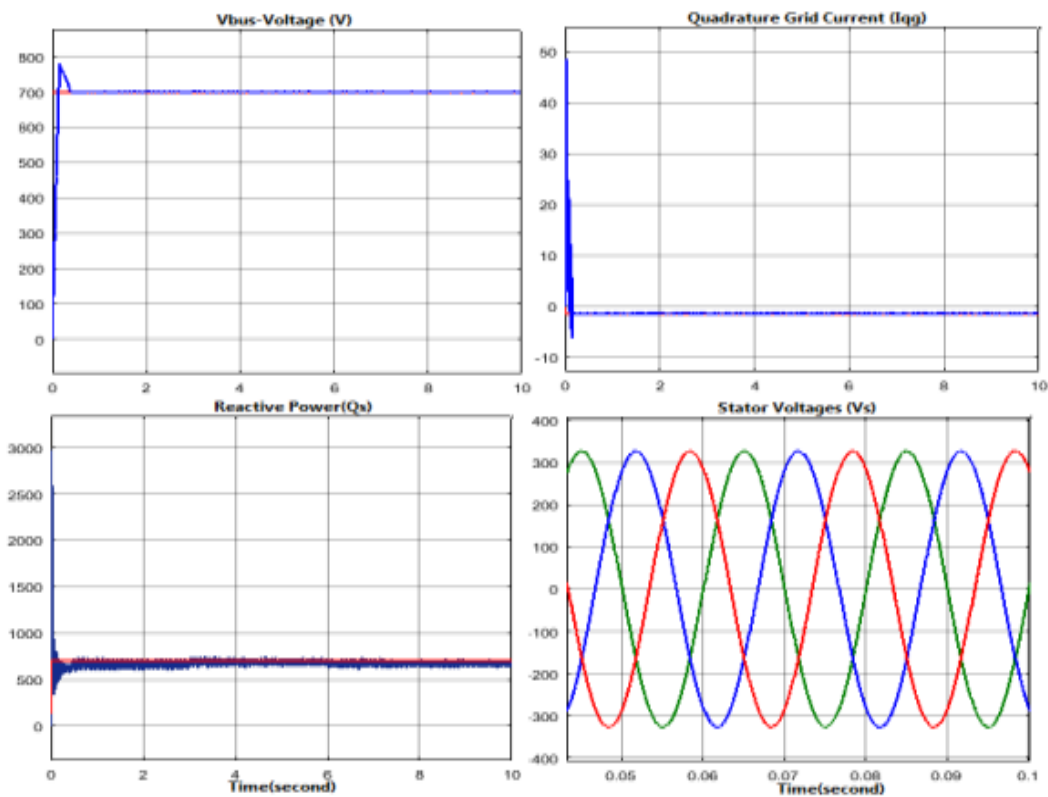


Fig.20. Grid Side Converter for PMSG-Based Tidal Turbine

6. Conclusion

This paper presented a robust energy management strategy for a hybrid micro grid system integrating renewable energy sources, demonstrating its effectiveness through diverse simulation scenarios. The developed control system successfully managed load demands in both islanded and grid-connected modes while ensuring the optimal operation of the Battery Energy Storage System (BESS) within the hybrid micro grid framework. The proposed Fuzzy Logic Controller (FLC) proved to be a highly effective strategy for offshore hybrid wind-tidal storage systems. MATLAB/Simulink simulations showed that the FLC efficiently coordinated power distribution among tidal and wind generators, the battery bank, and the load. The hybrid system consistently met load requirements, maintaining reliable battery charge during night-time and intelligently routing excess daytime energy from the tidal generator to the utility grid when the battery reached full charge. With its three input signals—hybrid power, demand, and state of charge (SOC)—the FLC leveraged a decision-making framework with 27 rule sets, employing the Centre of Gravity (COG) and Max-Min methods to manage energy flow effectively. The integration of the tidal generation system within the Hybrid Offshore Tidal-Turbine (HOTT) setup enabled the system to handle a 20 MW load demand efficiently. The inclusion of the BESS was pivotal in stabilizing power output, particularly for grid-connected scenarios. Fuzzy membership functions, designed to control the reference current (I_{ref}) and manage power output, demonstrated high efficiency in categorizing operational states into Low, Medium, and High outputs for both wind and tidal energy sources. The BESS adeptly mitigated short-term wind power fluctuations and addressed longer-term tidal energy imbalances, contributing to a stable and reliable energy supply. In conclusion, the FLC-based energy management strategy offers a resilient and adaptive solution for optimizing power generation and maintaining grid stability in hybrid renewable energy systems. Its demonstrated ability to handle the complexities of renewable power generation underscores its potential for future applications, enhancing energy quality and supporting large-scale renewable integration with improved system reliability and efficiency.

Author contributions: As the Corresponding Author: Ladislav Mutunda Kangaji, I confirm that all listed authors have read and approved the manuscript for submission. The first author, Ladislav Mutunda Kangaji, is designated as such due to his primary role in data acquisition, analysis, and the development of a practical, working energy management strategy testing model. Prof. Atanda Raji and Dr. Efe Orumwense are included as the second and third authors, respectively, in recognition of their vital contributions to project guidance, manuscript revision, and overall quality control.

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Ethical approval and consent to participate: The data collection for this project did not require participant consent as the research did not involve humans or animals.

Clinical Trial Number in the manuscript: Not applicable

Consent to Publish Declaration: not applicable.

Competing interests: The authors declare no competing interests that could have influenced the outcomes or interpretations of with this publication.

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CHAPTER ELEVEN: GENERAL CONCLUSIONS AND RECOMMENDATIONS

11.1. Work Summary

This dissertation provides a quantitative framework for the energy management of grid-connected hybrid offshore wind-tidal storage power systems. This framework emphasises the advancements in control, optimisation, and storage solutions to support grid reliability and economic feasibility. Battery storage is central in mitigating intermittency and enhancing load management, particularly beneficial for remote coastal areas. Cost of energy (COE) optimisation is addressed through array layout and battery configuration, achieving lower COE and ensuring minimal ecological disturbance.

Hydrodynamic modelling of South Africa's tidal resources using ROMS highlights high kinetic energy zones, with optimal sites yielding 20-45% energy capture while maintaining environmental integrity. Advanced PWM inverter controls with VOC and LCL filters, implemented via MATLAB/Simulink, ensure low harmonic distortion (<5%) and robust synchronisation with the grid, critical for efficient grid integration. Challenges, including high capital costs, environmental concerns, and the complexity of active/reactive power control and FRT requirements, are acknowledged. However, the integration of model predictive and AI-based control strategies with BESS offers promising solutions for stable, efficient power output. The study demonstrates that hybrid wind-tidal systems with BESS can meet peak loads and optimise energy distribution, with FLC enhancing system flexibility across diverse tidal and wind conditions.

The research underscores the complementary nature of tidal and wind energy – The research underscores the complementary nature of tidal and wind energy – where tidal generation provides a stable baseload and wind supplements energy production intermittently. Sensitivity analyses reveal the adaptability of hybrid systems for various coastal locations, with converter technology advancements facilitating cost-effective, environmentally responsible integration. Real-time control and predictive maintenance are identified as key to balancing ecological impact and grid compatibility. Overall, this dissertation establishes a rigorous model for the sustainable deployment of hybrid offshore systems, advancing South Africa's energy security and supporting broader renewable energy goals.

11.2. Recommendations

The primary main of this research project was to investigate the feasibility, operational efficiency, and economic viability of an offshore hybrid wind-tidal storage energy system integrated with a utility grid. The study focused on three system architectures: wind turbines, tidal turbines, and hybrid wind-tidal turbines. The study assessed the system's impact on

power output, correlating results with wind and tidal speed profiles. The statistical properties of these profiles suggest that hybrid systems could complement energy needs based on specific site conditions. The results emphasise the transformative potential of hybrid offshore energy systems, particularly the integration of wind and tidal power with advanced storage, control, and optimisation methodologies. Battery storage technologies are critical in stabilising renewable output, enhancing energy reliability, and reducing intermittency impacts on the grid. An in-depth analysis of battery performance demonstrates improvements in load management and economic viability for remote coastal communities, supporting the feasibility of implementing such systems in off-grid settings.

Optimisation of the energy array design, guided by cost-efficiency metrics, is central to minimising the overall COE. By employing economic models and advanced simulation tools, the study identified effective layouts for turbine arrays and optimal battery configurations, achieving significant COE reductions. This optimisation extends to the placement and operational strategy of tidal turbines, showing that strategic array design can maximise energy capture while minimising environmental disruptions, which is especially important in ecologically sensitive coastal areas.

Through numerical modelling of tidal stream energy potential, the dissertation evaluated resource availability and energy generation prospects along South Africa's coast. Using the regional ocean modelling system (ROMS) and validated hydrodynamic models, the study identified locations with high kinetic energy potential, effectively mapping zones for sustainable tidal energy extraction. Key findings reveal that optimal sites can yield power extraction rates between 20-45% of river kinetic energy, while careful management ensures that power generation does not disrupt local hydrodynamics. This approach is vital for accurately predicting long-term energy yields and supporting environmentally responsible turbine deployment.

The research advances grid-connected tidal power systems by implementing sophisticated PWM inverter control strategies. With VOC in a three-level inverter system combined with LCL filters, harmonic distortions were reduced to levels below 5%, enhancing power quality and system stability. Simulations in MATLAB/Simulink validate the controller's effectiveness in providing robust voltage control, precise grid synchronisation, and efficient reactive power management – key for large-scale grid integration. Overall, this dissertation provides valuable insights into hybrid wind-tidal systems' technical, economic, and environmental aspects, establishing a framework for coastal energy resilience in South Africa. This approach promotes marine renewables as a cornerstone of the country's sustainable energy future. However, the integration of grid-connected hybrid offshore wind-tidal storage systems remains challenging due to high capital costs, environmental concerns, and complex control system requirements. Technical and regulatory challenges, including grid code compliance and the

need for sophisticated active/reactive power control and FRT capabilities, are significant hurdles. Advanced converters and control techniques such as VOC and FLCs with BESS are essential to ensure stable and high-quality energy output. These control strategies aim to optimise energy conversion, reduce harmonic distortion, and maintain stability under variable conditions – crucial for both wind and tidal energy generation. Emerging trends in control theory, including model predictive and AI-based controls, further enhance system reliability and adaptability. Despite the promise of these innovations, the high initial investment for offshore systems – particularly in HVDC transmission and hybrid configurations – remains a barrier. As offshore farms move into deeper waters, HVDC transmission is expected to provide an efficient solution for grid integration, though further research on DC collection systems is needed. Balancing environmental impacts on marine ecosystems with grid compatibility through real-time control and predictive maintenance is also essential. Future research should prioritise cost reduction strategies, improved grid integration, and comprehensive environmental assessments to support the sustainable expansion of offshore hybrid systems. The integration of hybrid offshore wind-tidal energy systems for both grid-connected and off-grid applications offers a promising solution to meet South Africa's coastal energy demands. Combining wind and tidal energy addresses renewable energy intermittency and enhances reliability. In off-grid setups modelled for South African coastal cities, hybrid systems with diesel backup demonstrated reduced greenhouse gas emissions and environmental impact, supporting sustainability goals. Using HOMER Pro, the research identified optimal configurations that balance renewable fractions and minimise the net present cost (NPC). For grid-connected systems, as seen in Buffels Bay, hybrid setups with energy storage optimise costs and environmental impact, reducing CO₂, SO₂, and NO_x emissions. Tidal energy provides a stable base load, while wind energy, though intermittent, supplements output when available, highlighting the complementary nature of these two renewable energy resources. Sensitivity analyses demonstrated the hybrid system's flexibility across varying wind and tidal conditions, allowing tailored solutions for specific locations. Advancements in converter technology and system scalability are key to improving the cost-effectiveness and environmental viability of marine renewable energy systems, contributing to South Africa's energy security and sustainable development goals.

Future work and perspectives

1. **System optimisation:** future research should focus on optimising system performance under diverse environmental conditions. Developing advanced AI-based algorithms for real-time energy management, alongside improvements in storage optimisation, can enhance the system's responsiveness to generation fluctuations, improving efficiency and reliability.
2. **Expansion of hybrid systems:** this research demonstrates the potential for hybrid system replication in various coastal communities in South Africa. Expanding studies to different regions with unique wind and tidal conditions could help maximise energy generation and create tailored solutions for regional needs. The scalability and adaptability of hybrid systems across diverse geographies should be explored.
3. **Grid integration considerations:** research should explore the feasibility of integrating offshore hybrid systems with existing power grids, especially in areas with intermittent renewable generation. This requires a comprehensive understanding of grid stability, transmission technologies, and energy management strategies to maximise hybrid system benefits.
4. **Policy and funding support:** successful deployment of hybrid systems depends on policy support and financial incentives. Government-backed initiatives, such as subsidies, grants, and public-private partnerships, are critical to lowering capital costs and encouraging investment in renewable energy infrastructure.
5. **Environmental and ecological impact assessment:** large-scale deployment must be preceded by thorough environmental impact assessments, especially in ecologically sensitive areas. Ongoing monitoring and mitigation measures will help maintain ecological balance while advancing renewable energy goals.
6. **Advanced control systems:** continued development of advanced control systems, such as predictive maintenance using AI, should be prioritised. These innovations can improve operational efficiency, reduce downtime, and enhance reliability. Smart grid technologies and system diagnostics can further optimise performance and reduce maintenance costs.

Through addressing these technical, economic, and environmental factors, this research provides a strategic framework for the advancement of offshore hybrid wind-tidal energy solutions, with the potential to significantly contribute to the global transition toward sustainable, low-carbon energy systems.