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REVIEW

Different Types of Electrical Generators for Converting Wave Energy into Electrical Energy–A Review

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Abstract

This review paper examines the various types of electrical generators used to convert wave energy into electrical energy. The focus is on both linear and rotary generators, including their design principles, operational efficiencies, and technological advancements. Linear generators, such as Induction, permanent magnet synchronous, and switched reluctance types, are highlighted for their direct conversion capability, eliminating the need for mechanical gearboxes. Rotary Induction generators, permanent magnet synchronous generators, and doubly-fed Induction generators are evaluated for their established engineering principles and integration with existing grid infrastructure. The paper discusses the historical development, environmental benefits, and ongoing advancements in wave energy technologies, emphasizing the increasing feasibility and scalability of wave energy as a renewable source. Through a comprehensive analysis, this review provides insights into the current state and future prospects of electrical generators in wave energy conversion, underscoring their potential to significantly reduce reliance on fossil fuels and mitigate environmental impacts.

Keywords Wave energy; Rotary generators; Linear generators; Control systems; Wave energy converters

1 Introduction

Wave energy derived from the kinetic and potential energy of ocean waves offers a sustainable solution to the present energy crisis. This form of energy is particularly promising due to the ocean's vast and untapped energy potential. Unlike solar and wind energy, wave energy provides a more consistent output, as ocean waves are continuously generated by winds, gravitational effects, and geological activities (Guo and Ringwood, 2021).

The environmental benefits of wave energy are significant. It produces no air pollution or greenhouse gases, making it a cleaner alternative to fossil fuels, which are major contributors to environmental issues like climate change and air pollution (Mwasilu and Jung, 2019).

Technological advancements have improved the efficiency of wave energy converters, which transform the energy of ocean waves into electrical energy. These innovations have increased the feasibility of wave energy as a scalable and effective renewable energy source (Rahm et al., 2012).

Historically, interest in wave energy surged during the 1970s following the global oil crises, emphasizing the need for alternative energy sources. This period marked a significant increase in research and development efforts aimed at harnessing ocean wave power (Cruz et al., 2010). The first substantial commercial application came in the 1960s when Japanese inventor Yoshio Masuda developed oscillating water column devices for navigation buoys, marking a milestone in the commercial use of wave energy (Binh et al., 2016). Nowadays, wave energy technology continues to evolve, driven by global demand for renewable energy and supported by governmental and private sector investments.

Scotland and Japan are leaders in wave energy technology,

Article Highlights

- The article has discussed Linear and rotary generators that are used for converting wave energy into electrical energy, and their design principles, operational efficiencies and technological advancements are explained.
- The article provides a brief discussion for proper control system, because control systems ensure that the generator operates within safe and optimal conditions, maximizing energy extraction and lifespan.
- The paper has also provided a detailed table to compare the efficiency, rated power and excitation type of the existing generators for wave energy conversion.

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hosting several operational projects that highlight the technology's potential in contributing to a sustainable energy future (Friedrich and Lavidas, 2017). The ongoing development and increasing efficiency of wave energy conversion technologies hold promise for significantly reducing our reliance on fossil fuels and mitigating environmental impacts, positioning wave energy as a vital component of the global renewable energy portfolio.

As illustrated in Figure 1, the conversion of wave energy into electrical power involves a series of transformative steps. Initially, the kinetic and potential energy of ocean waves is captured by a mechanical converter system, which converts these natural movements into mechanical energy. This mechanical energy then drives an electric generator, converting the mechanical energy into electrical energy. Subsequently, an electrical converter system adjusts the electrical output to ensure compatibility with the power grid, modifying current type, voltage, and frequency as needed. Finally, this conditioned electricity is transmitted to the power grid, ready for distribution and use across various sectors.

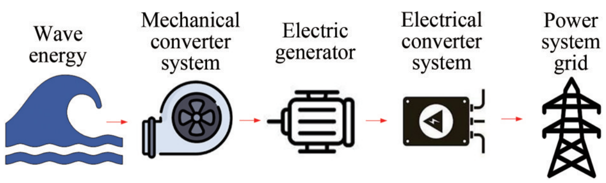

Figure 1 Wave energy conversion system

Ocean waves can be generated by various mechanisms, including wind blowing over the surface of the ocean. The velocity of these waves depends on the wavelength (λ) and the depth of the ocean (h), which is described by the following dispersion relation (Wang et al., 2018):

$$v = \sqrt{\frac{g\lambda}{2\pi}\tanh\left(\frac{2\pi h}{\lambda}\right)} \quad (1)$$

where g is the acceleration due to gravity. About 95% of wave energy is available between the surface and a depth equal to a quarter of the wavelength for deep water. The total energy per unit width below one wavelength of the ocean surface is given by (Wang et al., 2018):

$$E = \frac{1}{\lambda}\int_0^{\lambda}\int_0^1 \frac{1}{2} g\rho\eta^2 \mathrm{d}x\mathrm{d}y + \frac{1}{\lambda}\int_0^{\lambda}\int_0^1\int_{-\infty}^0 \frac{1}{2}\left(v_x^2 + v_y^2 + v_z^2\right)\mathrm{d}x\mathrm{d}y\mathrm{d}z \quad (2)$$

where ρ is the ocean water density, η is the wave elevation, and v_x, v_y, and v_z are the velocities in the x, y, and z directions, respectively (Wang et al., 2018).

The ocean surface waves driven by the wind are irregular and vary in height and period. One method to describe these irregular waves is via Fourier series with random phases. The Pierson–Moskowitz spectrum and the Jonswap spectrum are tools to match wave data under different conditions (Falnes, 2007). The Bretschneider spectrum, used for average sea conditions, is defined as follows (Wang et al., 2018):

$$s(\omega) = \frac{5}{16} H_s^2 \omega_0^2 \omega^{-5} e^{-5/4(\omega_0/\omega)^4} \quad (3)$$

where ω is the angular frequency, ω_0 is the modal frequency, and H_s is the significant wave height. The energy of unit area of sea surface in the irregular case is expressed as follows (Wang et al., 2018):

$$E = 2\rho g \int_0^{\infty} S(f)\mathrm{d}f \quad (4)$$

where f is the frequency in Hertz.

Figure 2 depicts a detailed diagram of a wave energy converter, specifically a point absorber type. This device captures the vertical motion of wave energy through its main component, the heaving buoy. The buoy's vertical movements are transferred via a connecting rod to the generator's mover, which is located within a supporting frame. As the mover ascends and descends, it induces movement in coils located around a fixed stator of generator, a crucial part of the electromagnetic generator. The interaction between the moving coils and the stator generates electrical energy. Additionally, a drag plate is attached at the bottom to stabilize the device and enhance the energy capture by increasing resistance against water movement. This setup efficiently converts the mechanical energy of ocean waves into usable electrical energy.

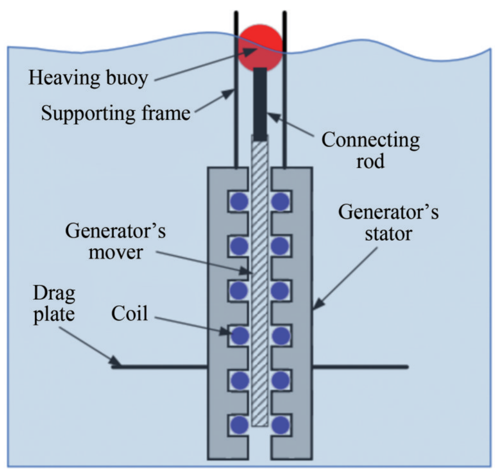

Figure 2 Schematic structure of linear converter

This paper explores the diverse array of electrical generators employed in wave energy conversion systems, as illustrated in Figure 3. The figure categorizes the generators into two main types: linear generators and rotary generators. Under the linear generators category, various subtypes including induction, permanent magnet synchronous, reluctance, vernier, superconducting synchronous will be examined.

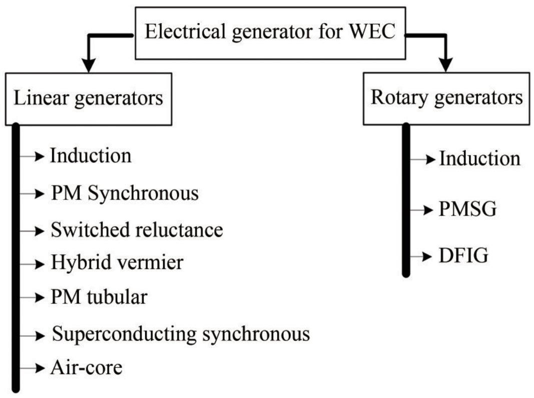

Figure 3 Generators used in wave energy converter

Each of these subtypes offers unique benefits and challenges in harnessing wave energy. Similarly, the rotary generators category encompasses subtypes such as induction, PM synchronous generator (PMSG), doubly-fed induction generator (DFIG), and Vernier generator. The detailed analysis of the above-mentioned generators will provide insights into their operational principles, efficiency, technological advancements, and application potentials in wave energy conversion. This structured approach will facilitate a comprehensive understanding of the current state and future prospects of electrical generators in the realm of wave energy.

2 Linear generators

Linear machines are part of a unique class of electric machines that directly convert electrical energy into kinetic energy (and vice versa) through linear motion without intermediaries (Kondelaji et al., 2021; Vatani et al., 2022; Ghaffarpour et al., 2023). These machines, which have been commercially available for various applications, trace their origins back to 1841 when the first proposal for linear machines was registered (Laithwaite, 1975). Between 1895 and 1940, linear induction motors were employed in the textile industry, and by 1905, they were being considered for transportation. Notably, the Westinghouse Company in 1945 used a linear induction motor to accelerate an aircraft, showcasing the potential of these machines in high-speed applications (Laithwaite, 1975). Over the subsequent decades, linear induction motors found additional applications, including in atomic reactor pumps in the 1950s and in steel industries in the 1960s. The 1970s saw a surge of interest in high-speed transportation systems utilizing magnetic levitation driven by linear motors (Polinder et al., 2005).

Linear generators, a subset of linear machines, are designed to convert mechanical energy from linear motion into electrical energy efficiently. One of the significant advantages of linear generators is their ability to produce linear motion directly, eliminating the need for gearboxes and thus, enhancing reliability and reducing noise and costs compared to rotating machines. However, challenges such as the inherent large air gaps and lower efficiency have hindered their widespread development. Despite these drawbacks, advancements in digital electronics, power electronics, and PMs are paving the way for newer and more innovative applications of linear generators, particularly in the field of wave energy conversion.

Figure 4 illustrates the structure of single-sided and double-sided linear generators, highlighting their design variations. The single-sided generator shown in Figure 4(a) consists of a stator and a mover with coils placed on one side, while the double-sided generator Figure 4(b) features coils on both sides of the mover, which can enhance performance and efficiency by balancing the magnetic forces more effectively.

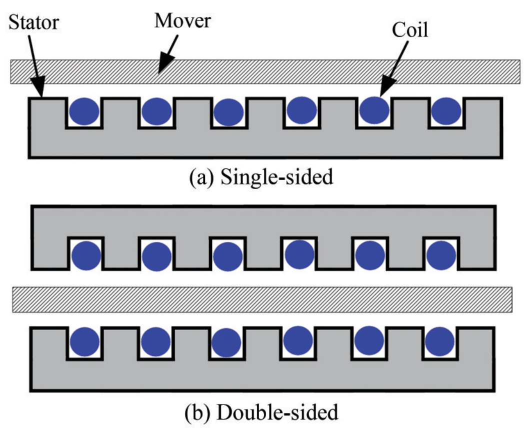

Figure 4 Linear generator structures

Linear generators offer several advantages, such as high acceleration, low tire wear, and easy maintenance, making them suitable for harsh environmental conditions. The ability to apply force without mechanical contact, easier speed and power control, and high endurance in adverse conditions are among the several advantages that make linear generators a promising technology for sustainable energy solutions (Boldea, 2013; Faiz et al., 2020). However, the wide air gaps in their design can lead to lower efficiency and increased leakage reactance, impacting their performance. Despite these challenges, the potential for linear generators in applications requiring precise linear motion and the growing interest in renewable energy sources underscore their importance. As the technology continues to evolve, linear generators are expected to play a crucial role in the future of energy conversion, particularly in harnessing wave energy (Nie et al., 2024).

2.1 Linear induction generators

Linear induction generators (LIGs) represent a significant advancement in the field of wave energy conversion technologies. Unlike traditional rotary generators, LIGs operate based on the principle of electromagnetic induction in a linear motion, which aligns well with the direct movement of ocean waves. This alignment allows for a more straightforward mechanical design by eliminating the need for complex transmission systems required to convert rotary motion to linear motion, thereby enhancing the overall mechanical reliability and reducing maintenance costs. One of the key advantages of using LIGs in wave energy systems is their robust design, which lacks slip rings and collectors, making them less expensive and more durable compared to other types of generators. It has been pointed out in (Wells et al., 2001) that the absence of these components not only reduces the initial costs but also decreases the operational complexities of the wave energy conversion systems.

However, LIGs are not without their challenges. One of the primary issues is the requirement for a high excitation current that stems from the low reactance of the windings. This necessity can significantly impact the energy conversion efficiency (Gargov et al., 2012). The large air gaps typically present in LIG configurations, whether flat, tubular, single-sided, or double-sided, further exacerbate this inefficiency by reducing the magnetic coupling between the stator and the moving parts. Despite these drawbacks, ongoing research and development are addressing these issues. For instance, the use of a linear Faraday induction generator that optimizes the electrical energy output by enhancing the relative motion between the stator and the rotor, has been detailed in (Phillips, 2014), thus attempting to mitigate some of the inefficiencies caused by wide air gaps and high excitation currents.

Further advancements in the control methods for LIGs demonstrate promising developments in improving their operational efficiency and adaptability. A novel normalized control algorithm specifically has been designed in (Kalla et al., 2014) for voltage control in self-excited induction generators This innovation is pivotal for maintaining stable voltage output in fluctuating load conditions commonly encountered in marine environments. Moreover, the structural robustness and minimal cogging force of LIGs indicate their suitability for harsh oceanic conditions (Trapanese et al., 2017). Cogging force, which can cause operational jerks and reduce the lifespan of the generator, is significantly lower in LIGs, making them more desirable for continuous operation in wave energy conversion (Di Dio et al., 2007). The ongoing research and experimental setups, such as the large-scale direct-drive linear generator test bench underscore the potential and commitment towards refining this technology for better efficiency and reliability in harnessing ocean wave energy (Baker et al., 2007).

2.2 PM Linear synchronous generators

PM linear synchronous generators (PMLSGs) represent a significant advancement in the technology used for converting wave energy into electrical energy. These generators are designed with multiple configurations and control strategies to optimize the energy conversion process in marine Recent studies have provided important empirical data that confirm the effectiveness of these generators under varying oceanic conditions. It specifically highlights the robust performance of double-sided linear PMLSGs, emphasizing their superior power generation capabilities in both regular and irregular wave environments (Seo et al., 2020). The primary components of linear PM generators (LPMGs) include PMs and coils. These generators can be categorized based on various design methodologies, such as structure, translator size and location, stator shape, core type, positioning of the PM, flux path, and installation method of the PM. The structure of the LPMG may be tubular or planar/flat (Wahyudie et al., 2017). Fabricating planar-type linear generators for wave energy converters (WECs) is relatively straightforward. These generators can be fabricated with different configurations, including two-sided, four-sided, octagonal, or multi-sided planar designs (Wahyudie et al., 2017). A hybrid generator concept has also been proposed, combining double-sided planar layouts with tubular designs, resulting in higher force density due to more effective space utilization (Joseph and Cronje, 2007).

In LPMGs for direct-drive WECs, different translator sizes and positions have been applied. The reciprocating linear motion requires either the translator or the stator to be longer to ensure continuous generation throughout the stroke. Typically, the PM translator is longer than the stator to keep the entire stator winding active during the stroke, thereby reducing series copper and conduction losses (Prudell et al., 2010). The translator can be mounted internally or externally in the generator design (Liu et al., 2014).

There are three primary methods for attaching PMs: axially aligned-buried, radially aligned-buried, and radially aligned-surface (Joseph and Cronje, 2007). To achieve maximum magnetic flux density, Halbach and quasi-Halbach arrays have been utilized in LPMGs for WECs (Liu et al., 2014). Linear generators can also be classified as transverse or longitudinal based on the location of windings relative to the translator's motion (Khatri and Wang, 2020). A novel hybrid transverse/longitudinal flux LPMG has been developed, employing both transverse and longitudinal flux (Vining et al., 2009). This design features a translator sandwiched between two stators carrying flux in the longitudinal direction, while the translator carries flux in the transverse direction. Both slot less and slotted stators have been investigated to identify the best generator design

(Tan et al., 2018).

The structure of PMLSGs often features a segmented stator; this segmentation helps to approximate the rotating structure found in tubular generators more accurately. A higher number of stator sections not only enhances this approximation but also helps in reducing the leakage inductance at the edges, thus improving the overall efficiency of the generator. However, designing these generators presents its challenges, particularly in the arrangement and fabrication of windings, which increases production costs, albeit still remaining lower than those of their tubular counterparts (Vining and Muetze, 2007).

LPMGs can be classified as iron-core or air-core based on their core structure. Both types have been utilized in direct-drive power take of (PTO)-based WECs (Ran et al., 2011). The use of air gap winding in PMLSGs eliminates the use of iron in the rotor, reducing the attractive forces between the rotor and the stator. These forces, while reduced, can still be significant and pose design challenges, especially over the long stator teeth (Vining and Muetze, 2007).

The excitation in PM synchronous generators is provided by PMs, which move synchronously with the magnetic fields and the translator. This synchronization is crucial in applications like the Archimedes wave swing (AWS), where such generators have been effectively employed. The design of these generators often includes innovative control mechanisms, such as the proportional differentiation (PD) controller, which enhances the control over the linear synchronous machine, thereby optimizing performance (Polinder et al., 2004; Sun et al., 2015).

Recent advancements have also seen the use of linear tubular PM generators (LTPMGs) with an iron-cored stator, which, while increasing harmonic content in the induced voltage, offers robust performance under marine conditions. Additionally, hybrid designs combining the features of transverse and longitudinal flux machines have been developed. These designs leverage the magnetic coupling of longitudinal flux machines with the high force density of transverse flux machines, offering a compact and efficient solution for WEC (Danielsson, 2006; Vining et al., 2009).

Moreover, the implementation of double-sided flux concentrators in synchronous generators has proven to enhance flux dispersion, which is a significant improvement over single-sided design. Such configurations not only improve the magnetic performance but also reduce the load on bearings, making the system more durable and efficient (García-Alzórriz et al., 2011). A noteworthy development in the field is the self-synchronous maximum power controller, which has been observed to maximize power output in doubly-fed field-wound machines. This controller optimizes the power extraction based on real-time dynamics, demonstrating the potential for enhanced energy conversion efficiencies in wave energy applications (Vining et al., 2010). Consequently, PMLSGs are at the forefront of technology for converting wave energy into electrical energy. With ongoing research and development, such as the innovative approaches detailed in (Seo et al., 2020) these generators continue to see improvements in design, efficiency, and application, making them a vital component in sustainable energy solutions.

2.3 Linear switched reluctance generators

Switched reluctance machines (SRMs) are a type of electric machines known for their simple structure, robustness, and low manufacturing cost. They operate based on the principle of varying reluctance, where torque is developed by the tendency of the rotor to move to a position where the inductance of the excited winding is maximized. However, SRMs typically suffer from issues such as low torque density and high torque ripple (Ma et al., 2008). To address these drawbacks, PM-SRMs have been introduce which incorporate PMs into the stator or rotor structure to enhance performance characteristics such as torque density and efficiency (Du et al., 2010; Pan et al., 2013; Ghaffarpour and Mirsalim, 2021; Kondelaji et al., 2021; Ghaffarpour and Mirsalim, 2022; Vatani et al., 2022; Ghaffarpour et al., 2023).

Linear switched reluctance generators (LSRGs) share several characteristics with switched reluctance rotating generators. Both types utilize the principle of magnetoresistive minimization, which enhances the reliability of these machines over linear induction machines (Ma et al., 2008; Calado and Mariano, 2012). This robustness is particularly beneficial for ocean WEC applications. LSRGs are known for their high efficiency and simple construction, traits that have also made SRGs favorable for variable speed WEC systems (Vijay Babu et al., 2016). Reviews of SRMs indicate that these machines offer a cost-effective solution for small-scale rural applications (Vijay Babu et al., 2016). The fundamental structure of a double-sided LSRG operating via a power electronics converter controlled by rotor position, facilitates efficient energy conversion (Ma et al., 2008; Calado and Mariano, 2012). In operation, the active stator poles of LSRGs attract rotor poles, with current switching to the next phase via power electronic switches when the stator and rotor poles align optimally (Vijay Babu et al., 2016). This process, managed by the power electronic converter, drives the rotor efficiently and keeps manufacturing costs low due to the absence of permanent magnets. LSRGs also deliver high torque output and exhibit low inertia. Despite these advantages, their practical implementation has faced challenges, primarily due to the need for highly accurate and efficient power electronic switches and controllers.

Recent advancements have successfully reduced output voltage ripples and enhanced the efficiency of LSRGs, as evidenced in (Du et al., 2010; Pan et al., 2013). Modeling techniques using matrix and tensor approaches have further validated the potential of these generators through finite element analysis (FEA), underscoring their viability WEC (Du et al., 2010). Figure 5 shows a view of the PM excited cross flux generator.

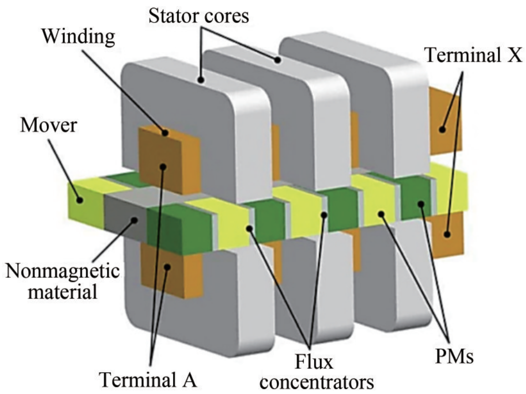

Figure 5 TFPM working principle. 3D-view of a double-sided TFPM with two sets of U-shaped stator cores (Sun et al., 2018)

2.4 Hybrid vernier generator

Hybrid Vernier generators, a subset of variable reluctance machines, are increasingly being explored for their potential in WEC. These machines are known for their low power factor, an issue that can be mitigated by incorporating auxiliary DC field excitation windings (Ching et al., 2016). The concept of Vernier machines with hybrid excitations has been elaborated by researchers, demonstrating characteristics typical of both rotational Vernier PM machines and consequent pole PM machines (Liu et al., 2011; Chau, 2015). Another notable approach involves the development of linear doubly-salient HTS machines, which offer higher power density, lower cogging force, and improved overall system efficiency compared to conventional machines (Du et al., 2011). A new linear Vernier hybrid PM generator design featuring E-core stators and a segmented chamfered translator has also been introduced, offering improved magnetic flux density and a higher back EMF compared to traditional C-core models (Raihan et al., 2017; Baker et al., 2018).

Recent advancements include the development of a dynamic model for a linear Vernier hybrid machine, which has been coupled with a wave energy emulator test rig (Mueller et al., 2006; Baker et al., 2018). Additionally, a novel cylindrical Vernier hybrid machine topology has been proposed for wave energy applications, showing enhanced performance due to superior magnetic flux paths and reduced translator mass (Mueller et al., 2006; Raihan et al., 2017; Baker et al., 2018). Analytical modelling techniques have been employed to compare surface-mounted and consequent-pole linear Vernier hybrid machines, revealing that consequent-pole designs can improve performance despite using less PM material (Botha et al., 2021). By optimizing parameters such as gear ratio and magnet shape, the proposed machine increases induced voltage, PM flux, and thrust force by 30%, 68%, and 27%, respectively, compared to traditional designs (Arish and Teymoori, 2020). Furthermore, a new linear PM Vernier machine structure designed for WEC has shown significant improvements in efficiency and performance (Arish and Teymoori, 2020). Optimization techniques such as genetic algorithms and neural networks can further enhance the performance of these machines (Toba and Lipo, 2000; Raihan et al., 2017).

This type of machine, while distinct from the reluctance PM machine family, is much simpler in terms of construction. Figure 6 shows a view of hybrid Vernier generators, in which the stator consists of C-shaped cores placed in pairs opposite each other, with each pole of the stator holding a coil. In the Vernier machine, the magnet is positioned in the fixed part of the machine, opposing the teeth of the moving part. Due to the arrangement of the magnets, two magnetic flux lines circulate around the C-shaped stator (Mueller and Baker, 2005). Despite the construction complexity of Vernier hybrid generators, their design offers some advantages. However, the 3D structure of these generators makes it impossible to laminate the ferromagnetic cores. Additionally, magnets tend to be placed in the path of least reluctance, resulting in significant cogging force. The high leakage flux in these generators causes a decrease in the power factor, necessitating a compensator to improve it. Furthermore, the large attraction forces between the translator and the stator and their distribution in the teeth are other disadvantages of these generators.

Moreover, novel optimal structures, such as a staggered tooth modular structure has been introduced in (Zhao et al.,

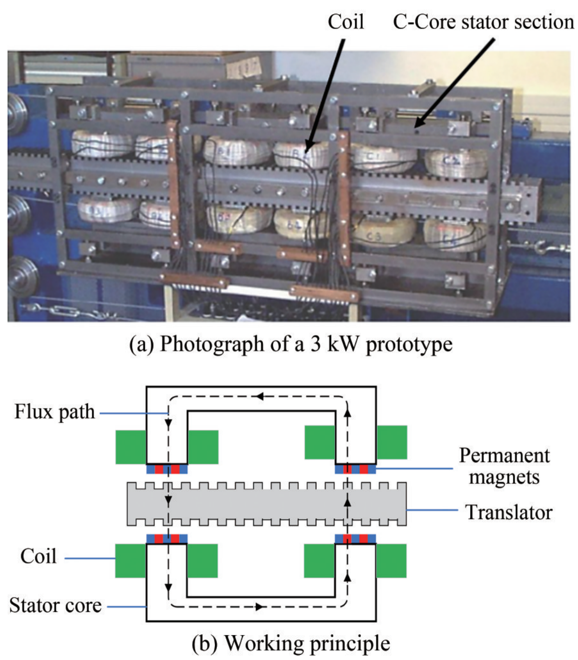

Figure 6 Vernier hybrid machine (Mueller and Baker, 2005)

2023) to reduce cogging force and improve output efficiency using a multi-objective optimization based on response surface models and particle swarm optimization algorithms. Additionally, the use of high-temperature superconductors (HTS) in dual stator linear Vernier machines has been shown to significantly increase back-EMF, air gap flux density, power factor, and thrust force, while reducing inductance (Ardestani et al., 2020). The adoption of hybrid-excited doubly salient PM linear machines with DC-biased armature current has also shown promise, significantly improving thrust force density and efficiency (Shen et al., 2021).

Furthermore, the integration of HTS bulks in tubular linear magnetic gears has demonstrated significant reductions in flux leakage and improvements in thrust force transmission capacity, making them highly effective for wave energy applications (Li et al., 2010b). Compared to pole-splitting PM Vernier machines, hybrid Vernier machines are noted for their reduced cost and overall weight (Li et al., 2010a; Chung et al., 2012).

2.5 Linear PM tubular generator

The operating principle of the PM tubular linear machine is based on electromagnetic induction, which involves generating an EMF across an electrical conductor within a changing magnetic field (Brooking and Mueller, 2005). These machines, particularly those using dual Halbach arrays, operate according to the Lorentz force law, where force is produced by the interaction of magnetic fields from PMs and current-carrying conductors. However, manufacturing these PM generators presents certain challenges, such as ensuring the translator remains perfectly aligned due to the perpendicular force to the translator's motion direction. Neodymium magnets (NdFeB) are commonly used due to their high magnetic field strength, although their costs have increased significantly over the recent years. Additionally, PMs tend to demagnetize over time, presenting a drawback (Brooking and Mueller, 2005). To address this, superconductor magnets with superconducting coils have been proposed as a promising solution, utilizing superconducting materials for core windings to reduce core losses (Farrok et al., 2016; Molla et al., 2019).

High-grade ferromagnetic cores, such as Armco DI-MAX M27 and DI-MAX HF 10, are employed in HTS linear generators to further minimize energy dissipation due to core losses. A direct-drive PM HTS linear generator (HTSLG) has been proposed, incorporating high-grade DI-MAX HF 10 cores to prevent temperature rise by reducing core loss during power generation (Molla et al., 2019). Using materials like Vitroperm 500F and supermendur magnetic cores can enhance power output and magnetic field intensity compared to conventional steel cores. N52 PMs, which possess the highest magnetic remanence, are also used to maximize efficiency (Molla and Farrok, 2019). Furthermore, different coil shapes have been explored to improve output power, with triangular coils proving more efficient than square ones (Memon et al., 2017).

Tubular PM linear generators, which consist of armature winding, iron core, PMs, and field winding, can be optimized through various design techniques. For instance, employing a long translator can reduce copper wire losses and improve system efficiency (Si et al., 2014). Utilizing a square-shaped cross-section for the stator also contributes to maximizing magnetic flux density (Boroujeni et al., 2009). While iron-cored generators generally exhibit higher induced voltage, air-cored machines eliminate iron losses and simplify mechanical design, though they typically produce lower power output (Mueller et al., 2008; Hamim et al., 2014). Experimental tests have shown that air-cored machines deliver advantages in mechanical design, despite lower power output compared to iron-cored machines (Mueller et al., 2008). Figure 7 illustrates the structure of a typical tubular PM generator, highlighting the arrangement of coils, magnets, and the translator within the stator yoke, which is crucial for efficient energy conversion (Azhari et al., 2021).

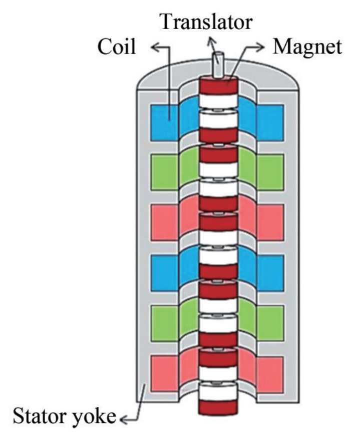

Figure 7 Tubular permanent magnet generator (Azhari et al., 2021)

Recent developments include the use of variable air gaps in linear generators to prevent demagnetization and enhance electrical power generation under identical operating conditions (Huang et al., 2014).

Power electronics devices are essential for interfacing these generators with the power grid, ensuring the output voltage aligns with grid specifications. Comparisons between linear tubular and four-sided PM generators have shown that while both types exhibit similar performance in terms of induced voltage and magnetic flux density, four-sided generators are heavier and incur higher friction losses.

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voltage aligns with grid specifications. Comparisons between linear tubular and four-sided PM generators have shown that while both types exhibit similar performance in terms of induced voltage and magnetic flux density, four-sided generators are heavier and incur higher friction losses (Huang et al., 2012). Additionally, tubular superconducting flux-switching PM generators have been found to produce minimal cogging force compared to linear Vernier hybrid and linear flux-switching machines (Huang et al., 2014). Various experimental and simulation studies, including FEA, have been conducted to optimize the design and performance of these generators (Huang et al., 2012; Sinnadurai et al., 2018). Multi-level design optimization methods have also been employed to further enhance the electromagnetic performance of tubular LPMGs, considering factors such as power density, thrust ripple, and total harmonic distortion (THD) (Liu et al., 2023). A novel single-phase tubular PM linear generator for Stirling engines has also been proposed, showing high power density and low harmonic distortion, making it suitable for small-volume applications (Chen et al., 2020).

2.6 Superconducting linear synchronous generators

Another alternative to LPMG in direct drive conversion of wave energy is the linear synchronous generator with field excitation winding. However, if copper winding is used to excite the generator, the air gap current density and therefore the power density decreases due to the limited current density of the copper. Superconducting materials provide high current density when the temperature is below a certain point called the critical temperature. Another attractive feature of superconducting materials is their negligible magnetic permeability due to the Meissner effect. Therefore, superconducting materials are used as magnetic insulators (Li et al., 2010a). The discovery of HTS led to cheaper cooling systems that use liquid Nitrogen instead of expensive liquid Helium. Recently, linear superconducting generators have been proposed for DD-WEC application. The excitation field current of these machines can be controlled in such a way that the power density increases and the voltage regulation decreases. For instance, a tubular superconducting flux-switching generator (TSFSG) has been proposed, where the magnetic circuit is closed due to the arc structure of the coils, minimizing magnetic leakage flux (Huang et al., 2014). The superconducting material magnesium diboride (MgB2) has been used for both the excitation coil and armature coil parts of this machine, offering advantages such as low cost, simple structure, and small bending radius. MgB2 is a medium-temperature superconductor that provides a current density higher than 10^4 A/cm^2 under magnetic flux density lower than 2 T. Additionally, the electrical resistance of MgB2 is almost zero at the critical temperature below 40° K. This temperature is lower than the boiling point of Nitrogen 77.2° K, necessitating the use of liquid Hydrogen, with a boiling point of 14° K, for cooling.

Yttrium Barium Copper Oxide (YBCO) HTS material is proposed for use in a tubular HTS generator with an external transducer, owing to its standard temperature of 93° K, which allows for a simple and relatively inexpensive cooling system using liquid Nitrogen (Du et al., 2011). Despite its higher cost compared to MgB2, YBCO offers significant advantages. For instance, a double-sided superconducting linear generator with YBCO tape windings significantly reduces higher harmonics in the voltage waveform, enhancing the quality of the air-gap magnetic field (Li et al., 2021).

Recent developments also include the dual-stator HTS modular linear Vernier motor (DS-HTS-MLVM), which is suitable for long-stroke applications. This motor features staggered stators to suppress force ripple and modular cryostats for HTS windings to reduce installation difficulty. Its design aims to improve thrust force density and power density while utilizing the magnetic gearing effect of Vernier motors (Shi et al., 2022). Besides, a power take-off device with an HTS synchronous reluctance linear generator (HTS-SRLG) has been proposed, which combines a novel buoy design with stationary HTS field coils to simplify cooling and enhance reliability (Jing et al., 2020). Another innovative design, the linear doubly-salient HTS machine, shows significant improvements in power density and reduced cogging force, which are critical for WEC applications (Du et al., 2011). Figure 8 shows phase A of a tubular superconducting flux-switching generator (TSFSG).

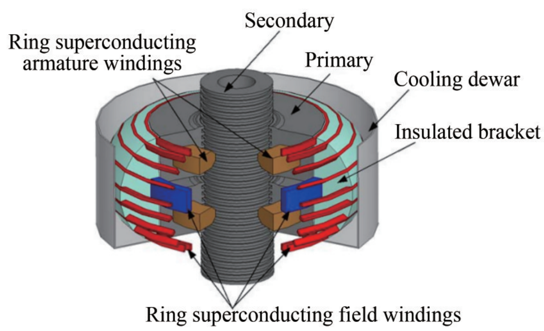


Figure 8 TSFSG configuration provided (Huang et al., 2014)

2.7 Air-cored generators

Air-cored PM generators have emerged as a significant technology for converting wave energy into electrical energy due to their unique benefits over traditional iron-cored machines. Figure 9 shows a novel air-cored topology which proposed in (Vermaak and Kamper, 2012). One of the primary challenges with iron-cored PM machines is the magnetic attraction forces between the stator and the translator, which complicates the structural and bearing design (Mueller et al., 2008). Unlike iron-cored generators, air-cored generators eliminate these magnetic attraction forces, leading to a reduction in structural mass and simplifying the mechanical design (Niknafs et al., 2022). For instance, the Archimedes wave swing and a device developed by Uppsala University both utilized iron-cored linear PM generators, facing issues with large magnetic attraction forces (Mueller et al., 2008). In contrast, air-cored machines, such as those introduced in (Spooner et al., 2005) and (Bumby and Martin, 2005), show potential for more efficient and reliable wave energy conversion.

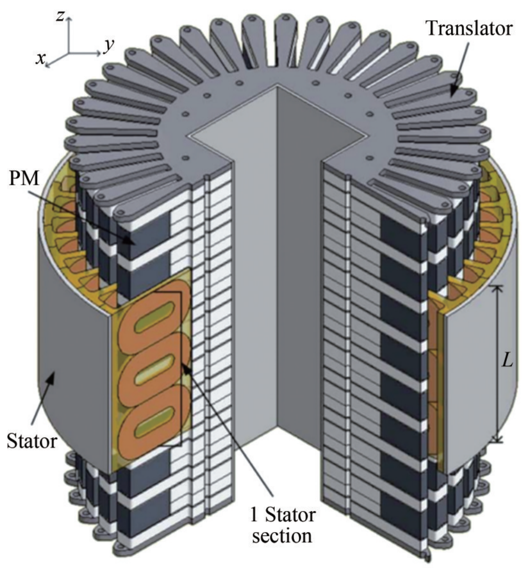


Figure 9 Three-dimensional cutout view of the novel air-cored PM LG (Vermaak and Kamper, 2012)

The advantages of air-cored linear generators in wave energy applications have demonstrated in (Niknafs et al., 2022) in which a flat double-sided linear PM generator designed and optimized using a particle swarm optimization algorithm to maximize efficiency and minimize weight. Their results indicate an increase in efficiency and a reduction in the generator's weight, validating the design through magnetic equivalent circuit and FEA methods. Similarly, an air-cored linear generator with a novel control strategy for maximum power transfer has been introduced in (Vermaak and Kamper, 2012), showing that allowing zero stator-translator overlap at the stroke ends can improve the power-to-weight ratio. It highlights the potential of air-cored generators to address the engineering challenges associated with wave energy conversion.

In addition, air-cored generators offer benefits in terms of reducing Lorentz forces and eliminating cogging forces, which are critical for WECs. A multi-phase air-cored tubular PM linear generator has been proposed in (Hodgins et al., 2008) that addresses the force parallel to the motion axis, reducing the Lorentz forces acting on the bearings. They also introduced a system for bypassing inactive coils, reducing thermal losses in the grid integration system through finite-element simulations. The elimination of cogging forces and the ability to operate without a steel core make air-cored generators a promising solution for efficient and reliable WEC. These advancements underline the importance of continued research and development in air-cored generator technology for harnessing wave energy.

3 Rotating generators

Rotary generators, including induction generators, PM synchronous generators (PMSG), and doubly-fed induction generators (DFIG), play a crucial role in converting wave energy into electrical energy. The rotary design of these generators is advantageous due to their well-established engineering principles and proven track record in various energy sectors. Rotary generators convert mechanical energy from wave motion into electrical energy through the rotation of a shaft connected to the generator's rotor. This rotational motion is typically produced by the oscillatory movement of wave energy converters. The rotary design allows for efficient energy transfer and can be easily integrated with existing grid infrastructure. Induction generators are particularly noted for their simplicity and durability, making them suitable for the harsh marine environment. PMSGs, on the other hand, offer high efficiency and compactness due to their use of PM, while DFIGs provide excellent control over power output and adaptability to variable wave conditions.

However, the deployment of rotary generators in WEC faces several challenges. One of the primary issues is the mechanical complexity and maintenance requirements associated with the rotary components, which are subjected to constant stress from the ocean's dynamic environment. The need for robust materials and designs that can withstand corrosion and mechanical wear is paramount. Additionally, the efficiency of rotary generators can be impacted by the irregular and often unpredictable nature of wave energy, necessitating advanced control systems to optimize energy capture and conversion. PMSGs, while efficient, rely on rare-earth magnets, which can be expensive and subject to supply chain constraints. DFIGs, despite their control advantages, require complex power electronics and maintenance of slip rings and brushes. These technical and economic challenges must be addressed through continued research and development to enhance the viability and competitiveness of rotary generators in the wave energy sector.

3.1 Rotary induction generator

The induction generator delivers the converted electrical power directly into the grid and it has a durable and suitable body for environments with harsh conditions such as seacoasts. The network provides the reactive power needed by the induction generator connected to the network, while providing the voltage and frequency. The required reactive power is supplied by the network. However, using the reactive power discharge inhibiting capacitor is a preventative and unavoidable thing that is often used together with induction generators. Figure 10 shows the induction generator in the WEC system using the water oscillator column method (Hodgins et al., 2008). The 150 kW power plant, located in Vizinjam port in the Kerala province of India, has been investigated and analysed as a research project model (Indiresan and Murthy, 1989). This project has been implemented by the Department of Ocean Development and Exploitation of India. The electrical parts of the project have been planned and designed by the Electrical Machines Department of the Delhi School of Electrical Engineering. The first induction generator for converting wave energy with a capacity of 150 kW was designed by the aforementioned group in 1994, and subsequently this generator was built according to the designed specifications by the Kilskar Company of India. At present, the mentioned power plant is in operation with full success. The turbine used in that project is "Wells" type. This turbine moves by the oscillating column method. Table 1 summarizes the specifications of the induction generator used in this wave power plant (Indiresan and Murthy, 1989).

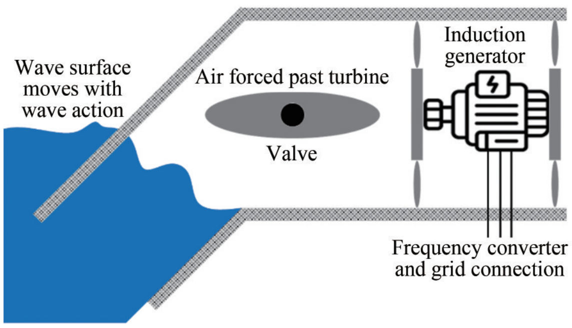


Figure 10 Induction generator in the wave energy conversion system using the water oscillator column method (Hodgins et al., 2008)

Induction generator is used in overload mode to achieve maximum power. The maximum overload of the generator is controlled by the internal temperature of the generator, which is determined according to the cooling capacity and losses of the induction generator. Here cheapness, ability to generate power, simplicity in control and compatibility with the type of project are the reasons for using induction generator (Indiresan and Murthy, 1989). Japan and Scotland, as leading countries, have used induction generators for the Japanese dolphin system and the limpet system in Scotland, respectively (Washio et al., 2001; Boake et al., 2002; Folley et al., 2006).

Using the second model shown in Figure 10, will lead to a reduction in these fluctuations. On the other hand, the resistances added to the rotor cause losses, which are undesirable (Kiran et al., 2007).

Table 1 Specifications of the induction generator (Indiresan and Murthy, 1989)

Parameter	Value
Power (kW)	150
Line voltage (V)	415
Line current (A)	250
Frequency (Hz)	50
No. of pleas	6
Base power (kW)	150
Connection type	Y
Stator resistance (Ω)	0.012
Rotor resistance (Ω)	0.082
Stator reactance (Ω)	0.080
Rotor resistance (Ω)	0.063
Core resistance (Ω)	43
Magnetization reactance (Ω)	2.67

An 18 kW PM generator model with 1 m impact turbine solves the problem of increasing losses. Nevertheless, according to Figure 11 the most suitable method is to use a 55 kW induction generator with a 1 m pulse turbine connected to a DC motor. Figure 12 shows the simulation result of this model indicating the quality of its correct performance.

Figure 11 OWC-based wave energy plant (Hodgins et al., 2008)

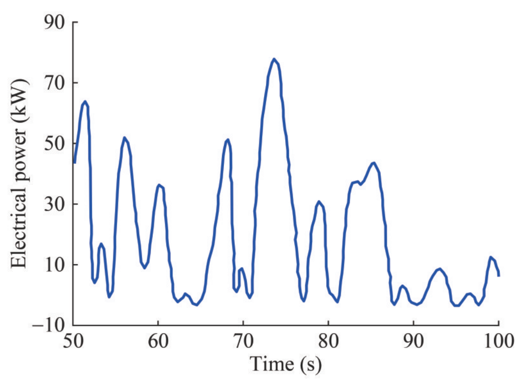
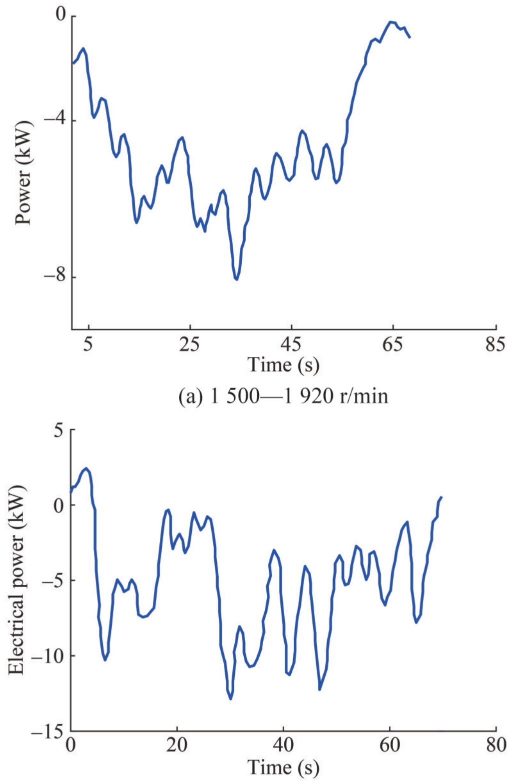


Figure 12 Power from 1 m impulse turbine with 55 kW slip ring IG (Kiran et al., 2007)

Figure 13 shows the time variations of the induction generator power with twin 1 m Wells turbine in different range of speeds (Kiran et al., 2007). In this method, to have the desired voltage and frequency in the generator stator, power electronics controllers have been used.



(a) 1 500—1 920 r/min

(b) 1 430–1 650 r/min (Kiran et al., 2007)

Figure 13 Time variations of power of 55 kW slip ring induction generator model with twin 1 m Wells turbine

Figure 14 illustrates the 55 kW induction generator coupled to a DC motor and Figure 15 shows its power and voltage variations (Kiran et al., 2007). The induction generator used in wave power plant cannot be used with the usual type of electric motors and must have special conditions.

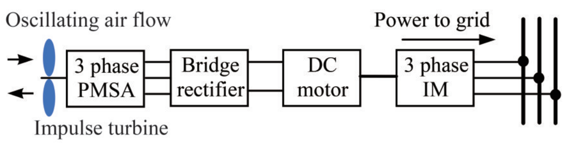
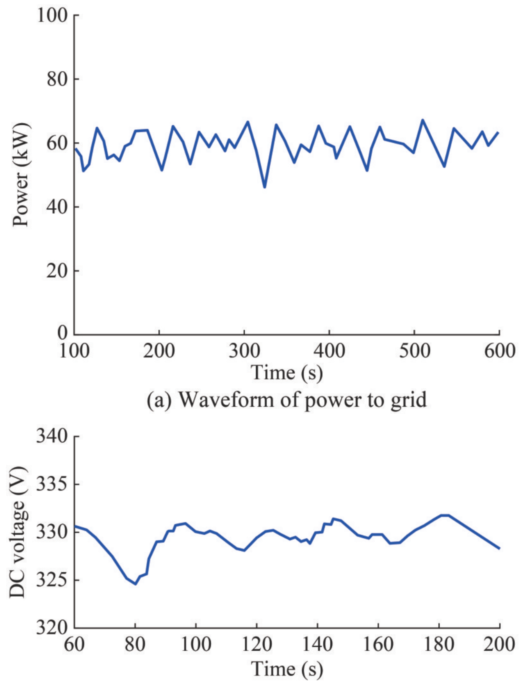


Figure 14 The 55 kW induction generator coupled to a DC motor (Kiran et al., 2007)

An 18 kW PM generator model with 1 m impact turbine solves the problem of increasing losses. Nevertheless, according to Figure 13, the most suitable method is to use a 55 kW induction generator with a 1 m pulse turbine connected to a DC motor. Figure 15 shows the simulation result of this model indicating the quality of its correct performance. To control the transferred power of the wave power to the network, control systems have also been proposed.



(a) Waveform of power to grid

(b) DC voltage produced by the rectifier

Figure 15 Power and voltage variation of the 55 kW induction generator (Kiran et al., 2007)

3.2 Rotary PMSG generators

PMSFs have emerged as a prominent choice for converting wave energy into electrical energy due to their high efficiency, robustness, and ability to operate without the external excitation. These generators leverage the magnetic properties of PMs to generate electrical power, which significantly reduces the energy losses associated with excitation systems in conventional synchronous generators.

The integration of PMSGs with WECs has shown promising results in terms of enhancing the overall efficiency and reliability of wave energy systems (Jamuna et al., 2014; Ammar et al., 2017; Hazra et al., 2017). The ability of PMSGs to maintain high performance over a wide range of operating conditions makes them ideal for the variable and unpredictable nature of wave energy (Fang et al., 2019).

One of the critical advancements in the application of PMSGs for WEC is the development of magnetic-gear PMSGs (MG-PMSGs). These systems combine the benefits of magnetic gears and PMSGs, offering high torque density and eliminating the need for mechanical gearboxes, which are prone to wear and maintenance issues. The use of magnetic gears helps in achieving a direct drive system that enhances the overall efficiency and reduces mechanical losses (Xue, 2005; Fang et al., 2020). Moreover, innovative control strategies such as flux weakening control have been implemented to extend the operational range of PMSGs, allowing them to handle varying power inputs from wave energy more effectively (Hazra et al., 2017; Shin et al., 2021). Advanced design techniques, including the use of Halbach arrays in rotor design, have further improved the performance by reducing cogging torque and enhancing the magnetic field distribution (Fang et al., 2019).

Extensive research and experimentation have been conducted to optimize the performance of PMSGs in wave energy applications. For instance, electromagnetic analysis using the subdomain method has been employed to optimize the force characteristics and minimize cogging torque, which is crucial for reliable and efficient operation (Fang et al., 2019; Fang et al., 2020). Dual-rotor designs have also been explored to increase the power output and efficiency of PMSGs, making them more suitable for large-scale WEC systems (Jamuna et al., 2014). These advancements, coupled with the integration of advanced materials and innovative design approaches, continue to drive the development of PMSGs, positioning them as a key technology for sustainable and efficient WEC (Xue, 2005; Ammar et al., 2017; Shin et al., 2021). The ongoing research and development efforts are focused on overcoming the remaining challenges and further enhancing the performance and reliability of PMSGs in WEC applications (Zhang and Zhu, 2010).

3.3 DFIG Generators

DFIG have emerged as a prominent technology for converting wave energy into electrical energy due to their ability to operate efficiently over a wide range of speeds and their capacity for variable speed operation. DFIGs are particularly advantageous in WECs, because they allow for the generation of power at both sub-synchronous and super-synchronous speeds (Marra and Pomilio, 2000; Tapia et al., 2003; Park et al., 2004; Koutroulis and Kalaitzakis, 2006; Xu and Cartwright, 2006; Brekken and Mohan, 2007; Pena et al., 2008; Zhi et al., 2009; Sguarezi Filho and Ruppert Filho, 2012; Subudhi and Pradhan, 2012) This characteristic is crucial in wave energy applications where the speed and direction of wave-induced motion are highly variable. The rotor of a DFIG is connected to the grid through a back-to-back power converter that handles only a fraction of the total power, typically around 25%–30%, which significantly reduces the cost and complexity of the power electronics compared to fully-rated converters used with synchronous generators (Elghali et al., 2010; Lagoun et al., 2012; Ghaffarpour et al., 2016).

One of the significant challenges in using DFIGs for WEC is managing the oscillatory nature of the wave motion, which causes the rotor speed to change direction periodically. This necessitates advanced control strategies to ensure smooth operation and efficient power extraction. For instance, a control method involving a thyristor-based stator phase sequence switching circuit has been proposed in (Hazra and Bhattacharya, 2014b) to adapt the changing rotor speed direction. This approach, combined with stator field-oriented control (FOC), allows the DFIG to maintain efficient operation and mitigate the impacts of speed reversal on the system. Similarly, the use of model-based predictive control (MBPC) has been discussed in (Lagoun et al., 2012) to improve the dynamic performance of DFIGs in WECs, highlighting the importance of precise control in achieving optimal power generation from fluctuating wave energy sources.

Moreover, the ability of DFIGs to provide reactive power support and their inherent capability for fault ride-through make them suitable for integration into grid-connected wave energy systems. It has been demonstrated in (Elghali et al., 2007) that DFIGs can effectively manage the reactive power requirements of the system, ensuring stable voltage levels and enhancing the reliability of the power supply. This capability is particularly beneficial in isolated or weak grid conditions commonly associated with offshore energy generation. Additionally, the use of DFIGs in WECs enables the implementation of advanced grid support functionalities, such as frequency regulation and voltage control, which are essential for maintaining grid stability in the presence of variable renewable energy sources.

4 Control systems of generators

In the wave energy conversion, the control system of electrical generators plays a crucial role in optimizing performance and efficiency. Effective control systems are essential for managing the variable and often unpredictable nature of wave energy. They ensure that the generator operates within safe and optimal conditions, maximizing energy extraction and minimizing wear and tear. Key factors in designing these control systems include the ability to adapt changing wave conditions, ensure grid compatibility, and maintain stability. Additionally, considering real-time monitoring, fault detection, and the integration of advanced algorithms for predictive maintenance are vital. These elements collectively enhance the reliability and longevity of wave energy generators, making control systems a pivotal component in the successful deployment of wave energy technologies.

To control electricity generation and provide motorized retraction for the floats, the linear generators are connected to the rig's DC-bus via full bridge active rectifiers of Figure 16. These rectifiers operate in current control mode, maintaining generator phase currents as dictated by an internal control signal. This current control allows direct manipulation of the machine's thrust, independent of induced back-EMF, and provides an effective inner-control loop for motion control when motoring the floats.

Each power converter has one H-Bridge per phase, driving a pair of parallel-connected generators. The phase inductance of the generator is used as an energy storage element for power conversion, as proposed in (Brooking and Muel-

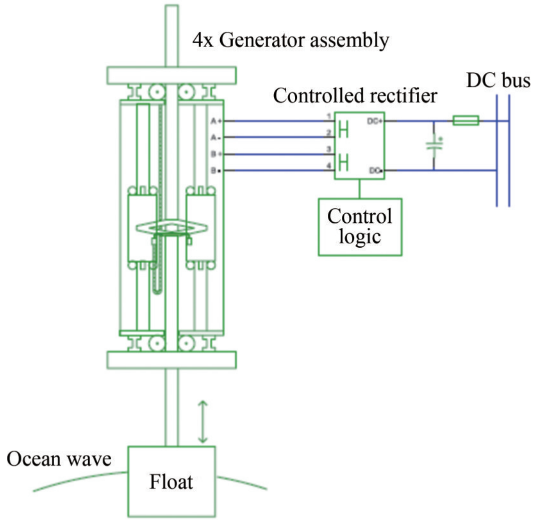


Figure 16 System diagram-generators and input converters (Clifton et al., 2010)

ler, 2005; Ran et al., 2006), enabling direct control of the current flowing through the generators.

The switching scheme employs hysteresis current control, applying the full DC-bus voltage either positively or negatively across the generator terminals based on whether the phase current is above or below the controller's demand. Switching decisions are made at fixed intervals, defining the maximum switching frequency. The generator inductance at the switching frequency must remain below the generator's self-resonant frequency, measured at 8.6 kHz for a single coil, so, the hysteresis controller's update rate is set below this frequency.

The machine is commutated by Hall sensors mounted in phase with the coils. If the machine's flux profile were sinusoidal, this would allow direct commutation by controlling each phase current with a scaled version of the corresponding Hall sensor signal. However, optimizing for other design goals can lead to generators with spatial harmonics in the flux cut by their coils. The Hall-effect sensors also detect spatial harmonic content (primarily the 3rd harmonic in the Trident Energy 5 (TE 5)), and a compensation scheme adjusts the amplitude of the sensor-derived phase currents at any given position. The commutation algorithm and its compensation are implemented in the input active-rectifier's FPGA-based controller.

When generating, the thrust demanded from the generators is set proportionally to their translating velocity, measured by a tachometer, which presents a mechanical load equivalent to a pure damper. Additional mechanical reaction to tune power extraction, similar to the approach introduced in Shek et al. (2007), could be introduced by adding terms to the controller.

The system was designed to use a closed-loop velocity controller for retracting and deploying the floats, overcoming variations in the thrust required to move the assemblies. Due to risks associated with testing a closed-loop system without water under the floats, simpler implementations were used for the launch. For retraction, a fixed thrust value sufficient for lifting was chosen, with the generator's lifting velocity limited by its back-EMF and the fixed battery voltage. For deployment, the active-rectifier short-circuits the generator before unlocking the float, breaking its descent through internal losses until it reaches the water.

For this prototype, an offshore grid connection was too costly, necessitating on-board dissipation of all generated electricity. The TE 5, being relatively small compared to incident ocean wavelengths, has a nominal 30 kW output that would not average out over its four generators, requiring a greater peak capacity. A 100 kW rated 3-phase power converter module is used to dissipate the generated electricity as 50 Hz AC in a switched resistor bank. An L-C filter removes switching frequency content, and the (nominally) 415 VAC is metered by a Ferraris wheel type meter for auditing. The converter's FPGA controller can switch resistor banks in and out while modulating its output voltage to stabilize the rig's DC-bus.

An auxiliary inverter attached to the DC-bus provides a 230 V single-phase AC supply for utilities on the rig, such as cooling fans for the generators and power electronics, lighting, and diagnostic equipment. Its main function is to recharge the rig's large lead-acid battery banks, ensuring critical functions continue during generation gaps and providing power to retract the floats during shutdowns.

For safety, the 230 V "mains" output is isolated from the converter output using a power frequency transformer to avoid high common-mode voltage from the DC-bus, which could pose a safety risk and damage insulation of powered loads. The auxiliary supply output is metered to account for the energy consumed in sustaining the rig.

The rig's battery system of Figure 17 is divided into two sections. An 800 Ah bank supplies 24 V to the control and communications equipment that manage the rig's operations, as well as the controllers for the active rectifiers and power converters. This large capacity is a legacy from its original use in powering winch motors for mooring the rig, and it also ensures the rig's electronics remain operational during extended periods of calm weather. A 60 Ah battery bank supplying 300 V provides energy to retract the rig's floats during shutdowns and maintains 230 V auxiliary systems during generation drop-outs. This is connected in series with the 24 V bank, resulting in a nominal 324 V. A large diode allows the battery bank to support the DC bus when generation ceases and its voltage drops below the battery voltage. A resistive pre-charge system reduces inrush currents when switching on the rig systems.

In a grid-connected wave farm, many of these battery requirements could be eliminated, potentially retaining only a small battery bank or a backup generator to maintain

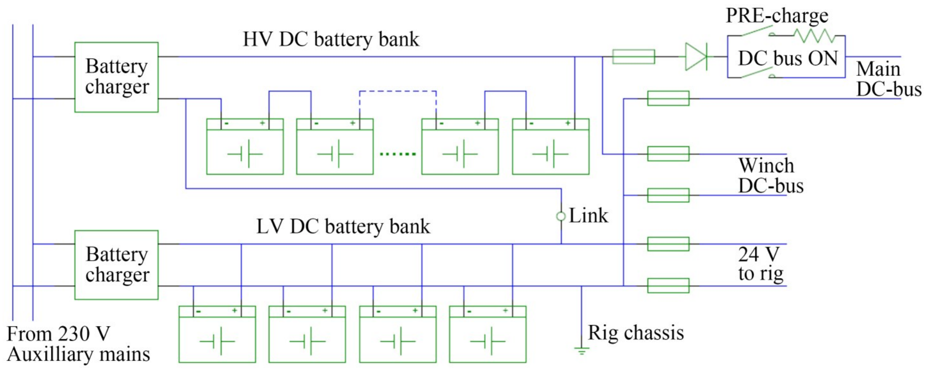


Figure 17 System diagram-batteries and charging (Clifton et al., 2010)

communications and navigation lights in case of a grid fault (Clifton et al., 2010).

5 Responses of variables of electrical generators

Since the waves are basically irregular, the responses of the variables of electrical generators are also irregular and will have a series of changes over time. These changes include speed, backEMF, output voltage, phase current and output power. Figure 18 shows the experimental results for no- load and a load resistance of 2 Ω (Seo et al., 2020).

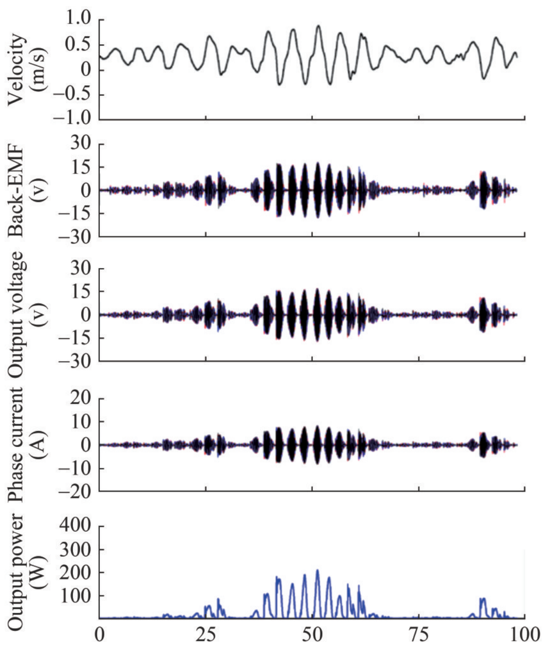


Figure 18 Performance characteristics of the manufactured linear PMSG according to irregular velocity condition (Seo et al., 2020)

In the experiment result in Figure 19 shows that the peak phase back-EMF is 221 V (Wahyudie et al., 2017). Figure 20 shows the mechanical quantities of PMLG. Figure 20(a) presents the measured displacement of the translator, and Figure 20(b) shows its corresponding velocity profile. The measured peak velocity is about 0.5 m/s, which occurs when the translator moves to its full speed of 1 m/s. Figure 20(c) exhibits the measured corresponding mechanical force. Figure 20(d) shows the instantaneous mechanical power and the corresponding average mechanical power (Wahyudie et al., 2017).

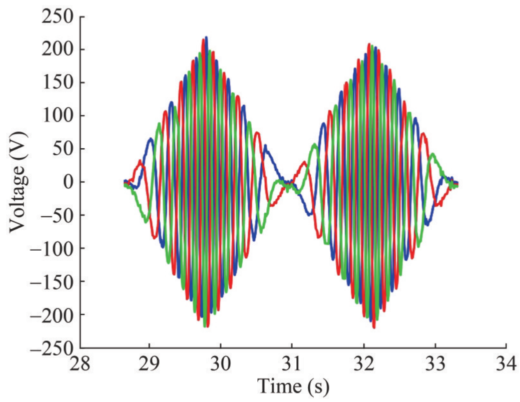


Figure 19 Three-phase EMF voltages of the test rig under no load operation (Wahyudie et al., 2017)

A linear permanent magnet Vernier machine is designed and analysed in (Zhao et al., 2015). In this paper, a new PM array is presented, which has a better flux density than the conventional model, which improves the back-EMF.

As shown in Figure 21 the back-EMF of the 3-phase machine with the translator speed of 1.5 m/s are measured. The current waveforms for steady-state situation are measured when the machine operates in the BLAC (suitable for brushless AC) mode at 0.3 m/s and 150 N are show in Figure 22. The measured responses of the mover speed and phase current to a step demand of 0.3 m/s are given in Figure 23 (Zhao et al., 2015).

6 Comparison of generator types for wave energy conversion

Table 2 offers a detailed comparison of various types of generators used in wave energy conversion (WEC) sys-

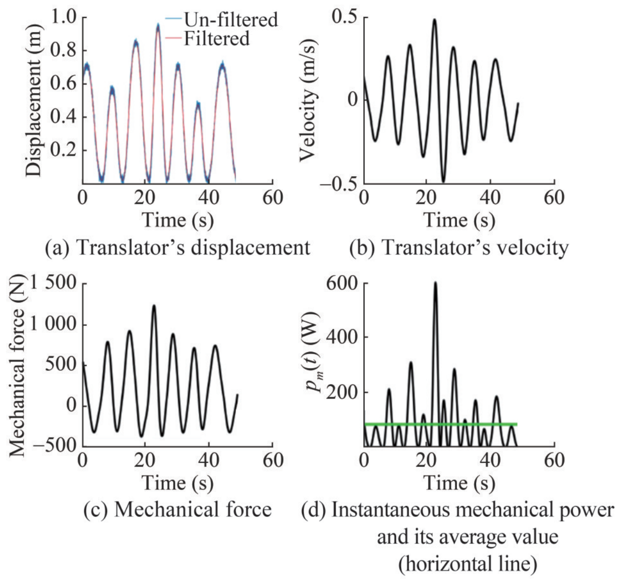


Figure 20 Mechanical quantities of test rig under the loaded condition with the irregular wave (Wahyudie et al., 2017)

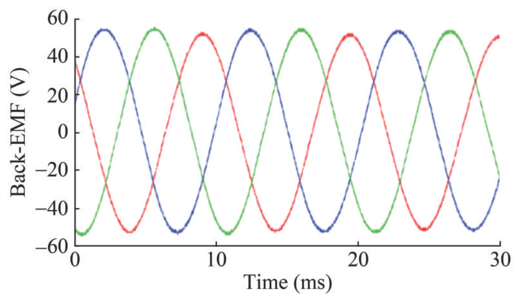


Figure 21 Measured back-EMF waveforms at 1.5 m/s (Zhao et al., 2015)

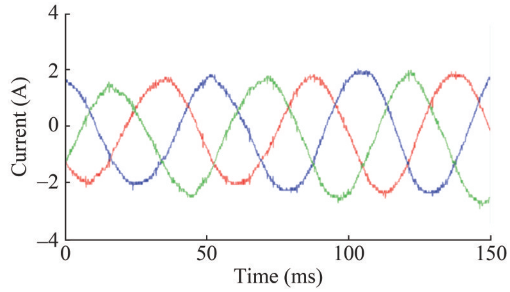


Figure 22 Measured currents at 0.3 m/s and 150 N (Zhao et al., 2015)

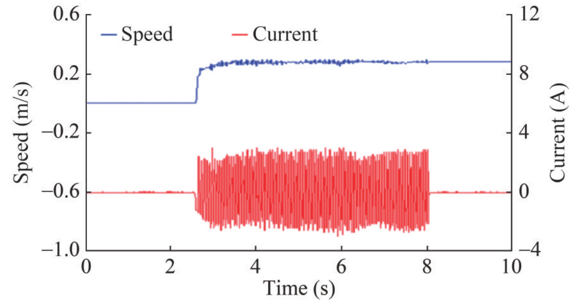


Figure 23 Measured responses of mover speed and phase current (Zhao et al., 2015)

tems. It categorizes the generators based on their structure, PM fixing location, PM location, excitation type, core type, translator, rated power, flux, and efficiency. This comparative analysis is crucial for understanding the strengths and weaknesses of each generator type, facilitating informed decision-making in the design and implementation of WEC systems.

The table highlights synchronous generators, both flat and tubular, which are designed for high-power applications with rated powers ranging up to 1 000 kW. These generators utilize advanced PM materials such as NdFeB, ensuring high magnetic field strength and efficiency. The flat synchronous generators are categorized into single-sided and double-sided configurations, with the latter offering enhanced magnetic coupling and reduced leakage flux. Tubular synchronous generators, on the other hand, provide a more compact design with axial flux paths, making them suitable for applications requiring high power density and efficiency.

Table 2 Comparison of generator types for wave energy conversion

Generator Type	Structure	PM fixing location	PM location	Excitation type	Core type	Translator	Rated power (kW)	Flux	Efficiency (Full load) (%)	References
Synchronous	Flat (single-sided)	Internal PM (Axial)	Stator	PM (NdFeB)	Iron	Short	1 000	Longitudinal	-	(Molla et al., 2020)
Synchronous	Flat (double-sided)	Surface PM (radial)	Translator	PM (NdFeB)	Iron	External long	1 000	Longitudinal	97.5	(Polinder et al., 2004)
Squirrel cage induction generator (SCIG)	Rotary	-	-	Excitation Winding	Iron	-	410	Radial	-	(Hazra and Bhattacharya, 2014a)
Squirrel cage induction generator (SCIG)	Rotary	-	-	Excitation Winding	Iron	-	150	Radial	57	(Indiresan and Murthy, 1989)

Table 2 Comparison of generator types for wave energy conversion (Continued)

Generator Type	Structure	PM fixing location	PM location	Excitation type	Core type	Translator	Rated power (kW)	Flux	Efficiency (Full load) (%)	References
Dual rotor PM synchronous generator	Rotary	Surface PM (radial)	Rotor	PM (NdFeB)	Iron	-	108	Radial	86	(Fang et al., 2020)
Synchronous	Flat (double-sided)	Surface PM (radial)	Translator	PM	Air (modular)	External long	50	Longitudinal and transverse	-	(Wang and Howe, 2005)
PM synchronous generator	Rotary	Surface PM (Axial)	Rotor	PM	Iron	-	50	Axial	-	(Sattarov and Ziganshin, 2019)
Synchronous	Tubular	Internal PM (axial)	Translator	PM	Air	External long	30	Longitudinal	78	(Colli et al., 2006)
Synchronous	Tubular	Internal PM (axial)	Translator	PM	Iron (Slot-less)	Internal long	30	Longitudinal	-	(Clifton et al., 2010)
Synchronous	Flat (four-sided)	Surface PM (radial)	Translator	PM (NdFeB)	Iron	Internal long	10	Longitudinal	-	(Leijon et al., 2006)
PM synchronous generator	Rotary	Surface PM (radial)	Rotor	PM	Iron	-	10	Radial	85	(Hazra et al., 2017)
Synchronous	Tubular	Internal PM (axial)	Translator	PM (NdFeB)	Iron	Internal long	3	Longitudinal	75	(Cappelli et al., 2013)
Hybrid Vernier	Flat (double-sided)	Surface PM (radial)	Stator	PM	Iron (modular)	Internal long	3	Longitudinal	-	(Du et al., 2015)
Synchronous (Air gap filled by seawater)	Tubular	Surface PM (radial)	Translator	PM (NdFeB)	Iron	External long	1	Longitudinal	80	(Prudell et al., 2010)
Synchronous	Tubular	Radial (PM)	Translator	PM (NdFeB)	Air (Stator or Translator)	Internal long	1	Transverse	-	(Vermaak and Kamper, 2011)
PM synchronous generator	Rotary	Surface PM (radial)	Rotor	PM	Iron	-	0.5	Radial	-	(Fang et al., 2019)
Synchronous	Tubular	Surface PM (radial)	Translator	PM (NdFeB)	Iron	Internal long	0.445	Longitudinal	85.5	(Zhang et al., 2013)
Synchronous (Vernier)	Flat (single-sided)	Surface PM (radial)	Stator	PM (NdFeB) and excitation winding	Iron	Internal long	0.160	Longitudinal	-	(Ghods et al., 2021)
Transverse-flux synchronous	Tubular	Surface PM (radial)	Stator	PM (NdFeB)	Iron	External Short	0.150	Transverse	79	(Qiu et al., 2021)
Synchronous (Vernier)	Flat (double-sided)	Surface PM (radial)	Translator	PM (NdFeB)	Iron	External Short	0.06	Longitudinal	75	(Zhao et al., 2023)

Rotary generators like the squirrel cage induction generator (SCIG) and permanent magnet synchronous generator (PMSG) are noted for their radial flux configuration and robust iron cores, making them suitable for harsh marine environments. SCIGs are particularly valued for their simplicity and durability, as they do not require slip rings or brushes, reducing maintenance needs. PMSGs, with their high efficiency and compact design, are ideal for applications where space and weight are critical constraints. The table also includes detailed performance metrics for these generators, such as their efficiency under full load, highlighting their suitability for different WEC applications. Innovative designs like the hybrid Vernier machines and superconducting linear generators are also included in the table. Hybrid Vernier machines combine the principles of variable reluctance and permanent magnet excitation, offering high torque density and efficiency. These machines are particularly suitable for applications where precise control and high performance are required. Superconducting linear generators, utilizing high-temperature superconductors (HTS), provide significant advantages in terms of power density and efficiency. The table details the specific materials used in these generators, such as YBCO and MgB2, and their impact on performance and operational costs.

The comprehensive comparison provided in underscores the diverse technological approaches in WEC. By detailing the structural and material optimizations of each generator type, the table guides future research and development towards more efficient and reliable systems. This structured approach not only facilitates a better understanding of the current state of generator technology but also highlights areas where further improvements can be made. The inclusion of quantitative metrics such as power-to-weight ratios, efficiency levels, and operational costs ensures that designers and engineers can make informed decisions when selecting the most appropriate generator for their specific WEC application.

Table 3 categorizes the generators into two main groups-rotary generators and linear generators. For the rotary generators, the listed parameters include the outer diameter of the stator, the outer diameter of the rotor, and the number of pole pairs. These parameters are important in determining the physical sizing and power density of the rotary machines.

In contrast, the linear generators are further divided into flat and tubular configurations. The key parameters for these linear machines include the length of the translator, length of the stator, width of the machine, and the bore diameter and air-gap length. These geometric dimensions directly impact the power conversion and force generation capabilities of the linear generators.

Table 3 Generator types for wave energy conversion

Rotary generators			Linear generators					
			Flat			Tubular		
Parameters	Value	References	Parameters	Value	References	Parameters	Value	Reference
Outer diameter of stator (mm)	142.4	(Fang et al., 2020)	Length of translator (m)	2.4	(Lagoun et al., 2012)	Bore diameter (mm)	28	(Clifton et al., 2010)
				8	(Polinder et al., 2004)		125	(Wang and Howe, 2005)
	120	(Shin et al., 2021)		-	(Elghali et al., 2007)		260	(Du et al., 2015)
				0.26	(Zhang et al., 2013)		71	(Colli et al., 2006)
Outer diameter of rotor (mm)	163.8	(Fang et al., 2020)	Length of Stator (m)	-	(Lagoun et al., 2012)	Air-gap length (mm)	2.5	(Clifton et al., 2010)
				5	(Polinder et al., 2004)		1	(Wang and Howe, 2005)
	184	(Shin et al., 2021)		3.6	(Elghali et al., 2007)		1	(Du et al., 2015)
				1.2	(Zhang et al., 2013)		-	-
Number of pole pairs	4	(Fang et al., 2020)	Width of machine (m)	2	(Lagoun et al., 2012)	Translator diameter (mm)	10	(Clifton et al., 2010)
				1	(Polinder et al., 2004)		170	(Colli et al., 2006)
	3HS 22LS	(Shin et al., 2021)		1	(Elghali et al., 2007)		100	(Du et al., 2015)
				0.7	(Zhang et al., 2013)		-	-

7 Conclusion

In conclusion, the conversion of wave energy into electrical energy presents a promising avenue for sustainable energy production. The various types of electrical generators, both linear and rotary, offer unique advantages and challenges in harnessing this renewable energy source. Linear generators, including Induction, Permanent Magnet Synchronous, and Switched Reluctance types, provide direct energy conversion, enhancing mechanical reliability and reducing noise and costs. However, challenges such as large air gaps and lower efficiency need to be addressed to optimize their performance. Rotary generators, including Induction Generators, PMSG, and DFIG, benefit from well-established engineering principles and are easily integrated with existing grid infrastructure. Despite their mechanical complexity and maintenance requirements, advancements in materials and control systems continue to improve their viability for wave energy applications.

The ongoing research and development efforts are crucial in overcoming the technical and economic challenges associated with wave energy conversion. Innovations in generator design, control strategies, 1and materials are enhancing the efficiency and reliability of these systems, making them more competitive with traditional energy sources. Countries leading in wave energy technology, such as Scotland and Japan, demonstrate the potential of these systems to contribute significantly to the global renewable energy portfolio. The environmental benefits of wave energy, including zero air pollution and greenhouse gas emissions, further underscore its importance in addressing climate change and reducing our dependence on fossil fuels.

As the technology continues to evolve, wave energy conversion systems are expected to play a vital role in the future of renewable energy. The comprehensive understanding of the current state and future prospects of electrical generators in this field, as provided by this review, highlights the potential for significant advancements. By addressing the remaining challenges and optimizing the performance of these systems, wave energy can become a key component of a sustainable and resilient energy infrastructure, contributing to a cleaner and more sustainable future for all.

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

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