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Design and Construction of a Wave Power Plant Using a Recoil Starter on a Prototype Ship

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***Abstract**. This research aims to design and develop a prototype wave power plant that utilizes the vertical motion of a buoy as a source of mechanical energy, which is then converted into electrical energy using a recoil starter mechanism. The system is designed to be installed at the stern of a prototype ship. The vertical movement of the buoy caused by ocean waves is transmitted to the recoil starter through a drive rope, producing a stable one-way rotational motion. This rotation is further transmitted to a gearbox to increase rotational speed before driving a DC generator. The electrical energy generated is stored in a 12 VDC battery, supported by a buck–booster converter to stabilize the output voltage. This study employs an experimental engineering approach to evaluate system performance based on empirical test data. The main components of the system include a buoy as a wave energy collector, a recoil starter as the initial rotating mechanism, a DC generator as the electrical energy producer, a buck–booster converter as a voltage regulator, a 12 VDC battery as an energy storage unit, and a monitoring system based on an ESP32 microcontroller integrated with a PZEM-017 sensor. Experimental results show that the recoil starter operates effectively in driving the generator under both no- load and buoy-loaded conditions. Increases in generator rotational speed are directly proportional to increases in output voltage and current. The PZEM-017 sensor demonstrates a high level of measurement accuracy, approaching 100% when compared with a multimeter. Overall, the proposed wave power generation system functions reliably and shows potential for further development as a small-scale alternative renewable energy source.*

Keywords: *Ocean Waves; Power Generation; Recoil Starter; Renewable Energy; Tidal Energy.*

1. INTRODUCTION

The trajectory of global energy consumption is on an unsustainable upward curve, driven by rapid industrialization, population growth, and the extensive development of infrastructure in emerging economies. The International Energy Agency (IEA) projects a 25% increase in global energy demand by 2030 (Agency, 2021), a trend that poses significant challenges for energy security and climate stability. In Indonesia, an archipelagic nation comprising over 17,000 islands, the energy landscape is characterized by a heavy reliance on fossil fuels—oil, natural gas, and coal. This dependency not only exacerbates greenhouse gas emissions but also creates logistical vulnerabilities in supplying fuel to remote coastal and island communities (Nasional, 2023). Consequently, the diversification of the national energy mix through the adoption of renewable resources is not merely an environmental preference but a strategic necessity for national resilience (IEA, 2022).

Among the various renewable energy sources, marine energy—and specifically wave energy— holds immense untapped potential. Unlike solar irradiance, which ceases at night, or wind velocity, which can be highly intermittent, ocean waves possess a high energy density

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and offer greater consistency and predictability. Waves act as efficient carriers of wind energy, concentrating the kinetic energy harvested over vast oceanic fetches into a localized resource at coastlines (Son, 2024). For a maritime nation like Indonesia, with its extensive coastline and active sea states, wave energy represents a strategic resource that remains largely underutilized due to technological and economic barriers.

The maritime industry itself is a significant consumer of energy, primarily in the form of marine fuel oil for propulsion and auxiliary power. There is a growing interest in "green shipping" technologies that can reduce the carbon footprint of vessels. While wind-assisted propulsion and solar-electric ferries are gaining traction, the integration of wave energy harvesting directly onto vessels remains a frontier area of research. A key technical challenge lies in the Power Take-Off (PTO) system—the mechanism responsible for converting the irregular, low- frequency oscillation of waves into the high-speed rotational motion typically required by electrical generators. Conventional PTOs often rely on complex hydraulic systems or expensive linear generators, which may not be economically viable for small-scale or auxiliary applications.

This research addresses this technological gap by proposing and validating a novel, cost-effective PTO solution: the modified recoil starter. Ubiquitous in small internal combustion engines, the recoil starter contains inherent mechanical logic—a retractable spring-loaded spool and a one-way clutch—that theoretically mimics the requirements of a point-absorber WEC. By tethering a heaving buoy to a recoil mechanism, the vertical kinetic energy of the waves can be translated into rotational energy. This study focuses on the "Rancang Bangun Pembangkit Listrik Tenaga Gelombang Laut Menggunakan Recoil Starter Pada Kapal Prototipe" (Design and Construction of a Wave Power Plant Using a Recoil Starter on a Prototype Ship), rigorously testing this concept to determine its viability as a decentralized power source for maritime applications.

2. LITERATURE REVIEW

Renewable Energy and Global Trends

Renewable energy is defined as energy derived from natural processes that are replenished at a rate equal to or faster than they are consumed (IEA, 2022). The urgent need to mitigate climate change has accelerated the adoption of solar, wind, and hydro power. However, the intermittent nature of these sources necessitates a diversified portfolio. Marine renewable energy (MRE), encompassing wave, tidal, and ocean thermal energy, offers a complementary profile. Wave energy, in particular, is distinct due to its high power density.

While solar insolation typically peaks at ~1 kW/m², wave power flux can exceed 50 kW per meter of wave crest in energetic sea states. This density implies that smaller devices can theoretically harvest significant amounts of energy, making it attractive for space-constrained applications like ships (Sianipar, Rifki, & Silalahi, 2022)..

Physics of Ocean Wave Energy

Ocean waves are generated by the wind transferring momentum to the sea surface. The resulting waves propagate energy across the ocean surface with minimal loss. The total energy of a wave is the sum of its potential energy (due to the elevation of the water mass above the mean sea level) and kinetic energy (due to the orbital motion of water particles) (Novi , Sudarti, & Yushardi, 2025).

Wave Energy Converter (WEC) Architectures

The WEC technologies are diverse, but they generally fall into three categories (Sukma, Sudarti, & Yushardi, 2023): 1) Attenuators: These are long, multi-segment structures aligned parallel to the wave direction (e.g., the Pelamis device). They harvest energy from the relative motion between segments as the wave passes along the device. 2) Terminators: These devices are oriented perpendicular to the wave propagation. Examples include Oscillating Water Columns (OWCs) and overtopping devices, which capture the water mass or air pressure generated by the wave front. 3) Point Absorbers: These are floating structures with dimensions small relative to the wavelength. They usually operate in a heave mode (vertical motion), harvesting energy from the relative motion between a floating buoy and a fixed reference (or a submerged reaction mass).

The system proposed in this research is a Point Absorber. This architecture is particularly suitable for ship-mounted applications because the ship itself can serve as the "fixed" reference point (assuming the ship's heave response is different from the buoy's). The relative motion between the water surface (buoy) and the ship's stern drives the PTO.

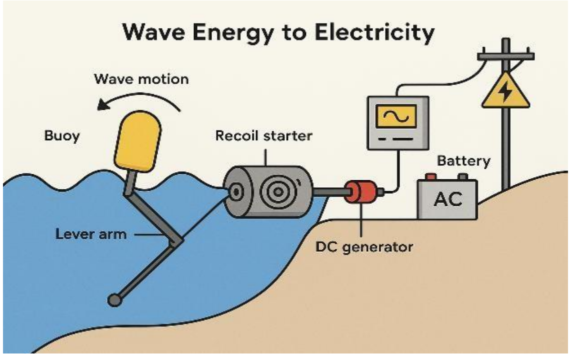

Figure 1. Wave Energy Converter (WEC) Architectures.

The Recoil Starter as a Mechanical PTO

The Power Take-Off (PTO) is the core of any WEC (Setiawan E. , 2022).. Conventional PTOs use hydraulic rams to drive motors or linear electrical generators. While efficient, these are complex, heavy, and expensive. This research investigates a mechanical PTO based on a recoil starter. A recoil starter consists of:

a. A Reel wound with a rope.
b. A Spiral Spring (torsion spring) that stores energy during the extension and provides the restoring force for retraction.
c. A Ratchet/Clutch Mechanism that engages the output shaft when the rope is pulled and disengages during retraction. In a WEC application, the buoy is attached to the rope.
d. Wave Crest (Upward Motion): If the WEC is mounted above the water, the rising wave lifts the buoy. In a "pull-down" configuration (where the mechanism is fixed below), the buoy pulls the rope. In the configuration for this prototype (mechanism on ship, buoy in water), the physics works as follows: As the wave drops (trough), gravity pulls the buoy down, extending the rope and driving the generator (power stroke). As the wave rises (crest), the recoil spring retracts the rope, resetting the system. Alternatively, the power stroke can be configured on the rise if the mechanism is inverted.
e. Rectification: The ratchet ensures that the generator only spins in one direction, regardless of the reciprocating nature of the rope. This effectively rectifies the AC-like wave motion into DC-like rotational motion.

Previous research by Lesnussa, Farhan et al. (2023) validated the use of recoil starters for shore- based WECs, finding that output power scales with wave height. This study builds upon that work by introducing the complexities of a floating platform (the prototype ship) and optimizing the ballast mass

Electrical Conversion: Generator and Conditioning

The mechanical rotation drives a Direct Current (DC) Generator. DC generators, particularly Permanent Magnet (PM) types, are favored for small- scale renewables due to their simplicity and linear torque-speed characteristics (Ramadhan, Herlambang , & Purwanto , 2024).. However, the rotational speed provided by waves is highly variable. To manage this, a Buck-Boost Converter is essential. This device can step up (boost) low voltages from slow rotations or step down (buck) high voltages from rapid rotations to a stable level required for battery charging (typically 13.8V - 14.4V for 12V lead-acid batteries). Additionally, Maximum Power Point Tracking (MPPT) technology is employed. MPPT controllers electronically adjust the load impedance presented to the generator to match its internal impedance, ensuring maximum power transfer efficiency under varying wave conditions.[1]

IoT Monitoring Framework

To validate the prototype, precise data is required. Traditional analog meters are insufficient for capturing rapid transients in wave power. This study employs an IoT framework using the ESP32 microcontroller. The ESP32 offers dual-core processing and integrated Wi-Fi, allowing for high- frequency data sampling and wireless transmission. The PZEM-017 sensor is used for electrical measurements. It utilizes a shunt resistor for current measurement and communicates via the Modbus protocol (RS485), providing industrial-grade accuracy for voltage, current, and energy accumulation (Ramadhan, Herlambang , & Purwanto, 2024).

3. RESEARCH METHODOLOGY

Research Design

This study utilizes an experimental research design with an engineering prototyping approach (Yulianti, et al., 2024). The methodology is iterative, moving from theoretical design to component fabrication, static testing, system integration, and finally, dynamic validation in a simulated wave environment. The approach allows for the isolation of variables—specifically buoy ballast and wave height to determine their independent and combined effects on system performance (Herlinda, et al., 2010.

System Architecture and Block Diagram

The system is conceptually divided into mechanical and electrical subsystems. The functional flow is as follows:

a) Energy Capture: A point-absorber buoy captures the kinetic and potential energy of the wave.
b) Transmission: A tether connects the buoy to the recoil starter unit mounted on the ship's stern. The recoil unit converts linear motion to rotation.
c) Gearing: A gearbox increases the rotational speed (RPM) to match the generator's efficient operating range.
d) Generation: A DC Generator converts mechanical rotation to electrical current.
e) Regulation: A Buck-Boost Converter stabilizes the voltage. An MPPT controller optimizes power flow.
f) Storage: A 12VDC Battery stores the harvested energy.
g) Monitoring: An ESP32 microcontroller reads data from a PZEM-017 sensor (via RS485) and transmits it to a web-based dashboard for real- time analysis.

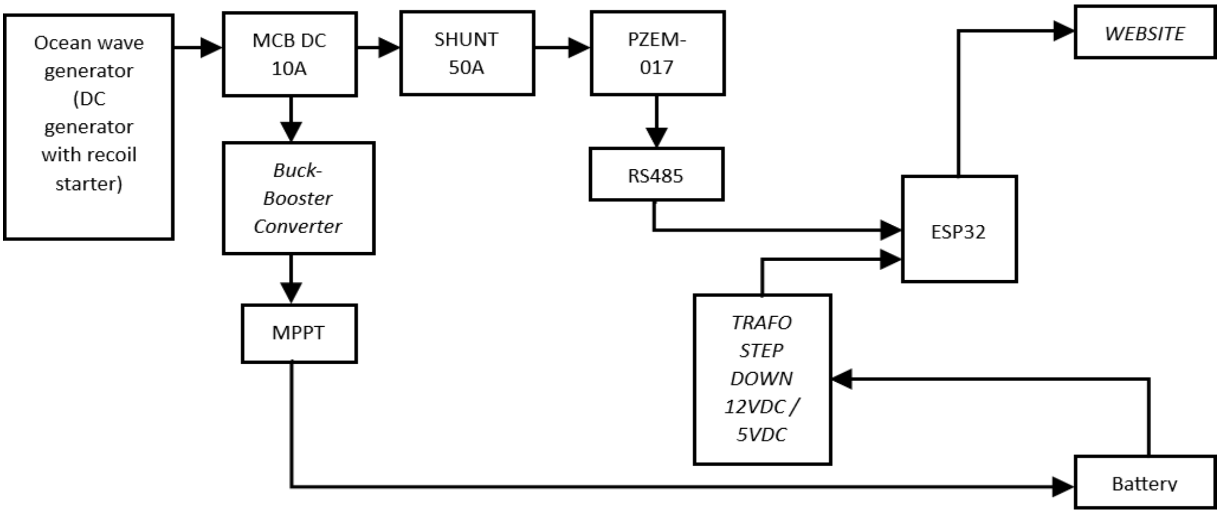

Figure 2. Block Diagram.

Operational Logic (Flow Chart)

Figure 3 depicts the operational flowchart of the prototype, focusing on the battery charging process. The electrical output from the generator is monitored by a PZEM-017 sensor, which reads voltage and current data processed by the ESP32 microcontroller. A specific set point is established (≤ 10V, 3A). If the sensor readings meet or exceed this set point, the system signals the relay to engage, allowing power to flow. Conversely, if the output falls below the threshold, the relay prevents power transmission, ensuring the battery is not subjected to insufficient charging conditions. Ultimately, the regulated power is directed towards battery storage.

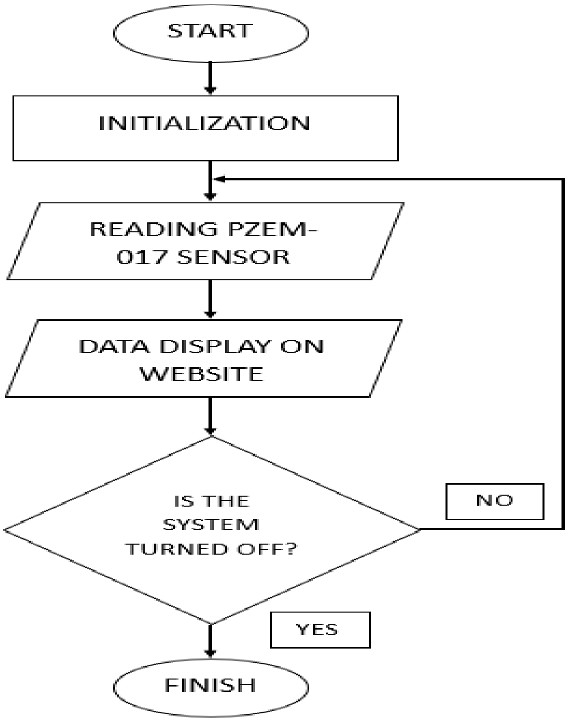

Figure 3. Operational Logic (Flow Chart).

Component Spesifications

Turbine Design

The selection of components was driven by the specific requirements of the marine environment and the scale of the prototype.

a. Recoil Starter: A standard heavy-duty recoil mechanism adapted for continuous cycling.
b. Generator: Permanent Magnet DC Generator, rated for low-RPM operation.
c. Buoy: A custom-fabricated hollow polyethylene container, allowing for variable water ballast filling.
d. Power Electronics:
   a) XL6009 DC-DC Buck-Boost module.
   b) MPPT Solar Charge Controller (adapted for DC turbine input).
e. Sensors: PZEM-017 DC Energy Meter (0- 300V, 0-50A range).
f. Controller: ESP32 DevKit V1.

Experimental Procedures

Dynamic Wave Simulation

The integrated system was tested in a wave tank environment capable of generating controlled waves.

1) Independent Variable 1: Wave Height. The wave generator was set to produce wave heights of 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, and 30 cm.
2) Independent Variable 2: Buoy Ballast (). The buoy was filled with varying volumes of water to alter its mass and natural frequency: 0-800 ml, 900 ml, 1300 ml, 1700 ml, and 1800-2000 ml.
3) Dependent Variables:
   - Recoil RPM: The frequency of recoil actuation (strokes per minute).
   - Output Voltage: The peak and average voltage generated.
   - Output Current/Power: Measured by the PZEM-017.
4) Procedure: For each ballast configuration, the wave height was incrementally increased. The system was allowed to stabilize for 2 minutes at each setting, and data was logged via the ESP32. Visual observations of the buoy's hydrodynamic behavior (submersion, riding, slamming) were also recorded.

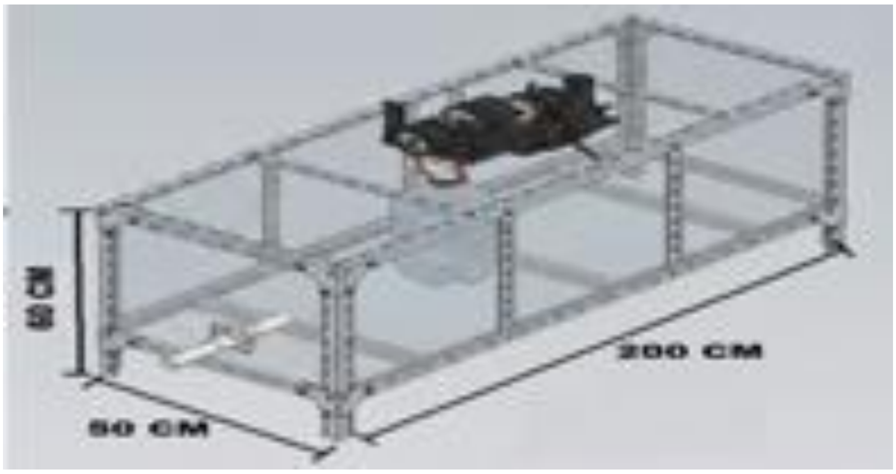

Figure 4. Design and Construction of a Wave Power Plant Using a Recoil Starter.

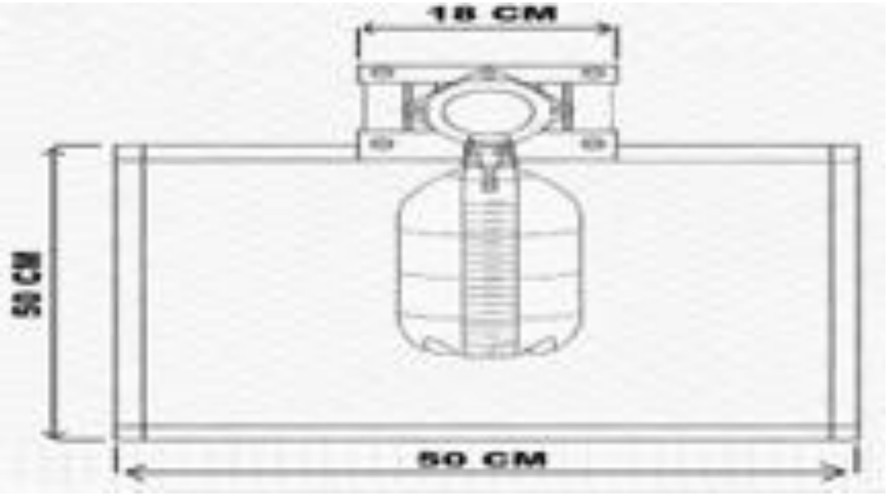

Figure 5. Design and Construction of a Wave Power Plant Using a Recoil Starter Front.

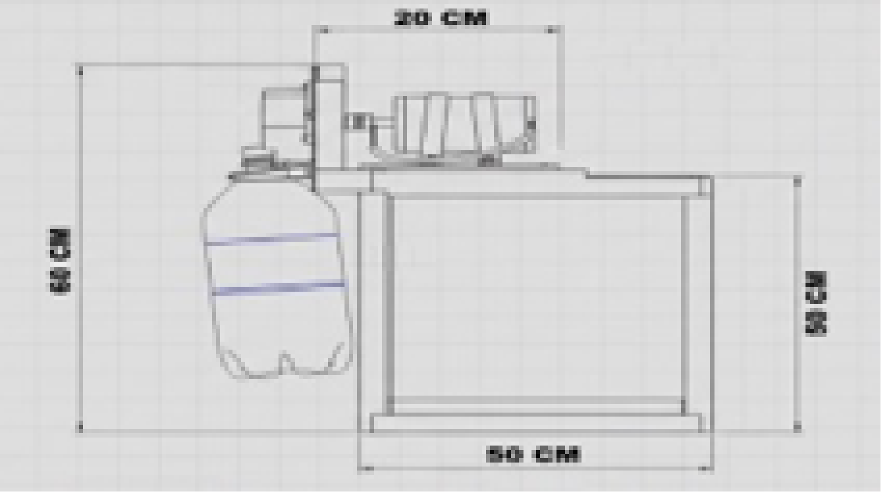

Figure 6. Design and Construction of a Wave Power Plant Using a Recoil Starter Side.

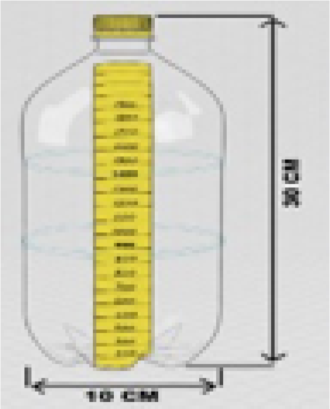

Figure 7. Design of the Float.

3.5 Data Analysis

The dynamic testing provided the most critical insights into the system's behavior, particularly the interaction between buoy mass and wave height.

a. Regression Analysis: Linear and polynomial regression were used to model the relationship between wave height and voltage.
b. Efficiency Calculation: System efficiency was evaluated by comparing the electrical energy stored in the battery against the theoretical energy flux of the generated waves.
c. Comparative Analysis: The performance of different ballast configurations was compared to identify the optimal mass for the specific spring constant of the recoil starter.

4. RESULTS AND DISCUSSION

Dynamic Performance Analysis

Dynamic testing evaluated the system's performance under actual water flow conditions. The results are categorized into minimum, maximum, and operational range performance.

Table 1. Minimum Testing Data.

No	Float Weight (ml)	Wave Weight (cm)	RPM (Revolutions Per Minute Recoil Starter)	Voltage (V)
1	0–800	0	0	0
2	900	5	45	2.9
		10	92	6.1
		15	131	9.3
		20	178	10.8
		25	223	11.6
		30	265	13.5
3	1300	5	42	2.7
		10	85	5.8
		15	121	8.8
		20	164	10.5
		25	206	11.2
		30	249	12.7
4	1700	5	39	2.4
		10	82	5.3
		15	117	8.4
		20	159	10.2
		25	202	10.8
		30	244	12.4
5	1800–2000	0	0	0

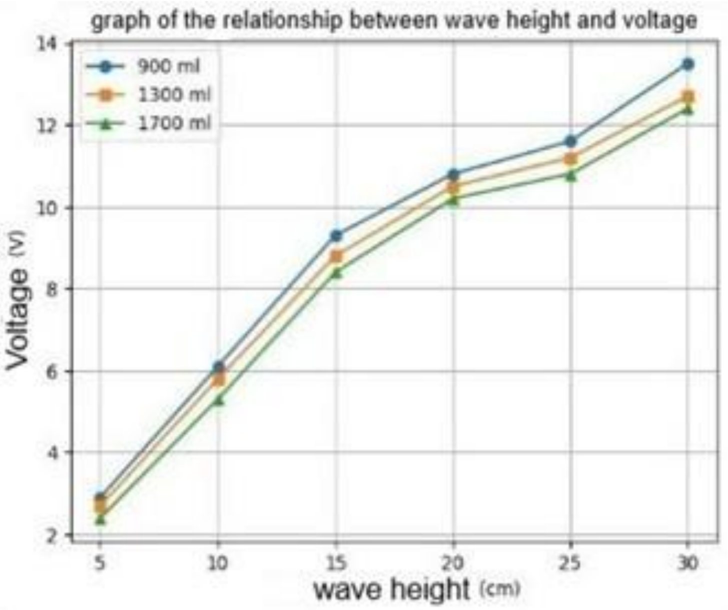

Figure 8. Wave Power Plant Testing.

The Physics of Ballast Optimization

The data reveals a distinct operational envelope determined by the ballast volume: 1) The "Dead Zone" (0-800 ml): At low ballast volumes, the system failed to generate any voltage. This can be explained by the mechanics of the recoil starter. The starter has a retraction spring that exerts a constant upward tension on the rope. If the buoy is too light, the spring tension overcomes the buoy's weight, keeping the rope fully retracted even as the wave drops. The buoy simply floats on the surface, moving up and down without extending the rope. There is insufficient gravitational restoring force to cycle the mechanism. 2) The "Sweet Spot" (900 ml): At 900 ml, the system achieved optimal performance. This mass represents the perfect impedance match. It is heavy enough to overcome the spring tension and extend the rope during the wave trough (gravity > spring force), but light enough to be in the highest RPM and voltage (13.5V at 30 cm waves). 3) The Damping Effect (>1300 ml): As ballast increased to 1300 ml and 1700 ml, performance degraded. While these heavier buoys have no trouble extending the rope, their increased inertia makes them sluggish. They react slower to the rising wave front. Instead of riding the crest immediately, they lag behind, reducing the relative velocity between the rope and the recoil mechanism. This "over-damping" results in lower rotational speeds and reduced voltage (dropping to 12.4V at 30 cm). 4) System Failure (>1800 ml): At very high ballast, the buoy's density approaches or exceeds that of water (or the reserve buoyancy becomes negligible). The buoy sits too low in the water or sinks, unable to provide the buoyant lift required to pull the rope during the wave crest (depending on the PTO configuration) or unable to float high enough to allow the spring to retract during the trough.

Wave Height Sensitivity and Power Scaling

The relationship between wave height and voltage for the optimal 900 ml configuration follows a clear upward trend: 1) Cut-in Threshold: At 5 cm wave height, the output (2.9V) is negligible. This indicates a "cut-in" threshold where the wave energy is insufficient to overcome the static friction (stiction) of the mechanical seals, bearings, and gearbox. 2) Linear/Quadratic Growth: Between 10 cm and 30 cm, the voltage grows significantly. Theoretically, power scales with (H2). Here, voltage (which is proportional to speed) scales roughly linearly with height (H). Since Power P = V2 / R, this implies that electrical power indeed scales with the square of the wave height (H2), validating the fundamental wave energy equation in this prototype setup. 3) Operational Viability: The system begins to produce useful charging voltage (>12V) at wave heights approaching 25-30 cm. This suggests that the prototype is viable for small sea states (Sea State 2 on the Douglas scale), making it suitable for sheltered waters or calm open seas.

System Integration and Practical Implications

The integration of the system on a prototype ship introduces the variable of vessel motion. In a real-world scenario, the ship also heaves. Ideally, the WEC should be designed such that the buoy's natural frequency is out of phase with the ship's natural frequency. If they move in phase (both rise and fall together), net energy capture is zero. The use of a relatively small, responsive buoy (900 ml) likely ensured that its response frequency was higher than that of the larger prototype vessel, maintaining the necessary relative motion.

The use of the ESP32 and PZEM-017 allows for "smart" energy management. In a deployed scenario, this data could trigger a dynamic ballast system (e.g., pumping water in or out) to maintain the 900 ml "sweet spot" or adjust it if the sea state changes (e.g., increasing ballast in larger, longer-period waves to prevent slamming).

5. CONCLUSION

Based Based This research successfully demonstrates the design, construction, and validation of a ship- mounted Wave Energy Converter utilizing a recoil starter PTO. The study arrives at several key conclusions: 1) Feasibility of Mechanical PTO: The modified recoil starter is a viable, low-cost solution for converting wave energy on a 0-30 cm. It effectively rectifies oscillatory motion into unidirectional rotation, provided the mechanical impedance is matched to the hydrodynamic forces. 2) Criticality of Ballast Tuning: The system's performance is highly sensitive to buoy mass. An optimal ballast of 900 ml was identified for this specific configuration. Deviations from this optimal mass resulted in either failure to actuate (0-800) or inertial damping (1800-200), highlighting the importance of precise hydrodynamic tuning. 3) Energy Generation Potential: The prototype demonstrated the capability to generate up to 13.5V in 30 cm waves, validating its potential as an auxiliary charging source for 12V marine battery systems. The linear relationship between wave height and voltage output confirms the scalability of the concept. 4) Reliability of Monitoring: The low-cost IoT monitoring architecture provided high-fidelity data (>99% accuracy), proving that sophisticated performance analysis is accessible without expensive industrial instrumentation.

This research paves the way for further development of decentralized marine energy systems. Future work should focus on developing active control systems for real-time ballast adjustment and testing the long-term durability of the recoil mechanism in corrosive saltwater environments.

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